Advances in Intelligent Systems and Computing 1358

Boris M. Velichkovsky
Pavel M. Balaban
Vadim L. Ushakov *Editors*

Advances in Cognitive Research, Artificial Intelligence and Neuroinformatics

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Preface

Cognitive Science in Northeastern Europe

Today's cognitive science is the latest version of the century-long quest for a better understanding of the human mind and brain. Various disciplines have brought together empirical methods and theoretical models from their respective fields to further these interdisciplinary efforts. Amongst major of them, one has to mention contemporary informatics with artificial intelligence and robotics, mind philosophy, psychology, linguistics, biology at large, and, of course, neurophysiology. What are scientific sources and organizational history of cognitive and neurophysiological studies in the northeast of Europe?

In this part of the world that is in the former USSR and the contemporary Russian Federation cognitive endeavor has the same root as elsewhere—the romantic tradition of European science. Hermann von Helmholtz was the central figure here in the nineteenth century. He graduated from the Prussian Medical-Military School in Berlin, where his education was paid for by the state. Therefore, he should work as military chirurgic in troops for the rest of life. It was Alexander von Humboldt—nature -philosopher, world traveler, and foreign member of St. Petersburg Academy of Sciences—who as high-ranking Prussian official together with his brother, the great linguist Wilhelm von Humboldt, freed him up from the duties of military service. This opened Helmholtz way to scientific carrier. In the following decades, he contributed a lot not only to his favorite physics but to physiology, mind philosophy, and psychology as well. The founder of this later discipline was his research assistant at Heidelberg University, Wilhelm Wundt. Ladies doctor by education, Wundt was also convinced that newborn "mental chemistry", as science could only be one of interdisciplinary and experimental kind.

The known Russian scholars, Ivan Sechenov and a bit later Vladimir Bechterev, made their studies with Helmholtz, Wundt, and the founder of electrophysiology Emil Duibois Reymond. They studied the same problems but sometimes with radically different accents. For example, when Duibois Reymond declared that consciousness and volition were and would be in the future outside of natural sciences competencies—*ignorabis et ignorabimus*—Sechenov indirectly replied that conscious thought can be understood objectively, that is, by methods of natural sciences, as inhibited reflex. This approach demonstrated a remarkable productivity in research on the role of prefrontal inhibition in cognitive control and working memory some 100 years later [1]. In the focus of Bekhterev's interests were brain anatomy, mental diseases, psychology, and sociology. In 1885, he founded the laboratory of objective psychology at Kazan University in Volga. This happened only few years after Wundt opened the first psychological institute in the world in Saxonian Leipzig. Linguistics already flourished in Kazan at those times in the work of Jan Baudouin de Courtenay and his students, one of which, Nikolay Trubetskoy, later became international celebrity in phonology. The major international acclaim in the 19th Century the Kazan University had for the work of its liberal rector, mathematician Nikolay Lobachevsky, author of non-Euclidian geometry

In the twentieth century, the idea of integrating different branches of mind-and-brain studies received further impetus from the rocketing development of informatics. In fact, the von Neuman architecture of conventional computer was the first metaphor of modern cognitive psychology [2]. Swiss biologist Jean Piaget even gave psychology a central place among the sciences and technologies, because, in his view, only this discipline studies the conscious mind that makes science and critical thinking possible [3]. However, he always insisted that he studied "epistemic" and not psychological issues. In a similar vein, some of researchers in artificial intelligence, neurophysiology, and psychology would say today that they belong to an interdisciplinary cognitive community whereby adjective "cognitive" replaces here what Piaget called "epistemic" half a century ago. Frankly, other researchers would rather emphasize higher nervous activity and behavior in this context as, for instance, founders and members of Physiological Society named after Ivan Pavlov. An important pioneer of cognitive neuroscience was neuropsychologist Alexandre Luria who became widely known for his research of cognitive development, neurolinguistics, and the functions of brain's frontal lobes [4]. At the end of his life, Luria worked in Moscow but he graduated from Kazan University.

On these historical reasons, the First International Conference of Cognitive Science in the former USSR took place in Kazan in 2004. The 2nd to 8th biannual conferences followed in St. Petersburg, Moscow, Tomsk, and different places of Baltic region. They were organized by the Interregional Association of Cognitive Studies (IACS). Many distinguished international speakers and guests were among hundreds of participants. In particular, one has to name a number of Nobel Prix winners visiting these and related scientific events at different times, such as Daniel Kahneman, Gerald Edelman, James Watson, and Roger Penrose.

The actual book is the postproceeding volume of the 9th International Conference of Cognitive Science, which took place in Moscow from October 10 to 16, 2020 (**Intercognsci–2020**). The Russian Academy of Sciences (RAS) participated in the organization of this conference, and it was partially supported by the Russian Foundation of Basic Research and a number of universities and institutions including the National Research Center "Kurchatov Institute."

In the particular circumstances of this year due to the coronavirus pandemic, only a few colleagues from other parts of Europe and the world were able to participate physically. On the contrary, the interdisciplinary character of reports and virtual discussions at this year conference was very strong. Contributions spanned from artificial intelligence and robotics, to consciousness and voluntary actions, and eye–brain–computer interfaces. For the first time, they also reported on the activities of the Physiological Pavlov Society, besides those of the IACS. We are glad to present a selection of peer-reviewed papers written by members of both these learned societies to our readership around the world.

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January 2021

Boris M. Velichkovsky
Pavel Balaban

References

1. Posner, M. I. (ed.): Cognitive neuroscience of attention. The Guilford Press, NY (2004)
2. Neisser, U.: The limits of cognition. In: P. M. Jusczyk & R. M. Klein (eds.). On the nature of thought. Essays in honor of D.O. Hebb. Erlbaum, Hillsdale (1980)
3. Piaget, J.: Psychology and epistemology: Towards a theory of knowledge. Penguin, Harmondsworth (1972)
4. Luria, A. R.: Basic problems in neurolinguistics. Mouton, The Hague (1976)

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Conference Invited Lectures

Language, Cognitive Systems, and the Methodology of Observation

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Abstract. Language and speech constitute one of the major manifestations of the covert cognitive systems. Each representative of Homo sapiens constantly and massively produces material that can be used as a source of data for the reconstruction of cognitive processes. At the present time linguistic corpora exist that represent linguistic behavior, both spoken and written. This observational resource remains underestimated. Linguists are usually interested in narrow linguistic issues, while specialists in cognitive science only infrequently consult observational data. I discuss a number of linguistic phenomena that manifest general cognitive systems. These linguistic phenomena include discourse structure, disfluencies, a range of reference-related processes, agreement, and multichannel communication. I demonstrate that corpus-based studies of these phenomena shed light on cognitive systems and processes, such as goal-oriented behavior, decision making, non-deterministic choice, working memory, attention, consciousness, theory of mind and so forth. Linguistic resources thus provide a window into general cognition. The methodology of observation may be very useful to this end, especially if used in conjunction with experimentation and modeling methods.

Keywords: Language · Cognitive systems · Observational evidence · Linguistic resources · Discourse structure · Reference · Multimodality

1 Introduction

In this paper I argue for the following two interrelated points:

- Cognitive science may gain from linguistic evidence much more than it currently does;
- Observation is a valuable and informative scientific methodology, along with the other widely recognized methodologies.

Language and speech are among the major **manifestations** of the covert cognitive systems. Each representative of Homo sapiens constantly and massively produces material that can be used as the source of knowledge on how cognitive systems operate. This source of knowledge is strongly underestimated in general cognitive studies, being

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usually delegated to specialized fields such as psycholinguistics or cognitive linguistics. In this paper I discuss a number of linguistic phenomena that manifest various cognitive systems or cognitive processes, such as dynamic structure of behavior, decision making, attention, working memory, consciousness, predictive planning, theory of mind, embodiment, etc. Such notions are *italicized* in the discussion below for a reader's convenience.

Nowadays, linguistic evidence is available in the form of various **resources**, or corpora, representing linguistic behavior, both spoken and written. Observation of the evidence contained in those resources complements the knowledge obtained via the methodologies of experimentation and modeling.

The importance of the **observation methodology** was pointed out many times in the history of science. For example, one of the founders of Gestalt psychology Wolfgang Köhler wrote: "There seems to be a single starting point for psychology, exactly as for all the other sciences: the world as we find it, naively and uncritically. The naiveté may be lost as we proceed. Problems may be found which were at first completely hidden from our eyes. < … > This origin is necessary because there is no other basis from which a science can arise." [1, p. 3]. Wallace Chafe, a linguist whose fundamental contribution will be salient in the discussion below, said: "I will be combining observations of natural language with introspective data concerning the meanings and functions of phenomena observable in compilations of naturally occurring corpora. < … > Furthermore, both spoken and written corpora have the decided advantage of providing data that are natural and not manipulated. < … > Certainly corpus-based observations must be supplemented with introspections, constructed sentences, and experiments, which can carry us beyond the accidental limits of a corpus and give us further insights and further verifiability. But introspections, constructions, and experiments without corpora are fatally limiting." [2, p. 19–20].

The **linguistic phenomena** considered below in six subsequent sections include:

- Discourse Structure
- Disfluencies
- Reference and Referential Choice
- Referential Strategies and Referential Conflict
- Agreement
- Multichannel Communication.

This particular selection is not uniquely suited to the goals of the paper. Virtually any linguistic phenomenon would work to demonstrate the point. I concentrate here on the linguistic phenomena I studied over the years. So this paper largely recounts studies done by myself and my coauthors.

My approach is in line with what George Lakoff [3, p. 40] called the **cognitive commitment**: "a commitment to providing a characterization of general principles for language that accords with what is known about the brain and mind from other disciplines, as well as our own." As was pointed out by Dagmar Divjak [4], this commitment is not always taken sufficiently seriously by cognitive linguists. Furthermore, Aleksandr E. Kibrik (1939–2012) proposed the idea of the **reconstruction of cognitive structure**: "At the foundation of the contemporary cognitive approach to language there is an idea of a focused reconstruction of cognitive structures on the basis of overt linguistic form. Such reconstruction relies on the postulate of cognitive motivation of linguistic form: to the extent that form is motivated it reflects the underlying cognitive structure" [5, p. 53].

In this paper I intentionally avoid numerous references to general cognitive literature; if I tried, for example, to involve vast literature on attention or working memory, my task would become boundless. Relevant references may be found in the specific linguistic studies that I cite here.

2 Discourse Structure

Discourse is a complex phenomenon. Particular discourses, such as a long conversation or a novel, can be very voluminous. The highest level divisions of discourse determine its global structure, such as chapters in a book. At the opposite end, there is **local discourse structure** consisting of minimal units of discourse. It is the local structure that is the subject of this section, and the discussion is limited to spoken discourse. Local discourse structure provides a window into the basic cognitive phenomenon of the *dynamic structure of behavior*.

The local structure of spoken discourse consists of **elementary discourse units** (EDUs), see [6]. Speech is produced not as a monotonous flow, but in a stepwise fashion. A study of local discourse structure done by our group is based on the corpora of Russian and some other languages, see www.spokencorpora.ru. Our approach was significantly influenced by the work of Chafe [2] and by the work of the Russian phonetician Sandro V. Kodzasov who explored various aspects of prosody, that is non-segmental sound, see [7]. Spoken discourse can only be explored via a procedure known as discourse transcription: a systematic graphic representation of the structural and functional phenomena of speech, see [6].

EDUs are identified on the basis of prosodic (behavioral) criteria, including pausing, tonal contours, accentual centers, tempo patterns, and loudness patterns. Consider example (1) from the Russian corpus "Funny Life Stories":

(1)

21.33	15	•••(0.90) Kogda mne budet /dvadcat' let, When I am twenty years old,
23.44	16	/–tebe budet ••(0.39) tol'ko \pjatnadcat'. you will only be fifteen.

An acoustic representation of example (1) appears in Fig. 1. This example contains two EDUs, #15 and #16. The first of these has an absolute boundary pause at the beginning marked as "A" in Fig. 1. Both EDUs have holistic tonal contours. Each of the EDUs has an accentual center; the corresponding syllables are marked by ellipses in Fig. 1. There is a clear deceleration effect: in EDU #15 the difference between the mean durations of the initial and final syllables is 128 ms to 206 ms, while in EDU #16 it is 118 ms to 176 ms.

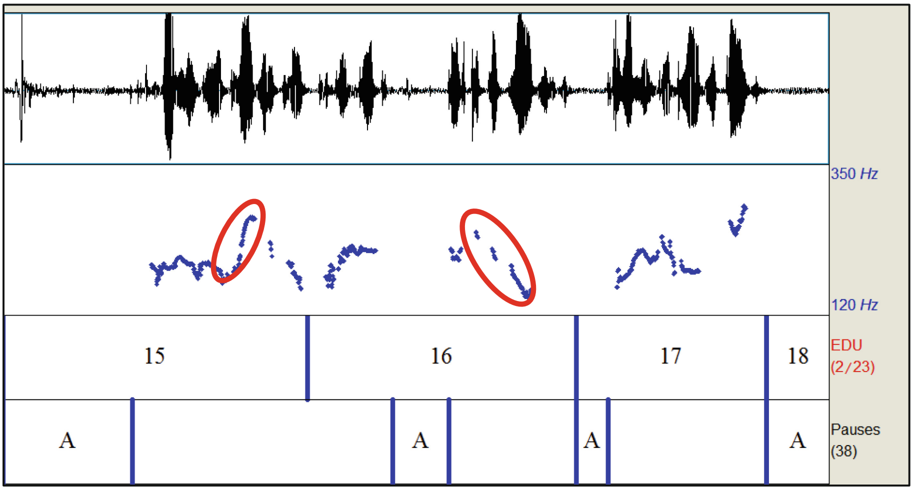

Fig. 1. An acoustic representation of example (1)

The stepwise character of speech and the organization of EDUs have deep evolutionary roots and have much in common with the structure of *goal-oriented behavior* in other species. Chafe [2] suggested that EDUs (intonation units, in his terms) are an overt manifestation of the *foci of consciousness* – a cognitive system that also progresses in a stepwise fashion. Semantically, EDUs typically represent events or states and form a network of connected nodes that can be depicted via hierarchical graphs of Rhetorical Structure Theory [8].

Syntactically, EDUs correlate with clauses. In a number of studies of various languages and various corpora, the level of such correlation was found to vary between 40% and 70%, the latter being more common. There are always residues of subclausal and superclausal EDUs; in a Russian corpus their shares were found to be 26% and 6%, respectively. Overall, clauses are target units via which discourse production progresses. At the same time, clauses are units of experience storage in *long-term memory*. Clause is thus at the intersection of two axes: online dynamic structure of behavior and offline storage. Clause as the fundamental unit of language must have arisen on the basis of the proto-humans' converging abilities to structure their own behavior and the reported experience. In contrast, sentences as groups of EDUs or clauses are much less robust, second-order units that can only be identified in spoken discourse through a fairly sophisticated prosody-informed procedure; see [6] for further details.

To recapitulate this section, spoken discourse is a structured and uniquely explicit manifestation of meaningful behavior. Local discourse structure consists of identifiable behavioral acts – elementary discourse units. EDUs conform to fundamental cognitive constraints, also found in non-linguistic behavior. EDUs correlate with the basic linguistic unit: clause. Human speech is shaped by the coordination of two kinds of segmentation: the quanta of one's own behavior (EDUs) and the quanta of reported experience (clauses).

3 Disfluencies

The delivery of speech is often less than ideal, cf. [9]. Various kinds of **disfluencies** occur. Roughly one can distinguish between two kinds: hesitation (mild disfluency) and self-correction (severe disfluency); see [10] for additional detail. An example of a **hesitation** is found in example (1): it is a pause in the middle of EDU #16, which is not a canonical place to make a pause. In general cognitive literature, this phenomenon is sometimes described as *lingering*; it results from some kind of a temporary *cognitive deficit*: the speaker has hard time finding an appropriate way to phrase his/her thought. This deficit is eventually overcome, and the structure under construction is completed.

Self-correction occurs when a speaker is not able to resolve his/her difficulties and has to cancel and redo some part of the already begun structure. Consider example (2) from the “Funny Life Stories” corpus.

(2)

22.99	23	mne \stydno bylo v /ško̲lu xodit’, I was ashamed to go to school,
24.12	24	••(0.38) a u nas /ma̲lčik učilsja, and there was a boy in our class,
25.53	25	•••(0.72) i ètot /malčik menja posto= == and this boy const= ==
26.94	26	(A on naoborot \otra̲ščival /vo̲losy, (While he the other way around was growing his hair,
28.28	27	i u nas s nim polučilos’ odnoj \dliny̲ gde-to primerno.) and he and I got the hair of about the same length.)
30.29	28	•••(0.28) i /on menja načal podka = ǁ nu tipa \postojanno /podka̲lyval, and he started teas = ǁ well he was like constantly teasing me,

In EDU #24 the speaker introduced a new character, and in #25 she starts telling about the boy teasing her but interrupts herself, having realized that the addressee lacks crucial information, necessary for understanding the reported events. This background information is introduced in EDUs #26 and #27 by way of a parenthetical construction, and subsequently the situation of teasing is reported anew in EDU #28. The cognitive basis of this phenomenon of self-repair is twofold. First, it is *self-monitoring*: the speaker not only speaks, but also listens to herself at the same time. Second, it is the permanent process of modeling the other, known as *theory of mind*: the speaker assesses her own discourse from the point of view of the interlocutor’s supposed cognitive states and, if such assessment suggests that her contribution was not satisfactory from the other’s point of view, she corrects her behavior accordingly.

4 Reference and Referential Choice

What is inside EDUs and clauses? One of the main phenomena found there is instances of **reference**, that is linguistic expressions mentioning referents, or entities. For example, at a certain point in discourse I may want to mention Peter the Great, as opposed e.g. to Catherine the Great. An elegant demonstration of how important referential expressions are was offered in [11, p. 230–232], where all referential expressions were removed from a piece of text, which operation rendered the text entirely incomprehensible. In contrast, if one removes everything except for referential expressions, a semantic backbone of the text remains partly recoverable. Reference thus constitutes a lion's share of all information conveyed in natural communication.

Reference is among the most basic cognitive operations performed by language users. Cognitively, reference is a linguistic manifestation of *attention*. Just like attention, reference is selective: at any moment one can only attend to a few things and can only mention a few entities. As was demonstrated in the Sect. 2, discourse tends to move forward via clause-size moments. Clauses typically involve one or two participants, much more rarely three participants and very rarely more than three. This linguistic limitation is a specific instantiation of a more general limitation of the attentional system. Furthermore, many languages attribute the privileged status of subject to one of clause participants. This corresponds to the cognitive notion of *focal attention*, cf. [12].

When the decision to mention Peter the Great is in place, the speaker needs to choose a particular referential expression among the available options. This is the process of **referential choice**.

Basic referential choice is the choice between a lexically full and a lexically reduced forms. Lexically full forms are also called full noun phrases (full NPs) and include, primarily, proper names (such as Peter) and descriptions based on common nouns (e.g. the tzar). Reduced mentions include pronouns (such as he) and zero expressions. Basic referential choice is driven by a referent's status in *working memory*, specifically by the degree of its *activation*:

- high activation in working memory => reduced mention
- low activation in working memory => full mention

Reference and referential choice are instances of *decision making*; speakers make decisions of this kind every moment and do that very rapidly. Table 1 summarizes the cognitive underpinnings of the two phenomena. In [13] I discussed the major issues in reference and referential choice, including both theoretical and cross-linguistic ones.

Table 1. Reference, referential choice, and the corresponding cognitive systems

Linguistic phenomenon		Cognitive phenomenon	
Reference	Decision to mention a referent	Attention	Selective processing of certain information to the exclusion of other information
Referential choice	Decision on which referential expression to employ	Working memory	High level of activation, allowing immediate access

Referential choice is based on referent activation in working memory. But where does activation come from? According to one of the suggestions, attention and working memory are two related cognitive systems: “attention can serve as a kind of ‘gatekeeper’ for working memory” [14, p. 202]. This idea is supported by the observation of linguistic evidence: what is mentioned (and therefore attended) at the discourse moment t_n is mentioned in a reduced way (and thus highly activated) at the discourse moment t_{n+1}. In linguistic terms, mention t_{n+1} is usually called an anaphor and mention t_n its antecedent. All models of referential choice (aka anaphora, coreference, etc.) recognize that proximity to antecedent is among the key factors of reduced reference. The omnipresent connection between a prior mention and the current reduced reference thus sheds crucial light on the issue of the *relationship between* these two central cognitive systems, *attention and working memory*, hotly debated in psychology for decades (see e.g. a recent review in [15]).

Distance to antecedent is among the main **activation factors**, contributing to a referent’s current activation. There is a number of metrics used in the measurement of referential distance, including linear distance in clauses, distance along the hierarchical discourse structure, distance in paragraphs, etc. Another activation factor is the role played by the antecedent in its clause: it is known that subjects make good antecedents for subsequent reduced mentions. Remember that subjects encode focal attention, which again corroborates the attention-working memory relationship.

The above mentioned factors are grounded in the current discourse context. Another group of activation factors is associated with the referent’s more permanent properties, such as the status of the current discourse’s protagonist or the inherent property of animacy. In particular, discourse evidence suggests that human referents are *maintained in working memory* better than inanimate ones; a similar conclusion was reached in some experimental studies, e.g. [16]. A flow chart of activation factors, activation level, and referential choice appears in Fig. 2 in the next section.

A number of studies in which activation factors were mathematically assessed and shown to work together in a calculative or a neural network model are reviewed in [13]. One of the results of such modeling is a linguistically based evaluation of the *working memory capacity*. Since the developed calculative model can compute each referent’s activation at each discourse moment, summary activation is easily obtained. In that model the value of 1 was the maximal activation of a referent. It was found that summary activation of all referents mostly fluctuates between 2 and 3 and does not exceed 4.

A machine learning study of referential choice in a corpus of English texts is reported in [17]. Several thousand anaphor-antecedent pairs were explored and a number of algorithms were tested. The basic referential choice between full NPs and reduced expressions was predicted with the accuracy of about 90%. Subsequently we inquired into the remaining 10% and found that many of those instances were appropriate to human language users as well. An experimental study demonstrated that the texts containing referential options proposed by the algorithm were comprehended as successfully as those that contained original expressions. This suggests that referential choice is a case of partly *non-deterministic decision making*.

To summarize the discussion in this section, reference and referential choice are decision making processes, related to attention and working memory activation, respectively. In particular, high activation is responsible for reduced reference. There is a set of activation factors, grounded in discourse context and in referent's properties. Discourse evidence suggests that working memory is controlled by attention and has a capacity limit of 4 items. Referential choice is partly non-deterministic.

5 Referential Strategies and Referential Conflict

When making referential choice, a speaker has direct access only to his/her referent activation. But it is also important to model one's addressee's cognitive processes. For example, if I say *he* or *them* without caring about the mental state of my interlocutor, the act of reference will likely be unsuccessful. The human ability of modeling the other's cognitive processes is conventionally called *theory of mind*. The observation of actual practices of referential choice in discourse suggests that there are three different **referential strategies**, related to modeling the other and employed by various speakers:

- Egocentric: assume that others' thoughts are just like mine → referential choice is overly economical;
- Overprotective: no assumptions about others' thoughts → referential choice is overly detailed;
- Optimal: make reasonable assumptions about others' thoughts → referential choice is just about right.

The egocentric strategy is found in young children, sometimes in the elderly, and in certain neurological disorders. The overprotective strategy, for example, is observed in certain computational applications imitating human behavior. Those who generally stick to the optimal strategy may occasionally slip into the egocentric strategy and then mend referential choice immediately after, as in example (3) from the "Night Dream Stories" corpus, similar to what linguists call "antitopic construction".

(3)

13.85	7	I /ja < 2 > ••(0.13) /podo-ošё̲l k nemu, And I approached it,
15.93	8	••(0.34) nu k ètomu /de̲revu, well this tree,
17.38	9	u kotorogo /sverka̲lo čego-to, near which something was flashing,

In EDU #7 the speaker uses a third person pronoun, apparently meaning the tree that was activated in his working memory at that time, and then realizes that the referent is not activated in the addressee. He then adds two EDUs that specify the referent by means of a noun phrase with a relative clause.

There is another important domain in which speakers need to utilize their theory of mind: those associated with referential ambiguity, or **referential conflict**. As was pointed out in the previous section, more than one referent may be activated in the participants' working memories at the same time. Consider the following constructed example.

(4) Uncle John was sitting at the table. Suddenly a boy approached him. He yelled at him.

By the beginning of the last sentence of (4) the system of activation factors brings two referents to a high level of activation, appropriate for the use of third person pronouns. Two pronouns are used in that sentence, but that is infelicitous: a potential addressee would not know who was the agent and who was the patient of the yelling event. A proper speaker, deploying his/her theory of mind, foresees this situation, filters out at least one of the pronouns and uses a full NP in spite of high activation.

It is important to realize that referential conflict is a separate component of referential choice and not one of the activation factors. It is easy to see that: suppose it is not a boy but a girl appearing in the second sentence of (4). Then *He yelled at her* or *She yelled at him* would be perfectly comprehensible. Therefore, the infelicitous character of (4) is certainly due to something different from insufficient activation. We see that gender is a feature of the English language that helps to remove a potential referential conflict. A variety of such devices (referential aids, or deconflicters, see [13]) are employed in each language and cross-linguistically.

We are now ready to consider the full organization of referential choice, shown in a flow chart in Fig. 2.

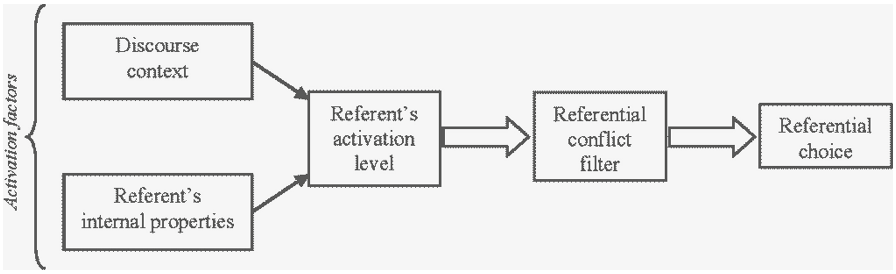

Fig. 2. The cognitive multi-factorial model of referential choice

6 Agreement

According to the linguistic tradition, many morphological facts about languages are explained via the notion of agreement: certain words agree with other words in categories such as person, number, or gender. Agreement is thought to be a purely grammatical asymmetric relationship between verbal units. This view is largely shared by psycholinguists, as well as the general learned public. Consider Russian examples in (5).

(5) a. my bež-im ‘We run’
We run(PRES)-1PL
b. ona beža-l-a ‘She ran’
she run-PAST-FEM.SG

Russian verbs happen to agree with the subject in person and number in the present tense (5a) and in gender and number in the past tense (5b). It seems unquestionable that –im in (5a) appears because the clause subject is the first person plural pronoun, and –a in (5b) because the subject is a feminine singular pronoun. But now consider (6), said by a woman.

(6) ja beža-l-a ‘I ran’
I run-PAST-FEM.SG

What does the verb agree with now? With the first person subject pronoun? Hardly, as that pronoun is not specified for gender. If the verb in (6) agrees with anything, it is the speaker’s own gender. This counterexample is very simple and basic, but it suffices to undermine the traditional grammatical approach. An alternative approach was proposed in [18], the so-called **cognition-to-form mapping**. Apart from instances such as in (6), there are other massive types of evidence that present problems to the grammatical approach. To mention just a few:

- Instances of exophora: in a language such as Russian or Spanish, where adjectives are specified for gender, one can use a sole feminine adjective as applied to a female that is visible to the speaker and the addressee but was never mentioned before verbally.
- Non-local context: agreement features may appear on certain words, while the nearest previous mention in discourse was beyond a reasonable syntactic context, for example in the previous sentence or the previous paragraph.
- Conjunction: conjoined singular nouns typically cooccur with plural forms of verbs, as in *John and Mary are singing*.

The cognition-to-form mapping approach suggests that referents are equipped with certain features in *mental representation*, and these features are mapped on certain sites required by the grammar of the given language. If features of one and the same referent are mapped onto two or several sites, we observe agreement between these sites, as in (5). But it is parallel agreement, resulting from a common external cause, rather than from a formal relationship between linguistic constituents.

The reason why linguists and other scholars still adhere to the problematic notion of form-to-form grammatical agreement is probably associated with the common but narrow view of language as a symbolic system operating on words and governed by formal rules. If language is seen as a cognitively-based and usage-oriented communication process, the picture becomes much more clear and makes better sense.

7 Multichannel Communication

When we communicate naturally, we not only produce chains of words, but also intonate, gesticulate, assume various postures, interact with eye gaze, etc. These processes are traditionally studied by different academic disciplines. Linguistics has been traditionally largely restricted to the verbal component, while some other components were considered in psychology, neuroscience, or other disciplines. However, the actual communication process is whole and undivided, and the realization of this truth gave rise to the idea of **multimodality**, see e.g. [19–23]. Verbal language is interwoven with other kinds of communicative behavior, and this is one of the facets of language *embodiment*.

In fact, the notion of multimodality is somewhat overstated, as just two modalities are explored at the present time: auditory and visual, or, from the addresser's perspective, vocal and kinetic. Each of the modalities involves a number of communication channels, so I prefer the notion of **multichannel discourse**; see [24] and Fig. 3 below.

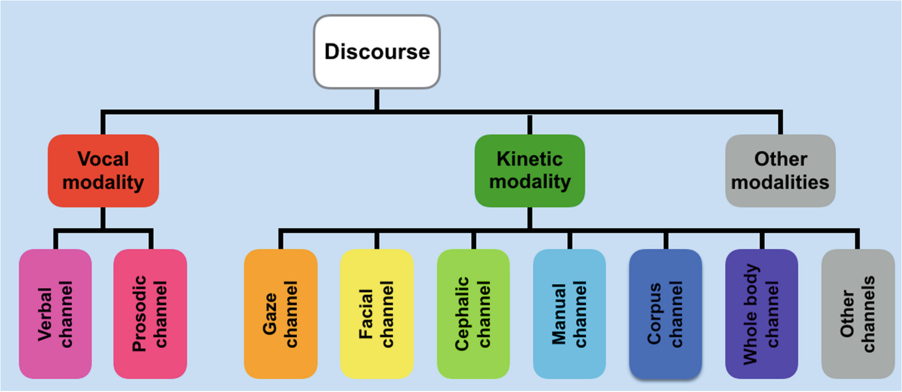

Fig. 3. A model of multichannel discourse

This approach was used as a foundation for the resource "Russian Pear Chats and Stories" (RUPEX) created for multichannel research, see www.multidiscourse.ru. This resource is intended to approach the actual richness of natural communication "as is" and registers multiple kinds of communicative behavior, including verbal, prosodic, gestural, and oculomotor behavior. These kinds of behavior are presented in the form of multimedia documentation and the corresponding detailed annotations. Figure 4 illustrates the organization of RUPEX. RUPEX has an advanced search system allowing one to find specific phenomena of various channels and combinations thereof, see www.multidiscourse.ru/search/?locale=en#!/query.

This kind of a resource allows one to address numerous research questions about the actual use of language in communication, for example:

- Cooperation of channels: how various commnication channels are coordinated with each other, for example how different is manual behavior while speaking and while listening;
- Temporal alignment of channels: how individual behaviors belonging to various channels are (de)synchronized with respect to each other, for example whether manual gestures anticipate the corresponding EDUs;

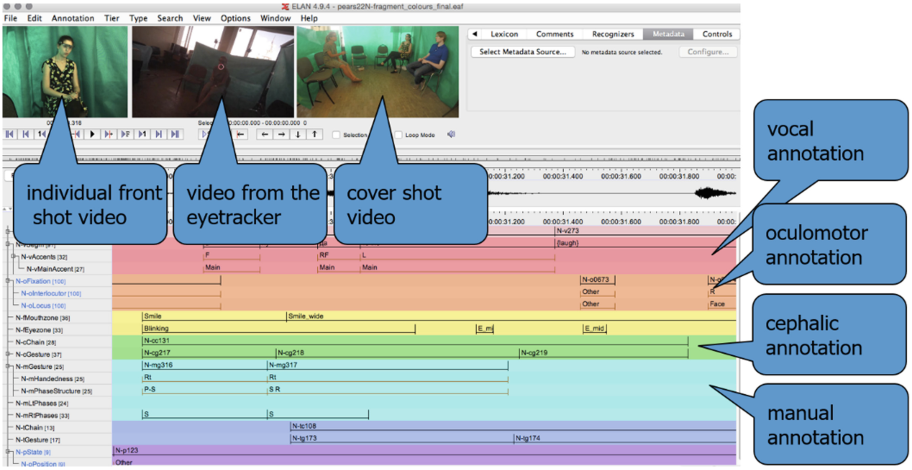

Fig. 4. An illustration of RUPEX organization

- Relationships between the vocal and and the kinetic channels: how different are the systems of speech and gestures, for example whether termporal characteristics of gestures and prosody are organized by the same or different basic principles;
- Addressee's attention to addresser's behavior: which communicative behaviors are produced in the interests of the addressee and which ones mostly help the addresser to formulate the message, for example whether addressees watch manual gestures produced by the speaker;
- Individual variation: what is the degree of variation in interlocutors' patterns, for example how the individual F0 range affects intonational patterns or how individual amplitude of manual movements affects the interpretation of such movements as communicative or physiological.

According to the widely held assumptions, linguistic communication consists of verbal code. An act of communication is a message sent from an addresser to an addressee. The speaker is an addresser, and the hearer is an addressee. Messages sent back and forth between interlocutors are temporally sequential (turn taking). Production and comprehension are two separate processes. All of these traditional assumptions are called into question in the multichannel perspective.

While speaking, the speaker visually tracks the hearer's behavior. That helps the speaker's *predictive planning* [25]. An interlocutor can simultaneously produce signal in one channel and receive signal in another channel (or even in the same channel). The speaker thus is, simultaneously, an addressee in communication. Accordingly, the hearer is an addresser at the same time. Instead of clear-cut communication turns we observe multiple communication acts across various channels. Channels conspire in building multi-channel turns. A complex **cognitive ensemble** of interwoven vocal and kinetic acts operates, in which interlocutors simultaneously transmit signals in various directions [26]. A new theory of natural communication must be developed along these lines, on the basis of the reality of face-to-face multichannel discourse.

8 Conclusions and Outlook

We daily produce a huge amount of talk and writing. Language and speech are an overt manifestation of our covert cognition. They represent a massive and directly observable source of knowledge on general cognitive systems, such as those mentioned in this paper: goal-oriented behavior, decision making, non-deterministic choice, working memory, attention, consciousness, predictive planning, self-monitoring, theory of mind, embodiment, etc. It would be equally easy to demonstrate how other cognitive systems surface in everyday language use, for example long-term memory, intentionality, categorization, affordances, or priming. The observation of natural language use may lead to novel insights and grounded conclusions on cognitive systems and processes.

At the present time, the observation of linguistic phenomena is expedited due to the existence of resources, or corpora. For example, the Google Books Ngram Viewer is a vast collection of written texts allowing diachronic cognitive studies such as [27]. The Russian National Corpus, mostly containing written texts (but speech as well) gives rise to studies in cognitive semantics such as [28]. The potential of various spoken and multichannel corpora was discussed above in sufficient detail. Apart from corpora, it is important to mention that grammars of various languages can also serve as resource for general cognitive studies.

I believe that the usefulness of linguistic resources remains underestimated. Most typically, linguists are interested in narrow linguistic issues, while those interested in cognitive science only infrequently consult rich observational data. I hope to have demonstrated in this paper that corpus-based studies, using the general scientific methodology of observation, may be quite powerful. It is useful to look at what people do when they communicate naturally. And nothing prevents one from using observation in conjunction with the complementary methods of experiment and modeling, as again was illustrated above.

Conversely, in order to understand linguistic phenomena, one needs to turn to general cognitive processes. Even though the interdisciplinary field of cognitive science has been around for a long time, serious convergence is still in the future. Such convergence may lead to a better understanding of how the human mind works.

References

1. Köhler, W.: Gestalt Psychology. Liveright, New York (1947)
2. Chafe, W.: Discourse, Consciousness, and Time: The Flow and Displacement of Conscious Experience in Speaking and Writing. University of Chicago Press, Chicago (1994)
3. Lakoff, G.: The invariance hypothesis: is abstract reason based on image-schemas? Cogn. Linguist. **1**(1), 39–74 (1990)
4. Divjak, D.: Cognitive linguistics: looking back, looking forward. Cogn. Linguist. **27**(4), 447–463 (2016)
5. Kibrik, A.E.: Lingvističeskaja rekonstrukcija kognitivnoj struktury [Linguistic reconstruction of the cognitive system]. Voprosy Jazykoznanija **2008**(4), 51–77 (2008)
6. Kibrik, A.A., Korotaev, N.A., Podlesskaya, V.I.: Russian spoken discourse: local structure and prosody. In: Izre'el, S., Mello, H., Panunzi, A., Raso, T. (eds.) In Search of Basic Units of Spoken Language: A Corpus-Driven Approach, pp. 35–76. Benjamins, Amsterdam (2020)

7. Kodzasov, S.V.: Issledovanija v oblasti russkoj prosodii [Studies in the field of Russian prosody]. Jazyki slavjanskix kul'tur, Moscow (2009)
8. Mann, W.C., Thompson, S.A.: Rhetorical structure theory: toward a functional theory of text organization. Text **8**, 243–281 (1988)
9. Clark, H.H., Clark, E.V.: Psychology and Language. Harcourt Brace Jovanovich, New York (1977)
10. Podlesskaya, V.I.: A corpus-based study of self-repairs in Russian spoken monologues. Russ. Linguist. **39**(1), 63–79 (2011)
11. Biber, D., Johansson, S., Leech, G., Conrad, C., Finegan, E.: Longman Grammar of Spoken and Written English. Pearson Education limited, Harlow (1999)
12. Tomlin, R.S.: Focal attention, voice and word order: an experimental cross-linguistic study. In: Downing, P., Noonan, M. (eds.) Word Order in Discourse, pp. 517–554. Benjamins, Amsterdam (1995)
13. Kibrik, A.A.: Reference in Discourse. Oxford University Press, Oxford (2011)
14. Awh, E., Vogel, K., Oh, S.-H.: Interactions between attention and working memory. Neuroscience **139**, 201–208 (2006)
15. Oberauer, K.: Working memory and attention – a conceptual analysis and review. J. Cogn. **2**(1), 36 (2019)
16. Daley, M.J., Andrews, G., Murphy, K.: Animacy effects extend to working memory: results from serial order recall tasks. Memory **28**(2), 157–171 (2020)
17. Kibrik, A.A., Khudyakova, M.V., Dobrov, G.B., Linnik, A., Zalmanov, D.A.: Referential choice: predictability and its limits. Front. Psychol. Lang. Sci. **7**, 1429 (2016)
18. Kibrik, A.A.: Rethinking agreement: cognition-to-form mapping. Cogn. Linguist. **30**(1), 37–83 (2019)
19. Gibbon, D., Mertins, I., Moore, R. (eds.): Handbook of Multimodal and Spoken Dialogue Systems: Resources, Terminology and Product Evaluation. Kluwer, Norwell (2000)
20. Granström, B., House, D., Karlsson, I. (eds.): Multimodality in Language and Speech Systems. Kluwer, Norwell (2002)
21. Adolphs, S., Carter, R.: Spoken Corpus Linguistics: From Monomodal to Multimodal. Routledge, New-York (2013)
22. Müller, C., Cienki, A., Fricke, E., Ladewig, S.H., McNeill, D., Teßendorf, S. (eds.): Body – Language – Communication: An International Handbook on Multimodality in Human Interaction, vol. 1. De Gruyter Mouton, Berlin (2013)
23. Grišina, E.A.: Russkaja žestikuljacija s lingvističeskoj točki zrenija. Korpusnye issledovanija [Russian gesticulation in a linguistic perspective. Corpus studies]. Jazyki slavjanskix kul'tur, Moscow (2017)
24. Kibrik, A.A., Fedorova, O.V.: A «portrait» approach to multichannel discourse. In: Proceedings of LREC 2018, Eleventh International Conference on Language Resources and Evaluation, Miyazaki, Japan, pp. 1908–1912 (2019)
25. Pickering, M.J., Garrod, S.: An integrated theory of language production and comprehension. Behav. Brain Sci. **36**(04), 329–347 (2013)
26. Kibrik, A.A., Fedorova, O.V.: Language production and comprehension in face-to-face multichannel communication. Comput. Linguist. Intellect. Technol. **17**, 305–316 (2018)
27. Solovyev, V., Batyrshin, I.: What does happiness depend on? quantitative comparative analysis of various cultures. Adv. Social Behav. Sci. **10**, 3–8 (2015)
28. Kustova, G.I., Lashevskaja, O.N., Paducheva, E.V., Rakhilina, E.V.: Verb taxonomy: from theoretical lexical semantics to practice of corpus tagging. In: Lewandowska-Tomaszczyk, B., Dziwirek. K. (eds.) Studies in Cognitive Corpus Linguistics. Peter Lang, Frankfurt (2009)

Trends and Perspectives in Cognitive Research

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Abstract. Here, we present a selective review of the tendencies in the development of mind-and-brain studies and their emerging perspectives. Our assessment is less subjective in the part, which concerns with major trends of cognitive science. Two of them are, firstly, the interdisciplinarity of research, and, secondly, an accent on intended (or at least claimed) practical results. In fact, the trends have been established decades ago but new quality was reached towards the beginning of the 21st century. Thus, natural sciences started to merge with the humanities and applied research was involved in advance of new and emerging technologies. This development requires assimilating basic cognitive results if they are sufficiently reliable. As perspectives, we discuss at more lengths four actual challenges: the necessity to implement gaze contacts in video-based conferences and distant communication; classical problem of *sensus communis*: evolutionary models of cognitive organization; possible methodological drawbacks in the recent brain-mapping studies of lexical representations while listening to orally presented narratives.

Keywords: Attention · Communication · Eye-to-Eye contacts · Sensus communis · FMRI · Evolution · Lateralization · Neurosemantics · Narratives

1 Introduction

Galilean revolution as the way of gaining new knowledge was connected to a radical simplification of picture of the world. These developments led to the rise of nature philosophy as a precursor to modern natural sciences. Centuries later, a prominent student of motivation, Heinz Heckhausen [1], described the early history of psychology in approximately the following words: "To become a science, psychology, first, lost soul, and then – consciousness and reasoning". New mentalist strain in psychology and related disciplines can be described as regaining these previously lost research territories, however under the methodological standards of natural sciences. While reasoning and intellect were central components from the beginnings of cognitive science the study of consciousness and awareness are at focus of many contemporary efforts. Though today's status of *soul* is less clear, phenomenology of shame, conscience, and personal significance is slowly becoming an important topic of research as well.

Similarly, Jerry Fodor [2] describing the organization of the mind-and-brain has assumed that besides sensory 'transducers' and classical cognitive modules some non-modular systems with isotropic architecture may exist. He called these hypothetical

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mechanisms of higher-order cognition ‘central systems’ and claimed that they will be outside of reach for scientific methodology. It seems that this last assertion was premature in the view of recent studies on neurosemantics, which we will discuss at the end of the article.

The major correlate of this trend to interdisciplinarity is the combination of methods, which virtually led to qualitative shift in the whole scientific landscape. There seems to be no impassable gap between the two branches of science–one which tries to understand (as in the humanities), and one which tries to explain (as in mathematics and natural sciences) mental phenomena. The splitting was popular at the beginning of the 20th century and afterward.

The second main trend is the intention to apply cognitive science to real world problems. The support for applied research was increasingly important for granting agencies and foundations. The members of scientific community were not always unanimously positive on this trend as it was sometimes different from the standards of basic science. However, applied studies have some obvious primacies vis-à-vis academic research. In basic research, one can be satisfied with rather spurious effects on the edge of statistical significance. We can easily accept a 5% level of significance in basic research of cognitive effects but hardly one would accept a flying apparatus that successfully lands only 95 times out of one hundred. Metaphorically speaking, the cognitive pudding has to be eaten. This means that we have to show that the results of cognitive manipulations are of some relevance for the domains of public practical interests, such as medicine, education, and technology. Fortunately, the development of these domains is fast and overwhelming, especially in new and emerging technologies. Therefore, demands on the applicability of predominantly basic studies are not very strong. One can even say that every reliably established effect in cognitive research will sooner or later get practical significance and the only problem is to find, which ones. A priority of applied research is also that we have to pay more attention to ecological validity. This emphasis on the world around us may be helpful in revealing the real cognitive mechanisms and facilities.

Of course, the issue of perspectives is more related to individual preferences and granularity of interests. There are many studies from various topics, where we see today a sudden progress in revision of seemingly well-established views, for example, in eye-tracking research [3, 4] and in discussing the classical problem of visual world stability [5–7]. For this paper, we have selected four such topics based on our personal research experience, and evaluation of their immediate and middle-term potential for application.

2 Communication Through Gaze Contacts

The pandemic has demonstrated once more that communication is the core cohesion element of our society and any functioning economy. Though telegraph and telephone made serious changes in behavior and, probably, mentality of people, these technologies raised only minor attention of the first experts to human factors engineering. It was the WWII that posed issue of attention and communication with the help of new technical means. As a young pilot in the Battle of England, Donald Eric Broadbent [8] first noticed that it is difficult to identify the content and to localize the source of one of the dozens voices simultaneously heard through his headphones during an air fight. These communication problems in understanding what was being said contrasted with a perfect understanding of one interesting talk among many others in natural spatial environment, for example, during a cocktail party. Broadbent's observation was a starting point for the decades of known cognitive studies of selective attention, initially auditory and then also visual.

By the end of 20th century, a variation of this general theme has arisen, as a bundle of new topics on human-robot interaction and joint human-machine activity. The first studies only mimicked the interaction. They demonstrated that gaze direction is of importance to disambiguate the notorious difficulty in understanding words involved in the description of an object's spatial locations [9]. Disambiguation of speech about spatial locations is crucial for any constructive enterprise, both for human-robot and for human-human interactions.

Besides the spatial aspect, eye movements in communication are of importance for something else, namely for establishing a channel of an immediate emotional feedback and for supporting mutual trust and affection in conversation. For example, eye-to-eye contacts facilitate alignment of emotional expression and feeling of human participants [10] and it helps in interaction with artificial agents [11]. Their implementation in prototypes of industrial communication systems dramatically improved mutual satisfaction and joint performance in constructive tests up to the level close or equal to that of face-to-faces meetings [12]. Moreover, dedicated brain 'machinery' seems to be behind these cognitive-affective effects with specific course of neurodevelopment in early ontogenesis [13]. The role of gaze contacts is different for children with disturbance such as Autistic Spectrum Disorders and Williams syndrome [14, 15].

Immediate feedback, fluency and mutual trust certainly do not belong to the strong features of all the conventional "talking heads" systems, which are used nowadays worldwide for distant teaching and business communication. Interacting with these systems is tiresome and irritating for most of participants. Perhaps, their major drawback is the lack of eye-to-eye contact? Not only in ordinary conversation but even in public lecturing in front of big audience as well, we select some persons face and eyes for such personal contact. This basic biosocial mechanism has to be better studied and implemented before long as one of the primary perspectives of cognitive research.

3 Metamorphoses of "Sensus Communis"

The next perspective is in fact a very old one. Around 350 BC, Aristotle in "De Anima" (III, 2) argued for the integrated sensorial capacity of the soul's possession that allows it to feel and to differentiate any, as we would say, intermodal qualities of objects. This "*koine aesthesis*" capacity –or "*sensus communis*", in Latin translation[1]– is instantaneous and therefore cannot be attributed to one of the many symmetrical organs of the human body. For Aristotle, that was the heart playing the role of a link between body and soul. With the progress in understanding of heart functioning in subsequent centuries, the focus of search for the seat of *sensus communis* shifted to brain structures. Descartes attributed it to the *pineal gland* on the reason that it is not an anatomically duplicated part of the

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[1] Unfortunately, the English translation of the Aristotle's term as "common sense" is rather misleading.

brain and, thus, could serve as the site of the Aristotelian *sensus communis*. On the eve of Christmas in 1640, Descartes wrote to his life-long friend Marin Mersenne: “And since it is the only solid part of the whole brain which is unique, it is necessary that it is the seat of the sensus communis, that is to say, that of thought, and as a consequence that of the soul; for the one cannot be separated from the other” [16; 264].

The story of locating reflective thought within the midbrain’s structure could be dismissed as one of “Descartes errors” but we cannot so easily discharge the very Aristotle-Descartes’s problem. In our century, a hypothesis about the special role in intermodal integration of the subcortical clausrum was proposed by Frencis Crick and Christof Koch [17]. Diffusion tensor imaging reinforced the view on the exceptional density and variation of sensory tracts in this structure and there was a report on reversible changes of consciousness during claustrum’s deep brain stimulation in clinical context [18]. At the same time, direct experiments did not support the idea of intermodal integration because the responses of the claustrum to sensory stimulation were primarely unimodal [19]. There is no obvious growth of the claustrum in anthropogenesis. This means that it may play a relay’s function in connection between the neocortex and the hippocampal formation [20].

Perhaps, the hippocampal formation, specifically the right parahippocampal gyrus, is a more promising target in the search. There was an asymmetry in the effective (cause-and-effect) connections of this part of the hippocampal formation and two intermodal areas, the left and the right inferior parietal cortex (LIPC and RIPC, respectively), as reported by a couple of studies [21, 22]. These were resting state functional neuroimaging studies were participants’ brain activity is recorded in the absence of a task, during rest, which is a basic state of consciousness. In this state, the right hippocampus was influenced by both LIPS and RISP, when the left hippocampus was influenced only ipsilaterally, by the LIPC activity.

If we take into account that the parahippocampal gyrus is one of the main destinations for the dorsal visual stream with its egocentric spatial coordinate system [23], then one can explain why the phenomenology of Cartesian cogito in health and disease seems to be particularly related to the right hemisphere [24]. Indeed, there may be a simple heuristics, which is to look for self-related data at the center of egocentric representation of environment. Therefore, normally, it is the right hippocampal formation providing an easy-to-find gateway into much of what we call “subjective experience”. After right-hemisphere lesions, representation of “Ego/Self” may vanish or be somewhere shifted and, thus, lost within the scrambled spatial frame of reference leading to a variety of more or less salient and predictable consequences for the behavior and mental life. This hypothesis can be better specified or possibly (dis)proven in the years to come.

4 Grand Design of Cognitive Organization

In 2020, a book was published by Routledge [25]. The book waited for a translation into English more than 70 years, since its first appearance in 1947 in Moscow. The author, Nikolai Bernstein, was one of the founders of biomechanics and an enthusiastic proponent of evolutionary view on the development of motor behavior. He and his work fell in disgrace for the overt criticism of Pavlov’s conditional reflexes and the theory of Higher

Nervous Activity in the last chapter of the book. But the main body of the text is a positive stance devoted to description of four levels of movements' construction in humans, from level A to level D. First level (*Paleokinetic Regulations*) involves spinal cord and brain stem up to midbrain. Its function is the regulation of the muscles' tonus, vestibular and defensive reflexes. At the second level (*Synergies*), the "thalamus-pallidum system" permits a broad sensory integration, which regulates movements of the organism as a whole and transforms it into a "locomotory machine". Rhythmic and cyclic patterns of movements are typical for this level's control. The next round of evolution (*Spatial Field*) adds exteroception to the sensory feedbacks. This makes possible one-time goal/place-directed movements and spatially-contingent behavior. The structures that support these functions are new parts of the basal ganglia (striatum) and stimulotopically organized cortical areas, especially in the posterior parietal cortex. Then, a new spiral of evolution leads to the building of secondary areas of the neocortex such as found in parietal, premotor, and temporal regions. This level of *Object Actions* permits detailed form perception and object-adjusted manipulations.

Not much could be said about cognition and affect in 1947. Bernstein sketchy described sensory side of these four levels and their forms of awareness, from protopathic sensitivity and proprio-/tangoreceptoric sensation within the body's frame of reference (levels A and B) to phenomenal experience of a stable voluminous surrounding and individualized objects affording some but not other actions at the levels C and D (the latter description is a bit in the spirit of Gestalt school [26]). He also said in one sentence that there are one or two levels of "higher symbolic coordination" above this hierarchy.

Now, the main problem of this remarkable book is the evidence base and relation to modern data. The distinction of levels C and D vividly reminds us all the discussions about two pathways (dorsal and ventral streams) in visual and auditory information processing [27, 28]. Extending Bernstein's model and linking it to the bulk of contemporary neurocognitive data, lead to the proposal of two additional levels [24, 29] – *Conceptual Structures* (as level E) and *Metacognitive Coordination* (as level F). These considerations are qualitative. In a more quantitative manner, there seems to be a strange difference in predominant hemispheric localization between levels. It is right-sided for levels C and F, and left-sided for levels D and E, with respect to functional and effective connectivity [22, 29, 30] as well as to the expression of molecular mechanisms such as classical protein-coding genes and regulatory microRNA [31]. Does evolution play Ping-Pong with our brain's hemispheres?

A number of other questions arise both on global and on micro scales of an analysis. Could the spontaneous natural evolution on its-own produce the well-organized hierarchy or does it rely on a flexible heterarchical structure? Dynamically changing roles of the leading and background levels are characteric for heterarchies [32]. William Bechtel and Leo Bich [33] recently argued for the heterarchical hypothesis and showed that cognitive control as decision-making does exist already in bacteria. These authors discussed how some species of cyanobacteria rely on an internal representation of the light–dark cycle (a circadian clock) to regulate a host of activities. For Bechtel and Bich, this is an example of 'grounding cognition', which is a decision-making demand placed on all living organisms. Thus, one could ask on how data on biochemistry and genetics of this kind have to be integrated into a general model of cognitive organization (Grand Design Model)? We must also explain other apparent paradoxes of the evolution of cognition such as the intellectual achievements in some species of birds, which are creatures without a neocortex. And what are the final stages in evolution of mind-and-brain? In any case, the newest part of the human brain, its frontopolar regions (BA 10), seems to be involved not in abstract cognition but rather in multitasking of banal everyday activities.

5 Semantics in the Brain and in the World

The last perspective to discuss here emerged only a few years ago. In 2016, Alexander Huth and his colleagues published a paper demonstrationg for the first time how semantic information is represented in the entire neurocognitive system [34]. As a matter of fact, previous studies tested only a small set of categories (living things, tools, food and others) [35, 36] or relied solely on clinical observations [37]. Huth and colleagues [34] studied brain representation of the English language words with the help of functional magnetic resonance imaging (fMRI) in seven participants in response to orally presented meaningful stories (narratives). The authors reported two main results. Firstly, brain mapping of natural language categories on a two-dimensional surface of the cortex showed a similarity in activated voxels and their zones to the outlines of the Default Mode Network (DMN). Secondly, these representations demonstrated a wide distribution with no obvious signs of the initially expected asymmetry towards the left hemisphere.

There were several follow-up studies. Dehghani et al. [38] used a slightly different methodology and three groups of native speakers of English, Chinese, and Farsi. They reported similar results for all languages confirming the DMN involvement. A number of different studies were conducted with meaningful texts in the Russian language [39, 40], two of which are published in this volume [41, 42]. These numerous studies reflect the search for an appropriate methodology of investigation on the intersection of linguistics, psychology, and neurophysiology. At last, they were closer in methods and results to the initial research of Huth and colleagues [34] with even broader distribution of active voxels across the whole brain. A few neurosemantic lexical clusters were clearly identified after processing the data. The clusters were thematically specific and relatively coherent. One can then speculate that meaning construction by the human brain is a process in the art of using Propp's "narratemes" grammar [43] or in the stylistics of Picasso's late paintings producing an exact meaning by a combination of only few crude brushes.

All these results are interesting and at the same time they are a bit suspicious. As to the unusually wide distribution of activated clusters it could simply be explained by the low level of significance and multiple comparisons as mostly the faults positive. However, individual data in a subgroup of participants –we selected them as committed to the study and interested in the content– were well correlated after only a minimal smoothing of voxels [42]. Our data also showed that lexical representations of narratives have situational nature [40]. Descriptions of situational semantics are well-known from this part of semantic literature [44]. Still, many questions remained unanswered. Why were the successful studies of the sort confined to the coherent stories with a plot and not to lists of words or fragments of otherwise meaningful texts? Is this a motivating effect that has better ecological validity? Or is it an artifact due to some circularity of the procedure? At the beginning, one builds-up the metrics of semantic similarity into features of multidimensional vectors that describe the words of narratives. Then, a long post-processing of combined linguistic and imaging data follows. Perhaps, at the end, we receive a kind of the same metrics again within and between the resulting neurosemantic clusters.

Disentangling the world and its brain representations is a formidable scientific and philosophical problem. For us, it seems plausible that the regularities of language and the world they reflect may shape the processing correlations in the brain. Moreover, the real world is represented in multiple imaginary worlds that are as subjective as are the stories in the most narratives. Hopefully, general considerations like these would be acceptable for the cognitive science community as a sufficient explanation, which is necessary at early stages of the long way to a better understanding of, in Donald Hebb's forulation, the "Conceptual Nervous System".

6 Conclusions

Based on an invited talk to the conference, in this article we described two major trends and four perspectives of modern cognitive research. The major trends of the last decades emphasize interdisciplinarity of research and potential for practical use. In the near future, the third trend may well be the emphasis on artificial – the introduction of virtual and mixed realities as well as artificial forms of life in ther standard experimental settings. Already today, there are many examples that point in this direction [10, 12, 45].

Our selection of perspectives was rather arbitrary. These respective four domains of research are new and old. For example, very new are imaging studies in neurosemantics, which were conducted only in couple of laboratories. Relatively new is the theme of communication by the gaze contacts. In contrast, very old is the classical Aristotle-Deascartes' *sensus communis* problem. The issue of hierarchical modeling in functional neurology is also started even before the book by Nikolai Bernstein was published in 1947. Names scolars such as John Hughlings Jackson [46] and Paul MacLean [47] should be mentioned. A common denominator in all the perspectives is that some dynamics is currently visible in their investigation. This permits us to hope on a further progress.

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References

1. Heckhausen, H.: Motivation and Action. Springer, Heidelberg (1991)
2. Fodor, J.A.: Modularity of Mind. MIT Press, Cambridge (1983)
3. Schweitzer, R., Rolfs, M.: Intra-saccadic motions treaks as cues to linking object locations across saccades. J. Vis. **20**(4), 17 (2020). https://doi.org/10.1167/jov.20.4.17

4. Clayden, A.C., Fisher, R., Nuthmann, A.: On the relative (un)importance of foveal vision during letter search in naturalistic scenes. Vis. Res. **177**, 41–55 (2020). https://doi.org/10.1016/j.visres.2020.07.005
5. Volkmann, F.C.: Human visual suppression. Vision. Res. **26**(9), 1401–1416 (1986)
6. Bridgeman, B., van der Heijden, A.H.C., Velichkovsky, B.M.: A theory of visual stability across saccadic eye movements. Behav. Brain Sci. **17**(2), 247–292 (1994)
7. Wurtz, R.H.: Neuronal mechanisms of visual stability. Vis. Res. **48**(20), 2070–2089 (2008)
8. Broadbent, D.E.: Perception and Communication. Pergamon Press, Oxford (1958)
9. Velichkovsky, B.M.: Communicating attention: gaze position transfer in cooperative problem solving. Pragmatics Cogn. **3**(2), 199–222 (1995)
10. Schrammel, F., Pannasch, S., Graupner, S.-T., Mojzisch, A., Velichkovsky, B.M.: Virtual friend or threat? the effects of facial expression and gaze interaction on physiological responses and emotional experience. Psychophysiology **46**(5), 922–931 (2009)
11. Shishkin, S.L., Zhao, D.G., Isachenko, A.V., Velichkovsky, B.M.: Gaze-and-brain-controlled interfaces for human-computer and human-robot interaction. Psychol. Russia State Art **10**(3), 120–137 (2017). https://doi.org/10.11621/pir.2017.0308
12. Kohler, P., Pannasch, S., Velichkovsky, B.M.: Enhancing mutual awareness, productivity and feeling: Cognitive science approach to design of groupware systems. In: Saariluoma, P., Isomäki, H. (eds.) Future Interaction Design, vol. 2, pp. 31–54. Springer, London (2009)
13. Jones, W., Klin, A.: Attention to eyes is present but in decline in 2–6-month-old infants later diagnosed with autism. Nature **504**(7480), 427–431 (2013). https://doi.org/10.1038/nature12715
14. Baron-Cohen, S.: Mindblindness: An Essay on Autism and Theory of Mind. MIT Press, Cambridge (1995)
15. Riby, D.M., Hancock, P.J., Jones, N., Hanley, M.: Spontaneous and cued gaze-following in autism and Williams syndrome. J Neurodev. Disord. **5**, 13 (2013). https://doi.org/10.1186/1866-1955-5-13
16. Descartes, R.: Letter to Mersenne, 24 December 1640. In: Adam, C., Tannery, P. (eds.) Oeuvres de Descartes, 2nd ed., vol. III, no. 223, pp. 262–268. Vrin, Paris (1640/1964–1974)
17. Crick, F., Koch, C.: What is the function of the claustrum? Phil. Trans. R. Soc. B. Biol. Sci. **360**(1458), 1271–1279 (2005)
18. Blumenfeld, H.: A master switch for consciousness? Epilepsy Behav. **37**, 234–235 (2014). https://doi.org/10.1016/j.yebeh.2014.07.008
19. Remedios, R., Logothetis, N.K., Kayser, C.: Unimodal responses prevail within the multisensory claustrum. J. Neurosci. **30**(39), 12902–12907 (2010)
20. Baizer, J.S., Sherwood, C.C., Noonan, M., Hof, P.: Comparative organization of the claustrum: what does structure tell us about function? Front. Syst. Neurosci. **8**. Art. 117 (2014)
21. Ushakov, V.L., Sharaev, M.G., Kartashov, S.I., Zavyalova, V.V., Verkhlyutov V.M., Velichkovsky, B.M.: Dynamic causal modeling of hippocampal links within the human default mode network. Front. Hum. Neurosci. **10**, Art. 528, (e64466) (2016). https://doi.org/10.3389/fnhum.2016.00528
22. Velichkovsky, B.M., Krotkova, O.A., Kotov, A.A., Orlov, V.A., Verkhlyutov, V.M., Ushakov, V.L., Sharaev, M.G.: Consciousness in a multilevel achitecture: evidence from the right side of the brain. Conscious. Cogn. **64**, 227–239 (2018). https://doi.org/10.1016/j.concog.2018.06.004
23. Dickerson, B.C., Eichenbaum, H.: The episodic memory system: neurocircuitry and disorders. Neuropsychopharmacol. Rev. **35**, 86–104 (2010). https://doi.org/10.1038/npp.2009.126
24. Velichkovsky, B.M., Krotkova, O.A., Sharaev, M.G., Ushakov, V.L.: In search of the “I”: neuropsychology of lateralized thinking meets dynamic causal modeling. Psychol. Russia State Art **10**(3), 7–27 (2017). https://doi.org/10.11621/pir.2017.0301

25. Bernstein, N.A.: Construction of Movements (English translation ed. by M. L. Latash). Routledge, Abingdon (2020)
26. Koffka, K.: Principles of Gestalt Psychology. Harcourt Brace Jovanovich, Orlando (1935)
27. Velichkovsky, B.M.: The levels endeavor in psychology and cognitive science. In: Bertelson, P., Eelen, P., d'Ydewalle, G. (eds.) International Perspectives on Psychological Science: Leading Themes, pp. 143–158. Erlbaum, Hove (1994)
28. Velichkovsky, B.M.: Towards an evolutionary framework for human cognitive neuroscience. Theor. Biol. **2**(1), 3–8 (2007)
29. Velichkovsky, B.M., Korosteleva, A.N., Pannasch, S., Helmert, J.R., Orlov, V.A., Sharaev, M.G., Velichkovsky, B.B., Ushakov, V.L.: Two visual systems and their eye movements: a fixation-based event-related experiment with ultrafast fMRI reconciles competing views. STM **11**(4), 7–18 (2019). https://doi.org/10.17691/stm2019.11.4.01
30. Bajaj, S., Killgore, W.D.S.: Association between emotional intelligence and effective brain connectome: a large-scale spectral DCM study. Neuroimage (2021). https://doi.org/10.1016/j.neuroimage.2021.117750
31. Velichkovsky, B.M., Nedoluzhko, A.V., Goldberg, E., Efimova, O.I., Sharko, F.S., Rastorguev, S.M., Krasivskaya, A.A., Sharaev, M.G., Korosteleva, A.N., Ushakov, V.L.: New insights into the human brain's cognitive organization: views from the top, from the bottom, from the left and particularly, from the right. Procedia Comput. Sci. **169**, 547–557 (2020). https://doi.org/10.1016/j.procs.2020.02.211
32. Velichkovsky, B.M.: Heterarchy of cognition: the depths and the highs of a framework for memory research. Memory **10**(5/6), 405–419 (2002)
33. Bechtel, W., Bich, L.: Grounding cognition: heterarchical control mechanisms in biology. Phil. Trans. R. Soc. **B376**, 2019075 (2021). https://doi.org/10.1098/rstb.2019.0751
34. Huth, A.G., de Heer, W.A., Griffiths, T.L., Theunissen, F.E., Gallant, J.L.: Natural speech reveals the semantic maps that tile human cerebral cortex. Nature **532**, 453–458 (2016). https://doi.org/10.1038/nature17637
35. Caramazza, A., Shelton, J.R.: Domain-specific knowledge systems in the brain: the animate-inanimate distinction. J. Cogn. Neurosci. **10**, 1–34 (1998). https://doi.org/10.1162/089892998563752
36. Mummery, C.J., Patterson, K., Hodges, J.R., Price, C.J.: Functional neuroanatomy of the semantic system: divisible by what? J. Cogn. Neurosci **10**, 766–777 (1998). https://doi.org/10.1162/089892998563059
37. Warrington, E.K.: The selective impairment of semantic memory. Q. J. Exp. Psychol. **27**(4), 35–657 (1975)
38. Dehghani, M., Boghrati, R., Man, K., Hoover, J., Gimbel, S., Vaswani, A., Zevin, J., Immordino-Yang, M., Gordon, A., Damasio, A., Kaplan, J.: Decoding the neural representation of story meanings across languages. Hum. Brain. Mapp. **38**, 6096–6106 (2017). https://doi.org/10.1002/hbm.23814
39. Velichkovsky, B.M., Zabotkina, V.I., Nosovets, Z.A., Kotov, A.A., Zaidelman, L.Y., Kartashov, S.I., Korosteleva, A.N., Malakhov, D.G., Orlov, V.A., Zinina, A.A., Goldberg, E., Ushakov, V.L.: Towards semantic brain mapping methodology based on a multidimensional markup of continuous russian-language texts: an attempt at validation and development. STM **12**(2), 14 (2020). https://doi.org/10.17691/stm2020.12.2.02
40. Zaidelman, L., Nosovets, Z., Kotov, A., Ushakov, V., Zabotkina, V., Velichkovsky, B.M.: Russian-language neurosemantics: clustering of word meaning and sense from oral narratives. Cogn. Syst. Res. **67**, 60–65 (2021). https://doi.org/10.1016/j.cogsys.2021.01.001
41. Nosovets, Z.A., Velichkovsky, B.M., Zaidelman. L.Y., Orlov, V.A., Kartashov, S.I., Kotov, A.A., Zabotkina, V.I., Ushakov, V.L.: Voxelwise localization of brain activity while comprehending oral Russian-language stories (This volume) (2021)

42. Velichkovsky, B.M., Kotov, A.A., Zabotkina, V.I., Nosovets, Z.A., Goldberg, E., Zaidelman, L.Y.: Heteroglossia in neurosemantics: The case of a word cluster with mentalist content (This volume) (2021)
43. Propp, V.: Morphology of the Folktale. In: Scott, L. (ed.) 2nd ed. University of Texas Press, Austin (1968/1927)
44. Yeh, W., Barsalou, L.W.: The situated nature of concepts. Am. J. Psychol. **119**(3), 349–384 (2006)
45. Pfeuffer, K., Abdrabou, Y., Esteves, A., Rivu, R., Abdelrahman, Y., Meitner, S., Saadi, A., Alt, F.: ARtention: a design space for gaze-adaptive user interfaces in augmented reality. Comput. Graph. (2021). https://doi.org/10.1016/j.cag.2021.01.001
46. Critchley, E.A.: John Hughlings Jackson, Father of English Neurology. Oxford University Press, New York/Oxford (1998)
47. MacLean, P.D.: The Triune Brain in Evolution: Role in Paleocerebral Functions. Springer, Heidelberg (1990)

Cognitive Development, Skills, and Aging

Theoretical and Empirical Criteria for Selecting Cognitive Over-Performers: Data from a Primary School in Moscow

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Abstract. Cognitive abilities are related to academic performance and professional success. Research shows that about 1–10% of individuals have outstanding cognitive abilities. Critically, theoretical and empirical criteria of assessing cognitive performance are understudied and less well understood. A measure of core cognitive performance is mental attentional capacity that reflects the number of items an individual can hold and manipulate in mind; quantitative changes in the development of mental attentional capacity have been theoretically defined. We examine normative performance, as well as theoretical and empirical criteria for identifying children with outstanding cognitive performance in early grades using a classic measure of mental-attentional capacity. Children in grades 1, 2, 3, and 4 (N = 277) completed the Figural Intersection Task (FIT). Results show that normative scores from Russian speaking children closely followed theoretical expectations for all grades and were in agreement with past empirical data. Criteria for over-performance were set to be +2 and +3 above theoretical expectations and empirical scores for each age group. Percentages close to those obtained in the literature were obtained primarily using the stricter criterion. Considerations for future research and practical implications are discussed.

Keywords: Cognitive ability · Cognitively gifted children · Criteria · Mental-attentional capacity

1 Introduction

A small percentage of children significantly outperform their peers on measures of cognitive abilities. Cognitively gifted children are usually defined as those who per- form within the top 1–10% of the same age sample [1–3]. This advanced intellectual capacity is linked to successful performance in school settings [4]. Intelligence tests and related metrics remain popular measures for identifying gifted children [5, 6]. Critically, intelligence tests have been widely recognized as being culturally biased [6]. More recently there has been a shift in measures from intelligence scales to tasks based on core cognitive abilities, such as executive function and working memory [7]. Core cognitive

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abilities improve across childhood and adolescence; however, developmental theories rarely quantify these changes. One theory that quantifies changes in cognitive abilities is the Theory of Constructive Operators by way of increases in mental attention [8, 9]. Mental attention is a limited resource, which corresponds to the ability to hold and process information in mind. Mental attention undergoes linear, quantitative increases that can reflect stagewise changes in capacity across typically developing children and adolescents [8–11]. Specifically, the Theory of Constructive Operators proposes that mental-attentional capacity increases by 1 unit every other year after the age of 3 years and reaches 7 units in 15–16 year olds [8, 12]. Thus, typically developing children entering school in Moscow at 7–8 years in grade 1 are expected to have on average a mental-attentional capacity of 3 units and at 9–10 years in grade 3 this capacity should increase to 4. Grade 2 (8–9 years) and grade 4 (10–11 years) can be considered as years with mental-attentional capacity between units 3 and 4 and units 4 and 5, respectively. This study examines for the first time normative performance of Russian speaking children on a classic measure of mental-attentional capacity and identifies the criteria for detection of comparable proportion (i.e., 1–10%) of over-performers for this task using theoretical and empirical thresholds.

Parametric measures of mental attentional capacity are characterized by multiple levels of difficulty and invariant executive demand across levels. Because these tasks require minimal background knowledge and pose minimal language demands they have been characterized as culture-fair [11, 13]. The original task that evaluates mental-attentional capacity is the FIT - Figural Intersection Task [8, 13], which demonstrated high correlations with intelligence tests [12, 14] and academic performance [15, 16]. Research shows that children who are identified as gifted using intelligence measures, on average score one unit above mainstream children on mental-attentional capacity tasks [14]. Another study showed gifted children scoring about two units higher on measures of mental-attentional capacity [17]. Critically, the proportion of over-performers in tasks of mental attentional capacity has not been directly investigated. To test methods that can help obtain 1–10% of over-performers on the FIT we consider the following criteria: Theoretical (prediction for their age $+ 2 \pm 1$) and Empirical (average M-score of an age group $+ 2 \pm 1$).

Overall, the aims of the present study are (a) to verify normative performance in school age children on the FIT and (b) to identify the optimal criterion of over-performance for the FIT.

2 Material and Methods

2.1 Participants

Children from grades 1, 2, 3 and 4 participated in the study (N = 277; 53% of males, 6–12 years old, M = 9.24, SD = 0.9; Table 1). Participants completed the FIT as part of a larger study. All methods and procedures were approved by the ethics committee at National Research University Higher School of Economics, and signed consent forms were obtained from parents.

Table 1. Sample characteristics by grade.

Grade	Age			Females	Males
	Mean	SD	N		
1	7.88	0.41	17	4	13
2	8.69	0.35	132	60	72
3	9.68	0.38	84	42	42
4	10.71	0.65	42	22	20

2.2 Materials

The FIT [13] was presented on paper. This task contained several levels with increasing complexity. Each assignment consisted of some geometrical shapes presented on the right side of the page that children had to mark with a dot, and the overlap of these shapes was presented on the left side of the page where respondents had to place only one dot where all the shapes intersected. The task has seven levels of mental demand, which were indexed by the number of relevant shapes that ranged from 2 to 8. Items were marked as correct or incorrect. The highest achieved mental demand level passed with a percentage of 75% or higher represented the mental-attentional (M)-score of the child and constituted its mental-attentional capacity.

3 Procedures

Testing was conducted in groups of 15–20 children in their classrooms using the paper-and-pencil FIT. After each session that lasted around 45 min, children received a small gift (e.g., pencil, ruler).

Average scores and proportion of over-performance were calculated. To achieve the top 1–10% of over-performers we consider the following two criteria: Theoretical prediction for their age $+ 2 \pm 1$, and empirical average M-score of age group $+ 2 \pm 1$.

4 Results

Mean M-scores for each age group are shown on Fig. 1. Figure 2 shows percentage of students who passed the theoretical and empirical criteria.

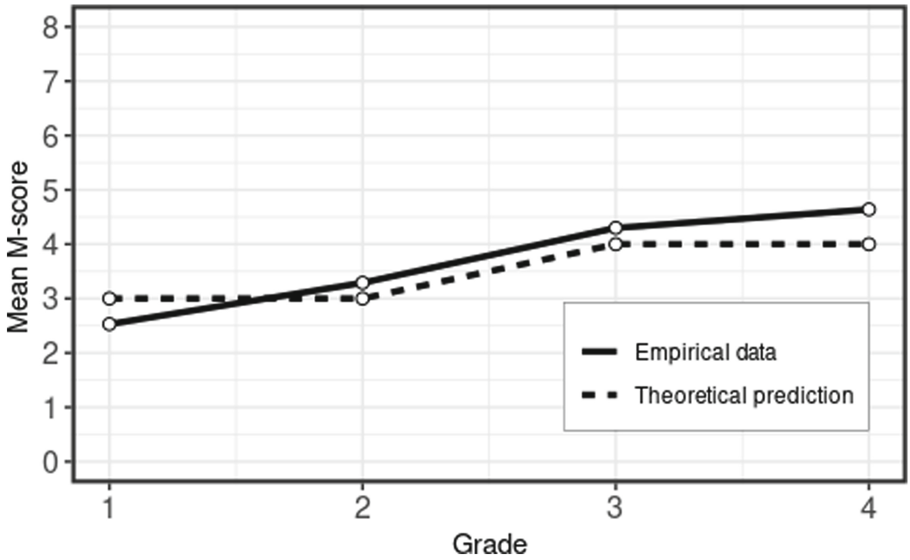

Fig. 1. Mean M-scores for all children.

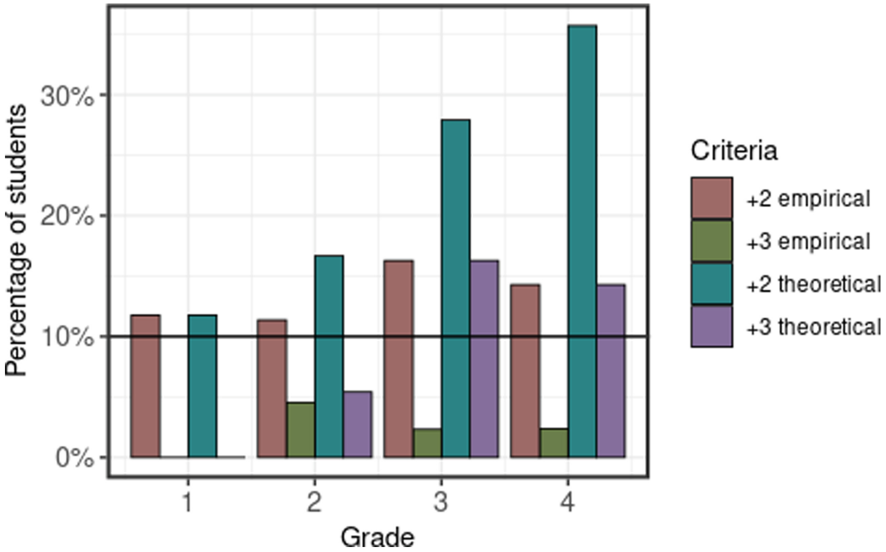

Fig. 2. The percentage of children that passed the +2 and +3 theoretical and empirical criteria. Note: The black line represents the expected 1–10% of over-performers, as proposed by the literature.

5 Discussion

We examined normative scores and criteria of cognitive over-performance using the FIT in young school aged children. Results show that children in our sample showed mean M-scores consistent with theoretical predictions [8, 18] that are also comparable with empirical scores from previous studies [11, 19]. These findings provide further support to past claims that parametric measures of mental attentional capacity are culturally fair [11, 20], and can be administered to Russian speaking children for assessing mental attention.

Percentage of children over-performing at +2 criterion was close to 10% for children in grade 1 and grade 2, however for children in grades 3 and 4 the +2 criterion was liberal as we obtained a higher-than-expected percentage of over-performers. The empirical criterion was more conservative than the theoretical criterion, for all grades, except grade 1. A stricter criterion of +3 units above theoretical predictions and empirical scores yielded no child over-performers in grade 1, and proportions closer to 5% for children in grade 2, consistent for both theoretical and empirical criteria. Children in grade 3 and 4 showed percentage discrepancy between empirical and theoretical percentages. In agreement with past reports on the proportion of over-performing children [1–3], the current data suggest that over-performance criteria on the FIT were better for younger children. Considerations for the factors of why a larger number of children over-performed in older grades may be related to situational aspects. Specifically, testing with a large number of children at the same time may have encouraged children, particularly older children, to interact and help each other. Also, older children may have used strategies that they were asked to avoid (i.e., using their fingers or pens to outline shapes). Future research should take this into consideration, as this is the first study that examines theoretical and empirical criteria to identify the percentage of over-performance on a classic measure of mental attentional capacity. Indeed, further research is needed to replicate the findings on this task and verify criterion validity with additional measures of mental attentional capacity.

6 Conclusion

The current study examined normative mental attentional scores in school age children and theoretical and empirical criteria for identifying over-performance using FIT. The M-score +2 criterion is too lenient for older children that required a higher criterion M-score +3 to reach percentage levels closer to expected 1–10% of over-performance. Theoretically, results suggest that core cognitive measures of mental attentional capacity generate comparable normative scores with Russian children, verifying culture fairness. Practically, this research points to additional research directions to replicate and verify over-performance criteria, useful for assessing children with high cognitive abilities.

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References

1. Plucker, J.A., Callahan, C.M.: Research on giftedness and gifted education: status of the field and considerations for the future. Except. Child. **80**(4), 390–406 (2014). https://doi.org/10.1177/0014402914527244
2. Koshy, V., Pinheiro-Torres, C.: 'Are we being de-gifted, Miss?' primary school gifted and talented co-ordinators' responses to the gifted and talented education policy in England. Br. Edu. Res. J. **39**(6), 953–978 (2013). https://doi.org/10.1002/berj.3021
3. Gridley, B.E., Norman, K.A., Rizza, M.G., Decker, S.L.: Assessment of gifted children with the Woodcock-Johnson III. In: WJ III Clinical Use and Interpretation, pp. 285–317. Academic Press (2003).https://doi.org/10.1016/B978-012628982-4/50010-6
4. Steiner, H.H., Carr, M.: Cognitive development in gifted children: toward a more precise understanding of emerging differences in intelligence. Educ. Psychol. Rev. **15**(3), 215–246 (2003). https://doi.org/10.1023/A:1024636317011
5. Bildiren, A.: Examination of the skill areas of gifted children using WISC-R intelligence scale scores. Eur. J. Educ. Stud. **3**(9), 378–391 (2017). https://doi.org/10.46827/ejesv0i0.1024
6. Rindermann, H., Becker, D., Coyle, T.R.: Survey of expert opinion on intelligence: intelligence research, experts' background, controversial issues, and the media. Intelligence **78**, 101406 (2020). https://doi.org/10.1016/j.intell.2019.101406
7. Diamond, A.: Executive functions. Annu. Rev. Psychol. **64**, 135–168 (2013). https://doi.org/10.1146/annurev-psych-113011-143750
8. Pascual-Leone, J.: A mathematical model for the transition rule in Piaget's developmental stages. Acta Physiol. **32**, 301–345 (1970). https://doi.org/10.1016/0001-6918(70)90108-3
9. Baillargeon, R., Pascual-Leone, J., Roncadin, C.: Mental-attentional capacity: does cognitive style make a difference? J. Exp. Child Psychol. **70**(3), 143–166 (1998). https://doi.org/10.1006/jecp.1998.2452
10. Arsalidou, M., Pascual-Leone, J., Johnson, J.: Misleading cues improve developmental assessment of working memory capacity: the color matching tasks. Cogn. Dev. **25**(3), 262–277 (2010). https://doi.org/10.1016/jcogdev.2010.07.001
11. Arsalidou, M., Im-Bolter, N.: Why parametric measures are critical for understanding typical and atypical cognitive development. Brain Imaging Behav. **11**(4), 1214–1224 (2017). https://doi.org/10.1007/s11682-016-9592-8
12. Johnson, J., Fabian, V., Pascual-Leone, J.: Quantitative hardware stages that constrain language development. Hum. Dev. **32**(5), 245–271 (1989). https://doi.org/10.1159/000276477
13. Pascual-Leone, J., Baillargeon, R.: Developmental measurement of mental attention. Int. J. Behav. Dev. **17**(1), 161–200 (1994). https://doi.org/10.1177/016502549401700110
14. Johnson, J., Im-Bolter, N., Pascual-Leone, J.: Development of mental attention in gifted and mainstream children: the role of mental capacity, inhibition, and speed of processing. Child Dev. **74**(6), 1594–1614 (2003). https://doi.org/10.1046/j.1467-8624.2003.00626.x
15. Onwumere, O., Reid, N.: Field dependency and performance in mathematics. Eur. J. Educ. Res. **3**(1), 43–57 (2014)
16. Alloway, T.P., Alloway, R.G.: Investigating the predictive roles of working memory and IQ in academic attainment. J. Exp. Child Psychol. **106**(1), 20–29 (2010). https://doi.org/10.1016/j.jecp.2009.11.003
17. Navarro, J.I., Ramiro, P., Lopez, J.M., Aguilar, M., Acosta, M., Montero, J.: Mental attention in gifted and nongifted children. Eur. J. Psychol. Educ. **21**(4), 401–411 (2006). https://doi.org/10.1007/BF03173510

18. Pascual-Leone, J., Johnson, J.: A dialectical constructivist view of developmental intelligence. In: Wilhelm, O., Engle, R.W. (eds.) Handbook of Understanding and Measuring Intelligence, pp. 177–201. Sage Publications, Thousand Oaks (2005).https://doi.org/10.4135/9781452233529.n11
19. Powell, T.L., Arsalidou, M., Vogan, V.M., Taylor, M.J.: Letter and colour matching tasks: parametric measures of developmental working memory capacity. Child Dev. Res. **2014**, 961781 (2014). https://doi.org/10.1155/2014/961781
20. Pascual-Leone, J., Johnson, J., Baskind, S., Dworsky, S., Severtson, E.: Culture-fair assessment and the processes of mental attention. In: Kozulin, S., Rand, Y. (eds.) Experience of Mediated Learning: An Impact of Feuerstein's Theory in Education and Psychology, Pergamon, pp. 191–214 (2000).

Perceptual-Cognitive Demands of Esports and Team Sports: A Comparative Study

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Abstract. Video game competitions known as "esports" are rapidly gaining popularity around the world. Esports is legally recognized as a sport in several countries. It was a demonstration event at the 2018 Asian Games and was discussed as a potential addition to the Olympic program at the 2018 Esports Forum, organized by the International Olympic Committee. Even so, the status of esports remains a highly disputed topic in academia. In this paper, we argue that to be promoted as a full-fledged sport esports has to be associated with talents and health benefits similar to traditional sports. Existing studies indicate that traditional team sports and amateur gaming are both related to cognitive advantages. To evaluate the extent of this similarity at the professional level, we assessed perceptual-cognitive abilities of (semi-)professional esports players ($N = 31$) and professional soccer and basketball players ($N = 43$). Esports players and athletes performed equally well in complex tests measuring attentional control, short-term and working spatial memory span, attention distribution, reaction time, and hand-eye coordination. Esports players outperformed athletes in the speed of visual search. This data supports the idea that esports and traditional team sports demand a similar level of perceptual-cognitive ability from professionals and might provide similar cognitive benefits.

Keywords: Esports · Video games · Competitive gaming · Perceptual-cognitive skills · Multiple object tracking · Visual attention · Sport psychology

1 Introduction

1.1 Relevancy of Esports

Today 2.7 billion people in the world play video games on different devices [1]. Rapid growth of the video game industry supports the rise of professional athletic ambition. Large-scale tournaments with championship titles and prize money are held every year

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for multiple competitive video games. Jointly they are recognized as "esports" (or "electronic sports"). In 2019 viewership of these tournaments has exceeded 450 million people; in 2020 global esports economy is expected to generate revenues of $1.1 billion, a year-on-year growth of +15.7% [2]. Today professional gamers can seek not only long-term contracts with esports organizations, salaries, and sponsorships, but also scholarships in universities around the world. They can also count on government support: for example, in 2016 esports was included in the Russian National Register of Sports [3]. In 2018 esports was featured as a demonstration event in the Asian Games (second largest multi-sports event after the Olympic Games) [4].

Despite the popularity and state recognition of esports in several countries, its status and ambitions remain a hot topic of discussion. Electronic sport has formal features of sport such as tournaments, referees, records, fans, federations, and so on. However, player's activity unfolds mainly in the virtual environment; player manipulates game objects through input devices (keyboard, mouse, controller) while maintaining a sitting position. The physical component of gaming is limited to fine motor skills of hands; there is no heavy load on the muscles, most of the work takes place in the mental sphere. This peculiarity has led some researchers to the conclusion that esports can't be considered a sport, and is instead an example of "sportification" (inclusion of sports elements into non-sports activity for monetization) [5, 6]. Others, guided, for example, by B. Suites' criteria, acknowledge esports as a full-fledged sport [5, 7, 8].

Conflicts of opinions about the status of esports are aggravated by the lack of scientific data. So far, little is known about professional gaming's physical and cognitive requirements and how they compare to the requirements of traditional sports activity. Is esports hard enough? Does it reveal peak human ability, and if it does – what kind of ability? Is competitive gaming beneficial to people who participate in it? These questions were voiced, for example, at the 2018 Esports Forum, organized by the International Olympic Committee in Switzerland [4]. Insufficient understanding of the cognitive and physical demands of esports makes it difficult to make decisions about its promotion.

Data presented in this article might offer a partial solution to this problem.

1.2 Studies of Amateur Gaming

The highest demands and benefits of competitive gaming most likely belong to the perceptual-cognitive domain. In the game, players must quickly react to a rapid change of events, make decisions in conditions of uncertainty, track movement of characters on the screen, discern relevant information in splashes of color, navigate the map - all while performing quick and accurate keystrokes, movements of the mouse or thumbsticks on the controller. These and other game tasks engage a wide range of perceptual-cognitive abilities. It is logical to assume that people with higher cognitive abilities (due to talent and/or training) are more likely to succeed in the game and achieve better results than people with lower abilities. Esports players, being the most successful players, could then possess the highest cognitive abilities among gamers that would reflect the peak demands of the profession.

Studies of amateur gaming indicate exactly that. Over the past twenty years, the topic of video game influence on perceptual-cognitive abilities has received decent coverage. It is established that fans of the so-called "action" genre surpass people without gaming experience in reaction speed, accuracy of visual and auditory perception, volume and distribution of attention, spatial abilities, subitizing, impulse control, volume of short-term memory, hand-eye coordination, cognitive flexibility and multitasking [9, 10]. Some of these abilities improve in people without gaming experience when they are tasked to play action video games for a period of time. The highest training effects are achieved for perception, attention, and spatial abilities [9]. (Although some studies deny existence of such effects [11]).

It is important to note that other genres of video games are less studied and are sometimes associated with different or lesser cognitive advantages [10]. Fortunately, in the discussion of esports, action video game studies are the most relevant. Many esports video games officially belong to the action category (shooters, fighting games), and others (e.g., MOBA, RTS) display key features of the genre that are relevant to cognition: high tempo, bright visual stimulation, high mobility of objects on the screen, rapid change of goals and input requirements, etc. Thus, the results of more general action video-game studies could apply to them. Few notable studies examined esports video games directly: for example, in one study women without gaming experience improved cognitive flexibility after hours of training specifically in an esports game Starcraft [12].

Cognitive advantages of amateur players over non-players do not guarantee that superior cognitive abilities also differentiate more successful players from less successful ones. Fortunately, this is addressed in several studies [13, 14]. For example, X.Li and colleagues [13] compared cognitive abilities of average and high-rated amateur players in the esports game League of Legends (participants were equal in how much time they have invested into the game). Successful amateurs have shown superiority in all abilities that were measured: cognitive flexibility, interference immunity, and impulse control.

Thus, existing studies provide some support to the ideas that cognitive abilities are heavily engaged in competitive gaming, that abilities are enhanced to some extent, and that elite players likely exhibit peak cognitive performance among gamers. How high is this peak, however? No studies, to our knowledge, examined professional players directly, nor explored whether cognitive demands of esports are high enough to match those of traditional sports.

Traditional team sports, such as soccer and basketball, are associated with high cognitive requirements. Studies confirm that high-skilled athletes are distinguished by superior foresight, visual search, pattern recognition, situational awareness, and attention distribution, not to mention reaction speed and hand-eye coordination [15, 16]. One would imagine that to be included in multi-sports events such as the Olympic games, that celebrate peak human ability, esports has to be associated with some perceptual-cognitive demands and benefits at least at the same level as traditional sports.

As a response to this concern, this article features results of our preliminary study in which we administered several cognitive tests to (semi-)professional gamers and professional soccer and basketball players and then compared the scores.

2 Methods

2.1 Measures

Assessment of perceptual-cognitive abilities was conducted at the Moscow center of advanced sport technologies. All data were collected in a single laboratory using one set of equipment. Both athletes and gamers viewed testing as an evaluation of their sport-related abilities and were instructed to try their best.

The following perceptual-cognitive skills were tested:

Visual attentional control was assessed by a Multiple object tracking task (MOT), administered as a one "Core" session on the Neurotracker system [17]. Participant stood in front of a screen with 3D glasses on. Before each trial, 8 identical targets (yellow balls) appeared on the screen. Participant was instructed to pay attention to 4 of these. Afterwards all 8 objects moved simultaneously for 8 s. At the end of the trial, participants had to identify 4 key targets: the correct answer increased the speed of movement of the objects in the next trial, mistake decreased it. The session consisted of 20 trials. Maximum effective speed of tracking was recorded.

Choice reaction time was assessed by the Choice test on the Thought Technology system. Participant stood in front of the PC screen divided into two halves; he was holding two joysticks in his hands. Occasionally an arrow appeared on the right or left side of the screen. Participant had to react as quickly as possible by pressing a button on the left or right joystick. Speed and accuracy were measured.

Reaction time, hand-eye coordination, attention distribution, and peripheral vision were assessed by two complex tests on Dynavision D2 system [18]. Dynavision D2 is a panel equipped with light bulbs that can be pressed like buttons and are positioned in the form of concentric circles. In the "standard" test, light bulbs lit up one by one in a chaotic order across the entire area of the device. Participant's task was to quickly notice the signal and press the correct bulb with his hand. The signal persisted until the press. The test lasted one minute. The best attempt of two in terms of speed was recorded. In the "periphery" test light bulbs lit one by one on the peripheral circles of the panel. Each signal only lasted 500 ms, after which the next bulb lit up. Participant was required to press the correct bulb before its light disappeared. The test lasted two minutes; the number of successful presses was recorded.

Visual search (switch) was assessed by the digital "Red-black tables" Schulte test. Participant saw a table filled with black and red numbers on a PC screen, and was instructed to click on these numbers in a given order: ascending – for black figures, descending – for red Figs. (1 BLACK, 24 RED, 2 BLACK, 23 RED…). Thus, participant had to quickly switch between principles of search. Speed was recorded.

Short-term spatial memory span was assessed by the "Geometric shapes" test. Nine shapes flashed rapidly one after another on a PC screen. After that, participant was presented with a series of shapes that included those he has seen before and new ones. The task was to correctly identify shapes from the first series. Accuracy was measured.

Working spatial memory span was assessed using the Corsi block-tapping test [19]. Participant saw nine cubes on a PC screen. A cursor directed by the computer then touched a certain number of cubes in a certain order. The task was to repeat the sequence.

The length of the sequence increased after every third attempt up to nine touches. Maximum length of successfully repeated sequence was recorded.

2.2 Participants

31 male Russian esports video game players aged 19–30 took part in the study. All have recently participated in official Russian and international esports tournaments and maintained top 2% ranked gaming profiles in their game of choice at the time of the study. 12 players were professionals, bound by contract to an esports organization. The rest participated in tournaments independently and identified as semi-pro. 14 participants specialized in shooter video games (CS:GO, Overwatch, Rainbow 6 Siege), the rest specialized in MOBA and RTS video games (League of Legends, Dota 2, Starcraft 2).

43 male professional soccer and basketball players aged 19–31 took part in the study. All have recently participated in national and/or European championships. 14 out of 43 athletes were basketball players.

2.3 Ethics Statement

The research protocol was approved by the ethics committee of the Moscow center of advanced sport technologies (Protocol 10, 30.09.2019) [20]. All participants gave their written consent.

3 Results

The comparison of samples was performed using Mann–Whitney U-test.

Table 1. Descriptive statistics for each test. 1 – Dynavision “Standard”, 2 – Dynavision “Periphery”, 3 – Neurotracker MOT, 4 – “Red-black tables”, 5 – “Geometric shapes”, 6 – Corsi block-tapping test, 7 – Choice reaction time test (left-hand speed), 8 – Choice reaction time test (right-hand speed).

Test	Median – esports	Median – athletes	Min – max esports	Min – max athletes	Range – esports	Range – athletes	p-value
1	0.70	0.68	0.60–0.80	0.57–0.98	0.20	0.41	$p > 0{,}39$
2	22.00	24.00	6.00–58.00	6.00–78.00	52.00	72.00	$p > 0{,}98$
3	1.22	1.28	0.55–2.37	0.60–2.11	1.82	1.51	$p > 0{,}27$
4	3.29	4.02	2.27–5.35	1.84–6.21	3.08	4.37	$p < 0{,}01$
5	0.83	0.81	0.58–1.00	0.35–1.00	0.42	0.65	$p > 0{,}07$
6	7.00	6.50	5.00–9.00	6.00–9.00	4.90	3.00	$p > 0{,}24$
7	239.00	245.65	125.30–279.00	209.20–290.00	153.70	80.80	$p > 0{,}4$
8	245.00	236.56	208.23–286.00	202.23–279.88	77.77	77.65	$p > 0{,}3$

Our data shows that esports players and team sports athletes perform equally well in tests that measure visual attentional control, short-term and working spatial memory span, choice reaction time, and hand-eye coordination. Esports players outperform team sports players in the speed of visual search (switch) in the “Red-black tables” test ($p < 0{,}001$).

4 Discussion

Interpretation of the results must take into account possible advantages that one group had over another. Neurotracker and Dynavision tests were developed specifically for the evaluation and cognitive training of athletes [17, 18]. Neurotracker presents objects in 3D, while Dynavision demands wide hand movements, favoring those who swing with strength; both tests involve a wide field of view. All this is more relevant to traditional sports activity rather than esports. Thus, it is unexpected that our esports sample has not fallen behind professional athletes in these tasks. Researchers have previously expressed concern that cognitive advantages of gamers over non-players are only significant due to the use of game-like digital tests in studies [10, 11]. Our results suggest that this might not be the case. Since Dynavision tests are complex tests, measuring several abilities at once, it is also possible that athletes and esports players relied on different abilities to achieve similar results.

Esports players could have had an advantage over athletes in PC-based tests due to their experience with mouse input. However, “Geometric shapes” test and Corsi block-tapping test require neither speed nor high precision of mouse movements when dealing with stimuli. It is unlikely that athletes were disadvantaged. We suggest that this also applies to the “Red-black tables” test – the only test where gamers outperformed athletes. In this task, speed of search was recorded, and one could argue that gamers clicked on numbers quicker than athletes purely because of superior mouse movement. Although this is true to some extent, it is important to note that the “Red-black tables” task is normally performed at a relatively slow speed due to the high difficulty of switching between search principles (participant needs to click black numbers in ascending order, and red numbers – in descending order). It is unlikely that gamers’ advantage in mouse movement rather than switch-efficiency and speed of visual search led to significant differences between groups.

Video games indeed seem to be very demanding of visual search ability. Players have to swiftly identify key units of information in a visual swarm of game events, being guided by different principles of search for different units in different situations. It makes sense that successful gamers succeed due to innate advantages in visual search. In addition, studies indicate that video game training can further enhance visual search ability [10].

5 Conclusion

Esports enthusiasts have long argued that esports deserves the same level of recognition and promotion as traditional sports [4, 5]. Yet we argue that any high-profile sport should be able to reveal peak human ability and offer potential health benefits to those who engage in it on an amateur or professional level. The results of our study provide evidence that esports might at the very least have similarly high cognitive requirements as soccer and basketball, and might provide similar cognitive benefits.

The main limitation of this study is that our esports sample included semi-professional players and thus was less elite than our sample of professional athletes. If samples were more equal, results could be more flattering for esports. It is also possible that our sample of tests was not broad enough to identify perceptual-cognitive abilities that are most involved in professional gaming. These concerns should be addressed in future studies.

Acknowledgement. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Newzoo: 2020 global games market report. https://newzoo.com/insights/trend-reports/newzoo-global-games-market-report-2020-light-version/
2. Newzoo: 2020 global esports market report. https://newzoo.com/insights/trend-reports/newzoo-global-esports-market-report-2020-light-version
3. Order of the Ministry of Sport of the Russian Federation № 470 of April 29 2016. https://www.garant.ru/products/ipo/prime/doc/71317030/
4. Hiltscher, J., Scholz, T.M.: Esports yearbook 2017/2018. Books on Demand. GmbH, Norderstedt (2019)
5. Cunningham, B.G., Fairley, S., Ferkins, L., Kerwin, S.: ESport: construct specifications and implications for sport management. Sport Manag. Rev. **21**, 1–6 (2017). https://doi.org/10.1016/j.smr.2017.11.002
6. Heere, B.: Embracing the sportification of society: defining e-sports through a polymorphic view of sport. Sport Manag. Rev. **21**, 21–24 (2018). https://doi.org/10.1016/j.smr.2017.07.002
7. Suits, B.: The element of sport. In: Morgan, W. (ed.) Ethics in Sport, pp. 9–19. Human Kinetics, Champaign (2007)
8. Funk, D.C., Pizzo, A.D., Baker, B.J.: eSport management: embracing eSport education and research opportunities. Sport Manag. Rev. **21**, 7–13 (2018). https://doi.org/10.1016/j.smr.2017.07.008
9. Bediou, B., Adams, D., Mayer, R., Tipton, E., Green, C., Bavelier, D.: Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. Psychol. Bull. **144**, 77 (2017). https://doi.org/10.1037/bul0000130
10. Oei, A.C., Patterson, M.D.: Enhancing cognition with video games: a multiple game training study. PLoS ONE **8**, e58546 (2013). https://doi.org/10.1371/journal.pone.0058546
11. Sala, G., Tatlıdil, S., Gobet, F.: Video game training does not enhance cognitive ability: a comprehensive meta-analytic investigation. Psychol. Bull. **144**, 111–139 (2018). https://doi.org/10.1037/bul0000139
12. Glass, B.D., Maddox, W.T., Love, B.C.: Real-time strategy game training: emergence of a cognitive flexibility trait. PLoS ONE **8**, e70350 (2013). https://doi.org/10.1371/journal.pone.0070350
13. Li, X., Huang, L., Li, B., Wang, H., Han, C.: Time for a true display of skill: top players in League of Legends have better executive control. Acta Physiol. **204**, 103007 (2020). https://doi.org/10.1016/j.actpsy.2020.103007

14. Large, A., Bediou, B., Cekic, S., Hart, Y., Bavelier, D., Green, C.: Cognitive and behavioral correlates of achievement in a complex multi-player video game. Media Commun. **7**, 198 (2019). https://doi.org/10.17645/mac.v7i4.2314
15. Scharfen, H.-E., Memmert, D.: Measurement of cognitive functions in experts and elite-athletes: a meta-analytic review. Appl. Cogn. Psychol. **3**, 343–860 (2019). https://doi.org/10.1002/acp.3526
16. Mangine, G.T., Hoffman, J.R., Wells, A.J., Gonzalez, A.M., Rogowski, J.P., Townsend, J.R., Jajtner, A.R., Beyer, K.S., Bohner, J.D., Pruna, G.J.: Visual tracking speed is related to basketball-specific measures of performance in NBA players. J. Strength Cond. Res. **28**, 2406–2414 (2014). https://doi.org/10.1519/JSC.000000000000055
17. Moen, F., Hrozanova, M., Stiles, T., Travlos, A.K.: The effects of perceptual-cognitive training with Neurotracker on executive brain functions among elite athletes. Cogent Psychol. **5**(1), 1544105 (2018). https://doi.org/10.1080/23311908.2018.1544105
18. Ong, N.: The use of dynavision in sport and exercise research: a review. Int. J. Sport Exerc. Psychol. **18**, 561–580 (2020). https://doi.org/10.1080/1612197X.2018.1549582
19. Orsini, A., Simonetta, S., Marmorato, M.: Corsi's block-tapping test: some characteristics of the spatial path which influence memory. Percept. Mot. Skills **98**, 382–388 (2004). https://doi.org/10.2466/PMS.98.2.382-388
20. Moscow center of advanced sport technologies Protocols of Meetings. https://cstsk.ru/science/committee/protocols/

The Relation Between Cognitive Flexibility and Language Production in Preschool Children

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Abstract. The understanding of the relations between executive functions (specifically cognitive flexibility) and language development (narrative production) in 5–6 years old children remains limited and contradictory. In this study we asked 269 monolingual children who were developing typically to perform Dimensional Change Card Sort (DCCS) method, Raven's Colored Progressive matrices test and to create four narratives (retelling, creating a story based on one picture and on a series of pictures). The aim of the study was to examine significant predictors of the language development level in preschoolers. In children's narratives one can distinguish macrostructure and microstructure. The macrostructure comprises the length of a story, its completeness, adequacy, narrative structure and narrative type, i.e. structure parameters form a narrative as a cohesive and coherent utterance. Phonetics, vocabulary, morphology, syntax compose narrative's microstructure. The results show that there is a strong correlation between cognitive flexibility and macrostructure indicators of narrative production whereas there are much fewer microstructure indicators that have correlations with cognitive flexibility. The children who were able to perform the most difficult task of DCCS method (with borders), were much better in narrative production. Raven's results showed that both indicators (non-verbal intelligence and cognitive flexibility) were predictors of the narrative structure. The results obtained in this study can contribute to better cognitive development of children and their readiness for school.

Keywords: Preschool age · Cognitive development · Executive functions · Cognitive flexibility · Oral language · Narrative production

1 Introduction

1.1 Executive Functions and Language

Executive functions and language are both very important for academic performance in different ages [1–3] but most of all they are key-factors that characterize readiness for school [4, 5]. Numerous studies show that there is a strong correlation between executive functions (EF) and literacy acquisition in 5–7 years old children [6, 7]. Among executive functions working memory seems to have the strongest relationship with language production [8], however cognitive flexibility and inhibitory control are also related to [9,

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10]. However, data on the relation between cognitive flexibility and language production remains limited and contradictory [11–14]. In particular, there is no data on the relation between cognitive flexibility and narrative production in children for Russian language.

The current study aims to fill in this knowledge gap. It examines the relationship between cognitive flexibility (as a component of executive functions) and oral narrative skills in 5–6 years old children. In addition, one more question is raised: are there any factors that can explain the relationship between EF and language development, for example non-verbal intelligence (assessed with the Raven's progressive matrices)? Our study aimed to specify the contribution of each factor to the level of narrative development.

1.2 Cognitive Flexibility

In this research cognitive flexibility is regarded as a component of EF. According to Miyake's model, EF are divided into the following three main components: working memory, inhibition and cognitive flexibility [15]. Despite the fact that this model was originally based on the results obtained in adults, the possibility of its use in describing EF development during childhood was confirmed in the works of many authors [16–19].

Cognitive flexibility is related to the ability to switch from one rule to another or «to shift between tasks or mental sets» [15]. One of the aspects of cognitive flexibility is being able to change perspectives on an object or situation (i.e. to see it from another position or point of view). Another aspect of cognitive flexibility involves changing the way of thinking about the task and the way of choosing the ways to solve it. This ability is based on two other EF components (working memory and inhibition) and comes later during a child's development [16]. For example, 3 years old children remain stuck in their initial way of perceiving tasks and they cannot switch perspectives, for instance, to change sorting dimensions in a sorting task [20]. Only at the age between 4 and 5 years most children can switch sorting dimensions on the Dimensional Change Card Sort (DCCS) task [21].

1.3 Language Production

Language development includes a number of skills. It begins with the development of phonetics and vocabulary; then grammar competence appears and becomes more and more complex, the syntactical development begins as one-word-phrase (holophrase), then complicates to two-words phrase etc. [22].

The most complex form of speech is a narrative (i.e. a monologue that is cohesive and of coherent utterance). This form appears at the age of 5–6 years and is developing until adulthood [23]. Narratives can be evoked by a story (retelling), by a picture and a series of pictures and by a given situation [24–26].

Narrative as a complex utterance includes a number of indicators, such as phonetics, vocabulary, morphology, syntax and structure parameters. These structure parameters (completeness, adequacy, narrative structure and narrative type) form a narrative as a cohesive and coherent utterance and differ it from just a number of sentences. Phonetics, vocabulary, morphology, syntax are represented on word or sentence level, so within the narrative they compose its microstructure. The means that allow to create a narrative as a cohesive and coherent utterance are called macrostructure of the narrative. The macrostructure comprises the length of a story, its completeness, adequacy, narrative structure and narrative type [27, 28].

1.4 Relation Between Cognitive Flexibility and Language Production

Numerous studies have revealed a significant relationship between language skills and EF in children [29]. Most of them revealed intercorrelations between working memory and language development. Nevertheless, the relationship between cognitive flexibility and inhibitory control and language production remains not very clear.

There are some indirect indices of this relationship. For example, the Uzundag and Küntay study [30] showed that for children at 5 years old the level of EF's development (including cognitive flexibility) is important for production of referential communication. Gillis and Nilsen [13] proved that preschoolers with better results in cognitive flexibility task were more successful in detecting ambiguity in a speaker's messages [14]. Blain-Briere [9] demonstrated that EFs (including inhibitory control and cognitive flexibility) are very important for developing pragmatic skills in preschool children (3,10 – 5,7 years old). Crosbie et al. [31] also showed a significant difference in cognitive flexibility among children with and without speech disorders. Slot and von Suchodoletz [10] managed to analyze the intercorrelations of language development and EF (including cognitive flexibility) in preschoolers aged 31–50 months. In this study EF were related to such language indicators as vocabulary and grammar. The researchers made the conclusion that the relationship was bidirectional: language development influenced EF's level and vice versa.

Consequently, our literature analysis showed that there was an intercorrelation between EF's and language development. Nevertheless, no studies of intercorrelation between cognitive flexibility and narrative production in children were found. Yet there remain unsolved questions: 1) is there a strong correlation between language development and cognitive flexibility; 2) is there a relationship between cognitive flexibility and narrative parameters.

1.5 Aims and Hypotheses

The goal of our study was to examine the relationship between cognitive flexibility and narrative production in preschoolers. In line with previous research [9, 10] we expected to reveal a relationship between these indicators. We hypothesized that there was not only a correlation between cognitive flexibility and microstructure of narrative (its lexical and grammatical aspects), but also between cognitive flexibility and macrostructure of narrative (its length, number of words, accordance to narrative structure, adequacy etc.). As a collateral variable we used nonverbal intelligence (assessed by Raven's matrices).

2 Materials and Methods

2.1 Ethics Statement

The study was approved by the Ethics Committee of the Faculty of Psychology at Lomonosov Moscow State University (the approval No: 2018/42).

2.2 Participants

A total of 283 children were recruited to take part in the study. Data from 4 children were excluded from the analysis. The final sample consisted of 279 monolingual children who were developing typically (i.e. who were not having delays in language and cognitive development) aged from 5 to 6 years (M = 5.6 years; Sd = 0.48). Children attended different kindergartens in Moscow. There were 139 boys and 140 girls.

2.3 Measures

2.3.1 Cognitive Flexibility Assessment

The Dimensional Change Card Sort method (DCCS) [20] was used to assess cognitive flexibility. In this technique children were required to sort a series of bivalent test cards with pictures of red rabbits and blue boats. Firstly, a child sorts 6 cards according to one dimension (color) and then 6 cards - according to another dimension (shape). In the third task a child had to sort cards according to the more complicated rule with the additional factor - cards with/without borders [20]. Performance on the border version is scored as the number of correctly placed cards out of 12. Children are considered to pass this third task if they sort nine or more cards correctly out of 12 test trials. The accuracy score for all three tasks was calculated (max = 24).

The DCCS is an easily administered and widely used measure of cognitive flexibility that is suitable to use with young children [16] and it was adopted in Russia [18, 19]. Main advantage of this method is that difficulties with task implementation cannot be attributed to problems with working memory for the relevant rules [20].

2.3.2 Language Assessment

To elicit narratives from children we used two main techniques, standard for this type of tasks:

1) "Story Retelling" technique: in this study the "The Jackdaw and the Pigeons" fable by Tolstoy was used [32]. The story was read to a child one, two or three times in accordance with the child's capacity to retell it.
2) "Creating a story based on one picture/on a series of pictures" technique, that [32] is centered around one or two series of pictures ("Broken Cup", "Tower", "Cat and Dog"), that children had to assemble in their logical sequence of events and to build a story based on those pictures.

The following linguistic variables were analyzed in these linguistic tasks: firstly, variables characterizing a text's **macrostructure**: such as semantic completeness, semantic adequacy, story programming, number of words, number of syntagmas (significant collocations) and simple sentences [33], narrative's type (complete, simplified or distorted [27]) and compliance with the narrative structure [33, 34]. Secondly, variables related to text's **microstructure:** lexical accuracy (how correctly a child used words), grammatical accuracy and syntactical gaps (e.g. omitting the significant parts of sentence).

2.3.3 Nonverbal Intelligence Assessment

We used nonverbal intelligence assessment as a collateral variable. Non-verbal fluid intelligence was assessed with the Raven's Colored Progressive Matrices test [35]. The task included three sets of matrices: 12 items per set. Children were tested individually with no time limit, but the task was stopped if a child responded incorrectly on four items in a row. Accuracy scores were calculated (max = 36).

2.4 Procedure

All tasks were performed in the second half of the school year during two individual meetings lasting 20–25 min with each child in a quiet room of kindergarten that a child was attending. Children's stories were recorded on a dictaphone.

3 Results

3.1 Correlation Analysis of Cognitive Flexibility and Oral Language Skills in Preschoolers

At the first step, we performed a correlation analysis between the scores of oral narrative language development of all four tasks and the total score obtained in the DCCS task (see Table 1).

Table 1. Correlation of linguistic variables and cognitive flexibility in preschool children (Pearson criterion).

Linguistic variables	Broken cup	The Cat and the Dog	Tower	Retelling
Macrostructure				
Semantic completeness	**0.190****	0.111	0.118	**0.208****
Semantic adequacy A***	**−0.183****	−0.079	**−0.142***	–
General semantic adequacy***	–	–	–	**−0.206****
Programming***	**−0.167****	−0.088	−0.108	**−0.196****
Number of words	**0.138***	−0.024	−0.05	**0.202****
Number of syntagmas	**0.142***	−0.044	−0.013	**0.224****
Number of simple sentences	**0.119***	−0.001	−0.036	**0.223****
Narrative structure	**0.132***	**0.122***	**0.133***	**0.136***
Narrative type	**0.151***	0.088	0.082	**0.146***
Microstructure				
Grammatical accuracy***	−0.03	−0.022	−0.050	−0.114
Lexical accuracy***	−.107	0.018	**−0.153***	−0.104
Syntactical gaps	0.039	−0.017	**−0.138***	–

* $p < 0.05$ (2-tailed); ** $p < 0.01$ (2-tailed), statistically significant correlations **in bold**.
***Please note that high scores indicate low performance.

According to the data, the largest number of correlations between the cognitive flexibility and the linguistic variables was found in the task "Broken Cup" and the "Story Retelling" method. Also it is notable that most of correlations were found with macrostructure indicators, whereas there are almost no correlations with vocabulary and grammar.

3.2 Differences in the Development of Oral Language in Preschoolers with Different Levels of Cognitive Flexibility

At the first stage of the analysis we checked the consistency between the four stories (one from retelling and three from creating a story on a series of pictures) for the 12 linguistic variables. All of them showed consistency by the Alpha-Cronbach criterion above 0.50. Then, we computed one cumulative score across the four narratives for each linguistic variable.

At the second stage we compared (using T-criteria) the linguistic variables of children who coped with the third task of the DCCS method (67 children) and those who failed (scored less than 9 points) (209 children) (see Table 2).

Children who coped with the third task (with/without borders) in the DCCS method made significantly more semantically complete and adequate stories, they had a higher rate of story programming, they used a larger number of sentences and syntagmas compared to children who did not cope with the third task. Also children who managed to successfully perform the third task in the DCCS, showed significantly better results with narratives: they produced complete narratives without distortion. At the same time there were no significant differences in the grammatical and lexical accuracy scores.

It is important to note that children, who coped with the third task in the DCCS method, had significantly higher levels of non-verbal intelligence than children who did not cope with it. In this regard the next step in the analysis was to evaluate the contribution of intelligence and cognitive flexibility to narratives performance.

3.3 Regression Analysis of Cognitive Flexibility, Intelligence and Oral Language Skills in Preschoolers

Linear regression analysis (Enter method) was used to check what was a more significant predictor of the level of storytelling linguistic indicators in preschoolers: the level of non-verbal intelligence or cognitive flexibility (see Table 3).

It was revealed that cognitive flexibility is a predictor of such linguistic variables as semantic completeness (general) and semantic adequacy, programming, number of words, syntagmas and sentences. At the same time the level of non-verbal intelligence is not a predictor of these variables. Both indicators (non-verbal intelligence and cognitive flexibility) are predictors of the narrative structure. Moreover, only cognitive flexibility predicts the type of narrative. Level of nonverbal intelligence is a predictor of grammatical accuracy, whereas the lexical correctness of the story is not associated with any of the indicators under consideration.

Table 2. Differences in linguistic variables in preschoolers who passed 3rd task in DCCS method and who didn't pass it.

Linguistic variables	Children who didn't pass 3rd task		Children who pass 3rd task		T-criteria	p-value
	Mean	St. Dev.	Mean	St. Dev.		
Macrostructure						
Semantic completeness	54.93	18.91	64.16	17.12	−3.557	**0.000**
Semantic adequacy A*	5.01	1.81	4.46	1.65	2.198	**0.029**
General semantic adequacy*	10.90	3.57	9.84	3.37	2.159	**0.032**
Programming*	7.64	2.15	6.99	1.80	2.24	**0.026**
Number of words	71.13	31.51	79.48	29.02	−1.922	0.056
Number of syntagmas	19.17	7.82	21.75	7.57	−2.366	**0.019**
Number of simple sentences	14.02	5.16	15.43	4.82	−1.975	**0.049**
Narrative structure	1.97	1.47	2.79	1.55	−3.95	**0.000**
Narrative type	2.06	1.49	2.61	1.55	−2.607	**0.010**
Microstructure						
Grammatical accuracy*	5.24	2.05	4.96	1.96	0.999	0.319
Lexical accuracy*	7.30	2.12	6.87	1.91	1.481	0.140
Nonverbal inntelligence	11.45	6.202	17.06	7.393	−6.173	**0.000**

* Please note that high scores indicate low performance.

4 Discussion

In this study we aimed to examine the relationship between cognitive flexibility and narrative production in preschoolers. We hypothesized that there are correlations between cognitive flexibility and macrostructure of narrative as well as between cognitive flexibility and microstructure.

According to the obtained data our hypothesis was confirmed. Cognitive flexibility and narrative production in preschoolers are indeed interrelated. However, the correlations were found between cognitive flexibility and narratives' macrostructure parameters. Also the largest number of correlations between the cognitive flexibility and the linguistic variables was found in the task of "Broken Cup" and the "Story Retelling" method. We suppose that these results are due to the fact that macrostructure parameters of narratives are more difficult than microstructure parameters. As we noted earlier, narrative structures appear only at the age of 5–6 years and continue to develop up to adulthood [28]. Also the "Broken cup" method is a narrative based on one picture. This type is

Table 3. Regression models of the linguistic parameters dependence on non-verbal intelligence and cognitive flexibility.

Linguistic variables	Model characteristics			Regression model					
	R	ANOVA		Constant		Nonverbal intelligence		Cognitive flexibility	
		F	P	t	p	t	p	t	p
Macrostructure									
Semantic completeness	0.25	9.24	0.000	3.62	< 0.001	1.115	0.266	**3.69**	**< 0.001**
Semantic adequacy A*	0.14	2.92	0.055	9.22	< 0.001	−0.024	0.981	−2.32	0.021
General semantic adequacy*	0.16	3.55	0.030	10.1	< 0.001	−0.527	0.599	**−2.37**	**0.018**
Programming*	0.15	3.23	0.041	11.3	< 0.001	−0.947	0.345	**−2.01**	**0.045**
Number of words	0.16	3.48	0.032	3.31	0.001	−0.345	0.731	**2.61**	**0.01**
number of Syntagmas	0.18	4.45	0.012	3.41	0.001	−0.169	0.866	**2.91**	**0.004**
Number of simple sentences	0.17	4.10	0.018	4.30	< 0.001	−0.632	0.528	**2.86**	**0.005**
Narrative structure	0.26	9.77	0.000	0.04	0.971	**2.54**	**0.012**	**2.79**	**0.006**
Narrative type	0.20	5.58	0.004	0.62	0.534	1.362	0.174	**2.57**	**0.011**
Microstructure									
Grammatical accuracy*	0.21	6.07	0.003	7.16	< 0.001	**−3.415**	**0.001**	0.27	0.79
Lexical accuracy*	0.14	2.63	0.074	9.90	< 0.001	−1.921	0.056	−0.69	0.493

* Please note that high scores indicate low performance.

more complicated for children than a narrative based on a series of pictures, as well as story retelling [36]. Thereby we see that at the age of 5–6 years children, who are able to flexibly use the rules, create more complex and adequate stories, especially in more difficult tasks.

Children who are not able to perform the third task in the DCCS test show significantly worse results in macrostructure of their narratives whereas there is no significant difference in microstructure indicators (lexical and grammatical performance). The obtained results may be interpreted on the basis of the cognitive development model suggested by Zelazo [37]. This model is called "levels of consciousness" (LOC). It suggests that through the "labeling of one's subjective experiences language helps to make those experiences an object of consideration at a higher LOC. Stepping up in LOC, in turn, allows for the flexible selection of perspectives from which to reason." [38: P.15]. Unexpectedly, there were almost no correlations between cognitive flexibility and microstructure parameters of narratives (lexical and grammatical correctness). This may be explained by the easiness of tasks from the lexical and grammatical correctness point of view or by the assessment technique that supposed only 0–3 points for these parameters.

Linear regression analysis (Enter method) showed that cognitive flexibility is a predictor of such linguistic variables as semantic completeness (general) and semantic adequacy, programming, number of words, syntagmas and sentences. At the same time, the level of non-verbal intelligence is not a predictor of these variables. Both indicators (non-verbal intelligence and cognitive flexibility) are predictors of the narrative structure. Moreover, only cognitive flexibility predicts the type of narrative. Thus, in this study we excluded the influence of nonverbal intelligence level as a predictor of narrative macrostructure. But it is possible that there are other collateral variables. For example, Diamond suggests that there is a strong correlation between the third task in the DCCS method and Theory of mind [16]. On the other hand, Theory of mind is highly related to language [38]. We hypothesize that Theory of mind can be a collateral variable and explain both cognitive flexibility and narrative production, but to prove this remains a task for the future research.

5 Conclusions

The aim of our study was to examine the relationship between cognitive flexibility and narrative production in preschoolers. We expected that there is not only a correlation between cognitive flexibility and microstructure of narrative, but also between cognitive flexibility and narrative's macrostructure. We also used nonverbal intelligence level as a collateral variable. The study showed that there is a strong correlation between cognitive flexibility and narrative production in 5–6 years old children whereas there are much fewer microstructure indicators that have correlations with cognitive flexibility. Children with lower level of cognitive flexibility showed significantly worse results in terms of macrostructure of their narratives whereas there is no significant difference in microstructure indicators (lexical and grammatical performance). It was shown that cognitive flexibility, in contradistinction to non-verbal intelligence, is a predictor of macrostructure parameters of children elicited narratives.

These results may be interpreted on the basis of "levels of consciousness" (LOC) model suggested by Zelazo [34]. In this study we managed to show that Zelazo's theory is correct especially for complex forms of speech, particularly narratives. Diamond suggests that there is a strong correlation between the third task in the DCCS method and Theory of mind. We hypothesize that Theory of mind can be a collateral variable and explain both cognitive flexibility and narrative production, but this task remains for the future research.

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Duff, F.J., Reen., G., Plunkett, K., Nation, K.: Do infant vocabulary skills predict school-age language and literacy outcomes? J. Child Psychol. Psychiatry **56**, 848–856 (2015). https://doi.org/10.1111/jcpp.12378
2. Duncan, G.J., Dowsett, C.J., Claessens, A., Magnuson, K., Huston, A.C., Klebanov, P., Japel, C.: School readiness and later achievement. Dev. Psychol. **43**, 1428–1446 (2007). https://doi.org/10.1037/0012-1649.43.6.1428
3. Willoughby, M.T., Kupersmidt, J.B., Voegler-Lee, M.E.: Is preschool executive function causally related to academic achievement? Child Neuropsychol. A J. Norm. Abnorm. Dev. Child. Adolesc. **18**, 79–91 (2012). https://doi.org/10.1080/09297049.2011.578572
4. Elkonin, D.B.: Detskaya psihologiya: Ucheb. posobie dlya stud. vyssh. ucheb. Zavedenij. In Child Psychology: Studies Textbook for Students of Higher Educational Institutions; Academy: Moscow, Russia, (2006). (in Russian)
5. Matthews, J.S., Ponitz, C.C., Morrison, F.J.: Early gender differences in self-regulation and academic achievement. J. Educ. Psychol. **101**, 689 (2009). https://doi.org/10.1037/a0014240
6. Aaron, P.G., Joshi, R.M., Gooden, R., Bentum, K.E.: Diagnosis and treatment of reading disabilities based on the component model of reading. J. Learn. Disabil. **41**, 67–84 (2008). https://doi.org/10.1177/0022219407310838
7. Cutting, L.E., Materek, A., Cole, C.A.S., Levine, T.M., Mark Mahone, E.: Effects of fluency, oral language, and executive function on reading comprehension performance. Ann. Dyslexia **59**(1), 34–54 (2009). https://doi.org/10.1007/s11881-009-0022-0
8. Acheson, D.J., MacDonald, M.C.: Verbal working memory and language production: common approaches to the serial ordering of verbal information. Psychol. Bull. **135**, 50–68 (2009). https://doi.org/10.1037/a0014411
9. Blain-Brière, B., Bouchard, C., Bigras, N.: The role of executive functions in the pragmatic skills of children age 4–5. Front. Psychol. **5**, 240 (2014)
10. Slot, P.L., Von Suchodoletz, A.: Bidirectionality in preschool children's executive functions and language skills: is one developing skill the better predictor of the other? Early Childhood Res. Q. **42**, 205–214 (2018). https://doi.org/10.1016/j.ecresq.2017.10.005
11. Pazeto, T.C.B., Seabra, A.G., Dias, N.M.: Executive functions, oral language and writing in preschool children: development and correlations. Paidéia (Ribeirão Preto) **24**, 213–221 (2014). https://doi.org/10.1590/1982-43272458201409

12. Veraksa, A.N., Bukhalenkova, D.A., Kovyazina, M.S.: Language proficiency in preschool children with different level of executive function. Psychol. Russ. State Art **11**, 115–129 (2018). https://doi.org/10.11621/pir.2018.0408
13. Gillis, R., Nilsen, E.S.: The role of cognitive flexibility in children's ability to detect communicative ambiguity. First Lang. **34**, 58–71 (2014). https://doi.org/10.1177/0142723714521839
14. Nilsen, E.S., Graham, S.: The relations between children's communicative perspective-taking and executive functioning. Cogn. Psychol. **58**, 220–249 (2009). https://doi.org/10.1016/j.cogpsych.2008.07.002
15. Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., Wager, T.: The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. Cogn. Psychol. **41**, 49–100 (2000). https://doi.org/10.1006/cogp.1999.0734
16. Diamond, A.: Executive functions. Annu. Rev. Psychol. **64**, 135–168 (2013). https://doi.org/10.1146/annurev-psych-113011-143750
17. Lehto, J., Juujarvi, P., Kooistra, L., Pulkkinen, L.: Dimensions of executive functioning: evidence from children. Br. J. Dev. Psychol. **21**, 59–80 (2003). https://doi.org/10.1348/026151003321164627
18. Veraksa, A., Almazova, O., Bukhalenkova, D., Bayanova, L., Popova, R.: Features of executive functions development in Moscow and Kazan preschoolers. In: European Proceedings of Social and Behavioural Sciences, vol. XLIII**,** pp. 648–658. (2018). https://doi.org/10.15405/epsbs.2018.07.86
19. Veraksa, A.N., Almazova, O.V., Bukhalenkova, D.A.: Studying executive functions in senior preschoolers. PsyCh J. **9**(1), 144–146 (2020). https://doi.org/10.1002/pchj.310
20. Zelazo, P.D.: The dimensional change card sort (DCCS): a method of assessing executive function in children. Nat. Protoc. **1**, 297–301 (2006). https://doi.org/10.1038/nprot.2006.46
21. Diamond, A.: Normal development of prefrontal cortex from birth to young adulthood: cognitive functions, anatomy, and biochemistry. In: Stuss, D.T. (ed.) Principles of Frontal Lobe Function, RT Knight, pp. 466– 503. Oxford Univ. Press, London (2002)
22. Bever, T.G., Fodor, J.A., Weksel, W.: On the acquisition of syntax: a critique of 'contextual generalization.' PsychRev **72**, 467–482 (1965). https://doi.org/10.1037/h0022697
23. Peterson, C., McCabe, A.: Developmental Psycholinguistics: Three Ways of Looking at a Child's Narrative. Plenum, New York (1983)
24. Bohnacker, U.T.E.: Tell me a story in English or Swedish: narrative production and comprehension in bilingual preschoolers and first graders. Appl. Psycholinguist. **37**(1), 19–48 (2015). https://doi.org/10.1017/S0142716415000405
25. Fichman, S., Altman, C., Voloskovich, A., Armon-Lotem, S., Walters, J.: Story grammar elements and causal relations in the narratives of Russian-Hebrew bilingual children with SLI and typical language development. J. Commun. Disord. **69**, 72–93 (2017). https://doi.org/10.1016/j.jcomdis.2017.08.001
26. Hudson, J.A., Shapiro, L.R.: From knowing to telling: the development of children's scripts, stories, and personal narratives. In: McCabe, A., Peterson, C. (eds.) Developing Narrative Structure, pp. 89–136. Lawrence Erlbaum, Hillsdale (1991)
27. Norbury, C.F., Bishop, D.V.M.: Narrative skills of children with communication impairments. Int. J. Lang. Commun. Disord. **38**(3), 287–313 (2003). https://doi.org/10.1080/136820310000108133
28. Nicolopoulou, A.: The elementary forms of narrative coherence in young children's storytelling. Narrative Inquiry. **18**(2), 299–325 (2008). https://doi.org/10.1075/ni.18.2.07nic
29. Nilsen, E.S., Graham, S.A.: The relations between children's communicative perspective taking and executive functioning. Cogn. Psychol. **58**, 220–249 (2009). https://doi.org/10.1016/j.cogpsych.2008.07.002

30. Uzundag, B.A., Küntay, A.C.: Children's referential communication skills: the role of cognitive abilities and adult models of speech. J. Exp. Child Psychol. **172**, 73–95 (2018). https://doi.org/10.1016/j.jecp.2018.02.009
31. Crosbie, S., Holm, A., Dodd, B.: Cognitive flexibility in children with and without speech disorder. Child Lang. Teach. Therapy **25**(2), 250–270 (2009). https://doi.org/10.1177/0265659009102990
32. Akhutina, T.V.: Methods of neuropsychological examination of 6–8 years old children [Metody nejropsihologicheskogo obsledovaniya detej 6–8 let]. In: Akhutina, T.V. (ed.) Sekachev, Moscow, Russia, p. 280 (2018). (in Russian)
33. Yagunova, E.: Struktura spontannogo narrativa: mul'timedijnost' iskhodnogo diskursa i ego otrazhenie v tekstah detej i vzroslyh. In: Professora, S.N., Kruglyakova, T.A., Kuz'mina, T.V. (eds.) Sankt-Peterburgskaya shkola ontolingvistiki: Sbornik statej k yubileyu doktora filologicheskih nauk, Zlatoust, St. Petersburg, Russia, pp. 159–177 (2013). (in Russian)
34. Mandler, J.M.: A code in the node: The use of a story schema in retrieval. Discourse Process. **1**, 14–35 (1978). https://doi.org/10.1080/01638537809544426
35. Raven, J., Raven, J.C., Court, J.H.: Manual for Raven's Progressive Matrices and Vocabulary Scales. Section 2: The Coloured Progressive Matrices. Oxford Psychologists Press, Oxford (1998)
36. Oshchepkova, E., Bukhalenkova, D., Yakupova, V.: Razvitie svjaznoj ustnoj rechi v starshem doshkol'nom vozraste. Sovremennoe doshkol'noe obrazovanie: teorija i praktika. **99**(3), 32–39 (2020). https://doi.org/10.24411/1997-9657-2020-10072. (in Russian)
37. Zelazo, P.D.: The development of conscious control in childhood. Trends Cogn. Sci. **8**(1), 12–17 (2004). https://doi.org/10.1016/j.tics.2003.11.001
38. Astington, J.W., Baird, J.A. (eds.): Why Language Matters for Theory of Mind. Oxford University Press, Oxford (2005)

A Digital Psychophysiological Mapping of Primary School Children with/without Learning Disabilities

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Abstract. School entry is a critical stage in children's development, that is intrinsically related to preparedness to learn as reflected in cognitive and behavioral maturation in terms of psychophysiology. The growing number of cognitive and behavioral disorders makes school maladjustment (SM) a socially relevant issue. Attention-Deficit Hyperactivity Disorder (ADHD) is reported as the most frequent but not the only reason for behavioral deviations, study difficulties and school maladjustment. The current study applies the methodology of digital psychophysiological mapping for primary-school children with and without learning difficulties. The analysis has revealed several quantitative indicators as non-specific indicators of psychopathology that accompany a high level of school maladjustment. Still other ones are specific to clinical populations. The study also revealed specific features characterizing SM and non-SM children's performance on various sensorimotor tasks. Children with ADHD and mild cognitive impairment (MCI) are characterized by overall power reduction in heart rate spectral variability and inhibition of central regulation activity. In contrast to ADHD-children, children with MCI did not show increased tension of the regulatory systems. Children diagnosed with anxiety (AD) demonstrate a juggled pattern of central regulatory activity induced by cognitive and sensorimotor load; parietal-occipital focus of alpha-rhythm is less pronounced in the right central-parietal area for children with MCI, and children with AD demonstrate the smallest deviation from the pattern that is typically observed and represents the norm. Theta/beta relation for the MCI and the ADHD-group is significantly higher than for the control group, and children with AD do not differ from the control group on this measurement type. Our results show that the method of adaptive neuromodulation for optimizing the functional brain status is a highly promising tool for diagnosis of different clinical groups.

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Keywords: ADHD · Personalized medicine · Psychophysiological markers · Reaction time · Event-related telemetry of the heart rate (ERT HR) · EEG · Adaptive neuromodulation

1 Introduction

School entry is a critical stage in children's development. Literature review shows that sustainable education success depends both on the child' personality and on their psychophysiological maturation to enter school [1–4].

Almost all developed countries are currently confronted with the problem of neural and mental disorders (most importantly cognitive disorders) among children and young people. Cognitive and behavioral disorders rank top on the children' disability scale in Russia. The number of children identified with cognitive and behavioral disorders increased by 33.5% from 2005 to 2016. Attention-Deficit Hyperactivity Disorder (ADHD) is the most prevalent reason for deviations in behavior, study difficulties and SM. There is increased attention to ADHD nowadays due to its pervasive nature and social significance [5, 6].There are still no common criteria for diagnosing ADHD [7, 8]. It is diagnosed by professionals (psychiatrists or neuropsychiatrists) based on several behavioral aspects. The issue is acute since there are no methods of early ADHD detection based on physiological aspects of a child' growing central nervous system. Consequently, there are no effective ways of ADHD treatment [9]. In the absence of biological markers revised DSM-V and ICD-11 diagnostics are mostly focused on children's behavioral problems with a recent extension to adults [10].

Fact-based international recommendations stress the importance of other methods and approaches to ADHD diagnostics that go beyond clinical interviews [11–13]. One of the directions for methodological development is to look at psychophysiological differences between children with and without ADHD, and children faced with SM problem [14].

Therefore, today it is highly relevant to further develop technologies that make diagnostic procedures more objective and the development of cognitive functions in children at risk of ADHD and clinical patients with inherently high SM more effective. It is also necessary to use interdisciplinary approaches for the functional diagnostics and rehabilitation with the use of telemetry information systems.

2 Materials and Methods

2.1 Ethics Statement

All the experimental procedures were designed and held in accordance with the ethical standards of the Lobachevsky University Committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all the participants (their legal representatives).

2.2 Participants

A total of 68 primary school children participated in the current study. Upon advice of school psychologists and caregiver consent, 44 schoolchildren underwent examination to initially determine the reason for study difficulty 23 students were taken as a control group displaying typical development. The groups are summarized in Table 1.

Table 1. Participants' grouping according to their diagnosis

Group	Age (years)	Number of participants
Control group (The typical development)	10.0 ± 0.5	23
ADHD (ICD-10, F90.0 Disturbance of activity and attention)	8.3 ± 0.2	22
MCI (ICD-10, F06.7 Mild cognitive impairment)	8.0 ± 0.3	12
Anxiety disorder (AD) (ICD-10, F40.9 Phobic anxiety disorder, unspecified)	8.5 ± 0.3	11

2.3 The Digital Psychophysiological Mapping. Assessment of the Level of Attention and Features of Sensorimotor Activity

The Toulouse-Pieron (TP) test was applied to evaluate the sustained and selective attention, processing speed, visuo-perceptive and inhibition abilities. The TP test demands high concentration levels and fatigue resistance. The stimulus material consisted of 8 types of squares, differing in which side or to which of the corners a black semicircle or a quarter circle is added. The participants were suggested to find and cross out the squares which are similar to the samples and underline the rest. Two parameters were fixated: speed (number of characters processed per minute) and accuracy (the ratio of correctly processed characters to the total number of characters processed per minute).

Additional tests were held for evaluating the participants' level of attention. Within the platform ApWay.ru three sensorimotor tasks were created:

1. Alertness test: this subtest measures the reaction time (RT) to a simple visual target; stimuli: the pictures of a cat and a mouse; a total of 20 trials.
2. «Go/NoGo» test: this subtest measures selective attention; stimuli: the pictures of a cat and a mouse (target and non-target stimuli), all in five positions of the screen; a total of 20 trials.
3. Semantic Attention test: this subtest measures semantic capacity; stimuli: the pictures of a fish, a pear, an apple, a crocodile, an eagle, and a cat; only «edible objects» were targets; a total of 30 trials.

The main parameters were the RT - the total time of the sensorimotor reaction from the beginning of the stimulus occurrence to the end of the motor response, the Motor reaction (MR) – the time from the start of pressing the key to its release, Cognitive reaction (CogR) - the time from the beginning of the stimulus occurrence to the beginning of the motor response for correct ones, and the number of false reactions - Errors (ERR1 - event skipping, ERR2 - double or multiple click, ERR3 - clicking on a non-target stimulus).

2.4 Monitoring of Heart Rate Variability and the Autonomic Regulation

The autonomic regulation peculiarities of the sensorimotor activity were estimated on the base of the event-related telemetry technology of the heart rhythm (cogni-nn.ru, Lobachevsky State University) [15]. The sequence of R–R intervals of the electrocardiogram (ECG) was transmitted from the placed on the participants' chests sensor (Zephyr TM HxM TM Smart – Zephyr BIO PACH BH3-M1 (Zephyr Technology, USA)) to the smartphone via Bluetooth. After processing, the data were transmitted to the dedicated server system in the Internet via GSM channels. The processing algorithm consisted of the following steps: 1) the R–R signal fragmentation with a time window of 100 s and a time shift of 10 s; 2) the calculation of the frequency spectrum by the method of nonuniform discrete Fourier transform; 3) the spectrum splitting (very low frequency band (VLF)—0.003–0.040 Hz, low frequency band (LF)—0.04–0.15 Hz, and high frequency band (HF)—0.15–0.4 Hz); 4) the calculating of the total spectrum power (TP) of heart rate variability (HRV) and sympathovagal balance (vegetative/autonomic balance index)—LF/HF. The main attention was paid to the TP as it reflects the adaptive potential of the central nervous system and to the LF/HF ratio as it reflects the level of regulatory systems tension.

2.5 Assessment of the Maturation of Cortical Rhythms

EEG signals were recorded using an EEG recorder (EEGA-21–26 «Encephalan – 131 – 03» manufactured by «Medicom MTD Ltd», Taganrog, Russian Federation). The registration was carried out with 16 electrodes with standard «10–20» positioning, with referent electrodes mounted to earlobes and ground electrode at vertex. Sample rate was 250 Hz.

On-line filtering was applied: cut-off frequency for high frequency filter is 0.5 Hz, cut-off frequency for low frequency filter is 70 Hz, notch filter for 50Hz. Discrete Fourier transform (DFT) was applied to calculate EEG spectral characteristics to estimate the power in theta (4-8Hz), alpha (8–13 Hz) and beta (13–21 Hz) frequency ranges.

«Brainstorm» software packet was applied for EEG processing [16] (v. 3.200909, 09-Sep-2020) as public license agreement software. The formation of parietal-occipital focus of alpha rhythm and theta/beta ratio were estimated.

2.6 Assessment of the Adaptive Neuromodulation for the Correction of School Disability

The neurofeedback sessions included the exposition of the LED stimuli with the gradually increasing frequency rate from 4 to 20 Hz for resonant detection of the EEG oscillators. The on-line registered amplitude of subject's EEG oscillator was automatically converted into music-like signals resembling flute sounds with smooth variations in pitch and intensity. These EEG-based music-like stimuli were supplemented with weak auditory signals corresponding to subject's heart rate. Simultaneously, LED stimuli were presented generated on the base of the subject's native EEG.

The shifts in the power of the main rhythms and in the peak frequency of the EEG under the influence of the neurofeedback session relative to the background sample were assessed.

Within the statistical analysis, Statistica12.0 and Microsoft Excel 2010 software packages were used. To validate statistical significance non-parametric Mann-Whitney Rank Sum Test and Kruskal-Wallis H-test were applied. The significance of the features' differences before and after neurofeedback session was calculated via Student paired t-test.

3 Results and Discussion

3.1 Representation of School Disability in the Level of Attention and Features of Sensorimotor Activity

Speed and accuracy on TP test are non-specific markers of psychopathology that is characterized by high level of SM. In all clinical groups the parameters of speed and accuracy are significantly lower compared to the control group (see Fig. 1).

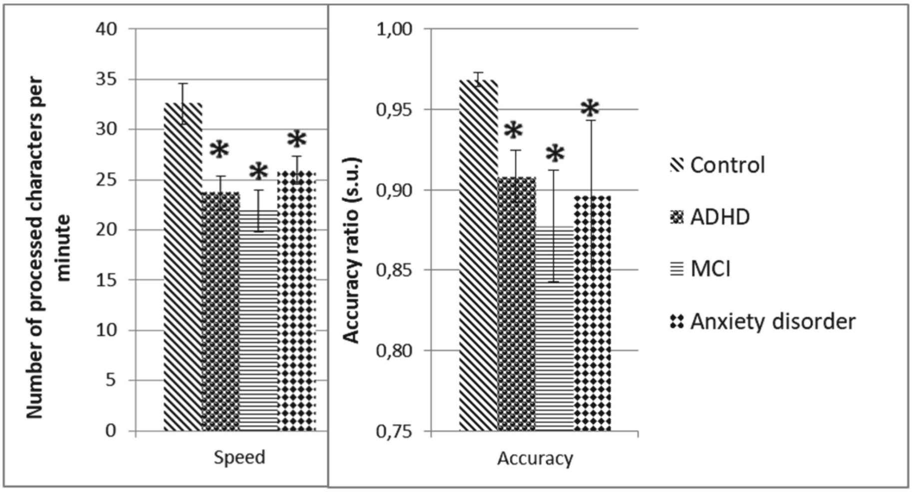

Fig. 1. Speed and Accuracy values by groups, asterisks mark significant differences with control ($p < 0.05$)

The overall time for simple sensorimotor reaction as well as for its cognitive component are significantly higher for children with ADHD (see Fig. 2, A).

The cognitive component marker of «GO/NO GO» task is significantly higher for children with ADHD, compared to other groups. The markers of overall time for «Go/NoGo» task and for Semantic Attention task, and also the cognitive component of

Semantic Attention task are specific not only being in the opposition "norm-pathology", but differ depending on the group (see Fig. 2, B–C), and the maximum reaction time we see in clinical ADHD- and MCI groups.

Thus here' a trend of time reaction increasing in clinical groups; in ADHD and AD groups it increases through cognitive sensorimotor component, while in MCI group children take more time both for conscious decision making and estimation, and for sensorimotor response.

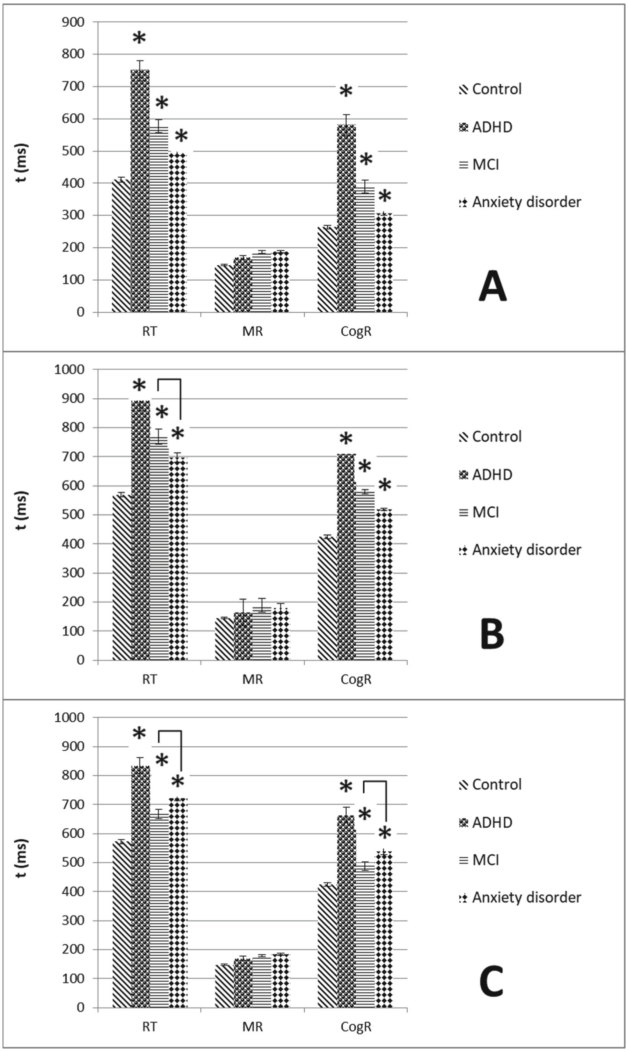

Fig. 2. Reaction time (RT), motor time (MR), cognitive time (CogR) for Alertness test (A), «Go/NoGo» test (B) and Semantic Attention test (C) by groups, asterisks mark significant differences with control, and lines – between clinical groups ($p < 0.05$)

Moreover, a non-specific marker of psychopathology that is characterized by high level of SM is total amount of mistakes while completing sensorimotor tasks, graded by its complexity.

3.2 Representation of School Disability in Heart Rate Variability and the Autonomic Regulation

The estimation of functional status of autonomic nervous system was made by analysis of heart rate recording in the context of sensorimotor task activity. We see it's typical for children with ADHD the reduction of total heart rate variability spectrum, the reduction of central regulation, the tension of regulatory systems with prevailing of sympathetic branch of autonomic nervous system. According to the index of sympatho-vagal balance, all groups significantly differ from each other; it seems atypical the essential increase of overall spectral power in AD group, that may be indicative of disorganization of central regulation over the phone of cognitive and sensorimotor loads (see Fig. 3).

3.3 Representation of School Disability in Cortical Rhythms

In parietal-occipital focus the values of alpha rhythm significantly differs for the focus group compared to other groups, and parietal-occipital focus of alpha rhythm in right central-parietal head area (P4, T6, Cz, C4, T4 electrodes) is a specific marker for ADHD-group (see Fig. 4).

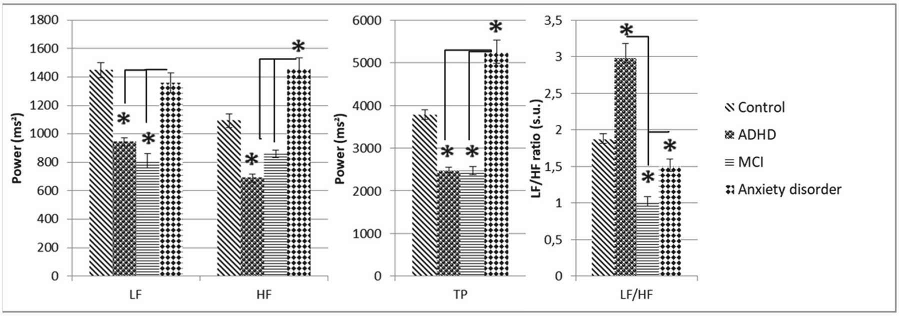

Fig. 3. The spectrum into ranges (LF—0.04–0.15 Hz, and HF—0.15–0.4 Hz), the total power of the HRV spectrum (TP), the sympathovagal balance (LF/HF) by groups, asterisks mark significant differences with control, and lines – between clinical groups ($p < 0.05$)

Theta/Beta ratio (TBR) coefficient for MCI- and ADHD groups is significantly higher than for the control group (see Fig. 5).

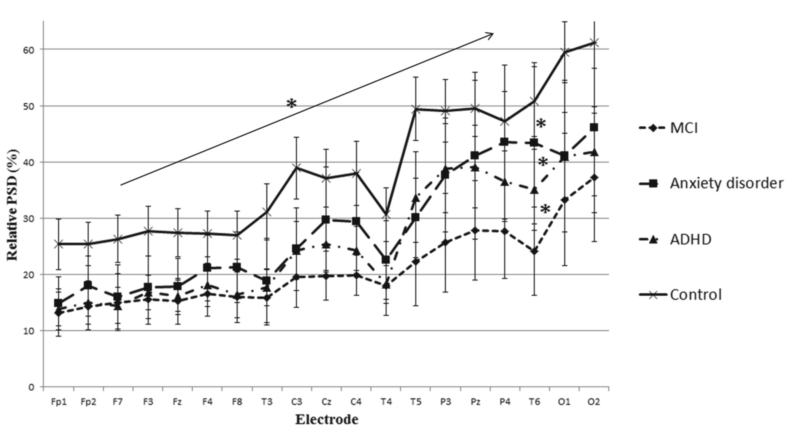

Fig. 4. The parietal-occipital focus alpha rhythm by groups ($p < 0.05$)

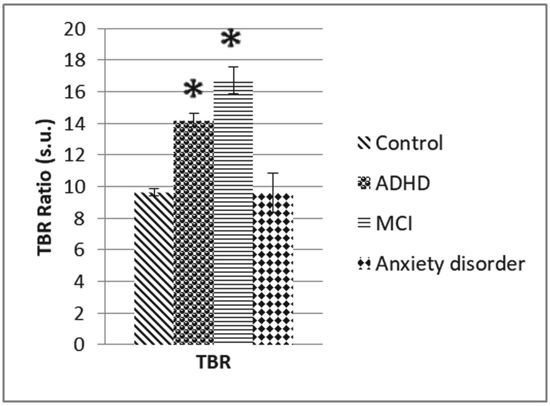

Fig. 5. The theta/ beta ratio by groups, asterisks mark significant differences compared to the control group ($p < 0.05$)

3.4 Effectivity of the Adaptive Neuromodulation for the Correction of School Disability

Within the analysis of neurofeedback sessions data for each group, the power shifts of theta, alpha, and beta EEG rhythms during neurofeedback sessions were calculated in relation to the background sample level.The analysis revealed that in the control group, under the influence of a neurofeedback session a significant increase was noted only for the power of the EEG alpha rhythm, and shifts in other indicators did not reach the level of significance. In case of encephalopathies and ADHD, on the contrary, the maximum shifts in all indicators were recorded: the power of the theta rhythm significantly decreased, and the power of the alpha and beta rhythms significantly increased. Within these two groups, the peak EEG frequency also increased significantly. In anxiety disorders, the shifts in all indicators were minimal (see Table 2).

Table 2. The shifts in the power of the main rhythms and peak EEG frequency under the influence of a neurofeedback session relative to the background sample and the level of significance of these shifts within different groups of subjects.

Indicator	Group	M ± m	p-value
Power shift of the theta rhythm (relative units)	Control	−0.07 ± 0.06	0.317
	MCI	**−0.41 ± 0.14**	**0.017**
	ADHD	**−0.28 ± 0.10**	**0.026**
	Anxiety disorder	−0.15 ± 0.17	0.254
Power shift of the alpha rhythm (relative units)	Control	**0.10 ± 0.03**	**0.017**
	MCI	**0.16 ± 0.04**	**0.004**
	ADHD	**0.31 ± 0.10**	**0.013**
	Anxiety disorder	0.18 ± 0.11	0.234
Power shift of the beta rhythm (relative units)	Control	0.03 ± 0.02	0.225
	MCI	**0.06 ± 0.01**	**0.004**
	ADHD	**0.11 ± 0.03**	**0.005**
	Anxiety disorder	0.01 ± 0.04	0.962
EEG peak frequency shift (Hz)	Control	0.10 ± 0.16	0.528
	MCI	**0.70 ± 0.17**	**0.002**
	ADHD	**0.81 ± 0.23**	**0.005**
	Anxiety disorder	0.88 ± 0.36	0.096

3.5 Psychophysiological Markers of Different Kind of School Disabilities

Thus, the examination has revealed several quantitative indicators that characterise each group of primary schoolchildren. Some of those indicators are non-specific psychopathological indicators in children characterized by a high level of SM. It is reflected in speed and accuracy on Toulouse-Pieron test as well as in total amount of mistakes when performing various sensorimotor tasks, and in overall formation of parietal-occipital alpha-rhythm focus. These estimates may be useful for clinical risk screenings therapy efficiency.

The study identified specific indicators to arrive at better differentiation of psychopathologies associated with a high level of SM. ADHD children take longer to complete different sensorimotor tasks; they take longer to become aware, evaluate and make a conscious decision. Children with MCI are less accurate on «Go/NoGo» task, both at the stage of decision making and in terms of their sensorimotor response, while children with AD are less accurate on semantic sensorimotor tasks.

The decrease in the overall heart rate spectrum variability and the reduction of central regulation contour were evidenced in children with ADHD and MCI. In contrast to ADHD-children, for children with MCI there's no increase in regulatory system while the sympathetic part of autonomic nervous system prevails For children with AD, we observe a jumbled central regulation contour against the background of cognitive and sensorimotor load.

Children with MCI have less shaped parietal-occipital focus of alpha rhythm at the right central-occipital head area (P4, T6, Cz, C4, T4 electrodes) followed by ADHD children. AD group deviated least from typical values. It is consistent with other results, mentioned the focus of alpha rhythm as a common method to determine EEG markers [17]. Theta/beta ratio is significantly higher in MCI- and ADHD-children than in the control group. The AD group does not deviate from the control group on this measurement type.

The data on changes in EEG rhythms in different groups of primary schoolchildren during neurofeedback sessions are as follows. In the control group, a significant increase in the power of the EEG alpha rhythm was noted, while in encephalopathies and ADHD, on the contrary, the maximum shifts in all indicators were recorded: the power of the theta rhythm significantly decreased, and the power of the alpha and beta rhythms significantly increased. The peak EEG frequency also increased significantly in these two groups. In anxiety disorders, the shifts in all indicators were minimal.

In the modern literature, neurofeedback sessions aimed at reducing the power ratio of the theta and beta EEG rhythms are considered one of the most effective non-drug treatments in the treatment of ADHD and comorbid disorders in children [18]. In our study, just such a result, which indicates the normalization of the EEG spectral composition, was recorded under the influence of a session of neurobiological control in schoolchildren with encephalopathies and ADHD.

As for the control group, an increase in the severity of the EEG alpha rhythm could be due to the formation of an "alpha state", which is characterized by general relaxation with a decrease in the level of stress, anxiety and depression [19]. In addition, model studies have shown that the interaction of endogenous and exogenous oscillations during EEG neurofeedback opens up the possibility of personalized control of brain rhythms, leading to an increase in cognitive activity and an improvement in overall well-being [20].

4 Conclusion

The undertaken research shows that the developed methodology of digital psychophysiological mapping is an effective tool for identifying precise quantitative indicators that determine the psychophysiological status of junior schoolchildren who are experiencing and not experiencing learning difficulties. The revealed features of each of the surveyed groups can contribute to an objective clarification of the reasons for school maladjustment.

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References

1. Chizova, E.: Recommendations for effective interaction of teachers and children suffering from hyperkinetic behavior syndrome. Psihologicheskie Nauki (Psychol. Sci.) **3**(93), 57–63 (2020). https://doi.org/10.23670/IRJ.2020.93.3.038

2. Efimova, V.: Psychophysiological approach to the analysis of mechanisms of learning difficulties in children. Psihologiya Obrazovaniya v Polikulturnom Prostranstve (Psychol. Educ. Multicult. Space) **2**(50), 28–39 (2020). https://doi.org/10.24888/2073-8439-2020-50-2-28-39(inRussian)
3. Kuzmina, T., Chizhova, A.: Analytical review of approaches in the study and correction of behavioral disorders in children and adolescents (evidence from attention deficit and hyperactivity disorder). Klinicheskaia I Spetsial'naia Psikhologiia (Clin. Spec. Psychol.) **8**(1), 1–18 (2019). https://doi.org/10.17759/cpse.2019080101
4. Zavadenko, N.: How to Understand a Child with Hyperactivity and Attention Deficit). Shkola-Press, Moscow (2001).(in Russian)
5. Goncharova, O., Vetrov, P., Gorshkov, O.: Prevalence, diagnosis and methods for correcting the syndrome of attention deficiency with hyperactivity in children. Meditsinskiy Sovet (Med. Counc.) **12**, 96–103 (2012). (in Russian)
6. Xu, G., Strathearn, L., Liu, B., Yang, B., et al.: Twenty-year trends in diagnosed attention-deficit/hyperactivity disorder among US children and adolescents, 1997–2016. JAMA Netw. Open **1**(4), e181471 (2018). https://doi.org/10.1001/jamanetworkopen.2018.1471
7. Gribanov, A., Kanzhin, A., Iordanova, J., Deputat, I.: Features of behavioral reaction and sensomotor organizations at children with the attention deficit hyperactivity disorder). Ekologiya Cheloveka (Hum. Ecol.) **4**, 28–32 (2008). (in Russian)
8. Pankov, M., Gribanov, A., Deputat, I., Starceva, L.: Clinical and physiological characteristics of attention deficit hyperactivity disorder in the children. Vestnik Novyh Medicinskih Tekhnologij (Herald New Med. Technol.) **20**(3), 91–97 (2013). (in Russian)
9. Fesenko, Y., Fesenko, Y.: Methods of integrated diagnostics attention deficit hyperactivity disorders (ADHD) in children. Pediatrija (Pediatrics) **5**(2), 35–39 (2014). (in Russian)
10. Groeneveld, K., Mennenga, A., Heidelberg, R.: Z-Score neurofeedback and heart rate variability training for adults and children with symptoms of attention-deficit/hyperactivity disorder: a retrospective study. Appl Psychophysiol Biofeedback **444**, 291–308 (2019). https://doi.org/10.1007/s10484-019-09439-x
11. Cabral, M., Liu, S., Soares, N.: Attention-deficit/hyperactivity disorder: diagnostic criteria, epidemiology, risk factors and evaluation in youth. Transl. Pediatr. **9**(1), S104–S113 (2020). https://doi.org/10.21037/tp.2019.09.08
12. Marsh, P., Beauchaine, T., Williams, B.: Dissociation of sad facial expression and autonomic nervous system responding in boys with disruptive behavior disorders. Psychophysiology **45**, 100–110 (2008). https://doi.org/10.1111/j.1469-8986.2007.00603.x
13. Snyder, S., Rugino, T., Hornig, M., Stein, M.: Integration of an EEG biomarker with a clinician's ADHD evaluation. Brain Behav. **5**(4), 00330 (2015). https://doi.org/10.1002/brb3.330
14. Thomas, R., Sanders, S., Doust, J., Beller, E., Glasziou, P.: Prevalence of attention-deficit/hyperactivity disorder: a systematic review and meta-analysis. Pediatrics **135**(4), e994–e1001 (2015). https://doi.org/10.1542/peds.2014-3482
15. Polevaya, S.A., Eremin, E.V., Bulanov, N.A., Bakhchina, A.V., Kovalchuk, A.V., Parin, S.B.: Event-related telemetry of heart rate for personalized remote monitoring of cognitive functions and stress under conditions of everyday activity. Sovremennye tehnologii v medicine **11**(1), 109 (2019). https://doi.org/10.17691/stm2019.11.1.13
16. Tadel, F., Baillet, S., Mosher, J., et al.: Brainstorm: a user-friendly application for MEG/EEG analysis. Comput. Intell. Neurosci. **2011**, 879716 (2011). https://doi.org/10.1155/2011/879716
17. Heinrich, H., Busch, K., Studer, P., Erbe, K., Moll, G., Kratz, O.: EEG spectral analysis of attention in ADHD: implications for neurofeedback training? Front. Hum. Neurosci. **8**, 611 (2014). https://doi.org/10.3389/fnhum.2014.00611

18. Enriquez-Geppert, S., Smit, D., Pimenta, M., Arns, M.: Neurofeedback as a treatment intervention in ADHD: current evidence and practice. Curr. Psychiatry Rep. **21**(6), 46 (2019). https://doi.org/10.1007/s11920-019-1021-4
19. Frederick, J.: Psychophysics of EEG alpha state discrimination. Conscious. Cogn. **21**(3), 1345–1354 (2012). https://doi.org/10.1016/j.concog.2012.06.009
20. Nuidel, I., Kolosov, A., Demareva, V., Yakhno, V.: Using a phenomenological mathematical model to reproduce the interaction of endogenous and exogenous oscillations under neurocontrol. Sovremennye Tekhnologii v Meditsine (Mod. Technol. Med.) **11**(1), 103–108 (2019). https://doi.org/10.17691/stm2019.11.1.12

Theory of Mind and Behavioral Control in Children with and without Borderline Intellectual Functioning

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Abstract. In this paper, we have compared the development of theory of mind (ToM) and behavioral control in children with special needs with/without borderline intellectual functioning. An assessment of ToM included tasks for understanding visual perspectives, false beliefs, deception, and “white lies”. “Reading the Mind in the Eyes” (child version) test was used to assess the understanding of mental states by the expression of eyes. Behavioral control is assessed by Kogan’s task of combining attributes, Tower of Hanoi, Temple-Dorky-Amen “Test of children anxiety”, neuropsychological tasks. For assessment of intelligence, we used Wechsler Intelligence Scale for Children (WISC). The study involved 34 children 7–11 years old (13 girls). The research revealed significant differences in the understanding of communicative intentions in situation of deception and “white lies” and in recognition of emotions and other mental states between children with and without mild disorder of intellectual functioning. Thus, children with special needs 7–11 years old with borderline intellectual development have ToM deficit comparing with their peers with normal verbal intelligence, while the deficit of self-regulation is weakly expressed in them.

Keywords: Theory of mind · Behavioral control · Executive functions · Verbal intelligence

1 Introduction

The theory of mind and self-regulation are abilities that are of importance to school in children with special needs. The theory of mind is the ability to attribute mental states (intentions, desires, emotions, and beliefs) to ourselves and other people and to predict our own and others’ behavior [1]. Regulatory aspects are investigated within the framework of the concept of control of behavior [2], which unites the cognitive, emotional, and volitional aspects of self-regulation. Recently, a lot of studies investigate the role of individual differences in the development of these abilities in ontogenesis. One of these factors may be an intellectual development.

Data about the role of intelligence in the development of the self-regulation ability and ability to understand the mental world are contradictory. It is not entirely clear whether the executive functions (EF) are poorer in children with intellectual disabilities.

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Even though EF and intelligence partially overlap, a meta-analysis by Ackerman et al. [3] indicates that EF and intelligence share less than 25% of the diversity. In general, the available data suggest a possible lag in the development of EF in children with intellectual delay, but it at great extent depends on the degree of intellectual delay and on the assessment methods of EF [4]. Similar results were obtained in a study of the relationship between the theory of mind and intelligence: some studies did not reveal a linear relationship between these abilities in children with typical development and intellectual disabilities [5], but other studies show a delay in theory of mind development in children with low intelligence [6, 7].

In the present study, we compared the development of a theory of mind and behavioral control in disabled children with moderate and low verbal intelligence. The division of children into subgroups according to verbal intelligence was due to the results of previous studies on the relationship between the theory of mind, EF and verbal intelligence [8, 9].

2 Methods

2.1 Ethics Statement

Written informed consents to participate in the study had obtained from parents/legal guardians of participants of this research. Parents/legal guardians were informed about the purpose and methods of research and confidentiality of the results.

2.2 Participants

Data were collected and analysed on 34 students with special needs studying in primary school (1st–4th Grade). The characteristics of the groups are presented in Table 1.

Table 1. Demographical and intellectual characteristics of children.

Groups	N	Age M (SD)	M:F	VIQ	PIQ	FIQ
Children with verbal IQ $>$ 85	17	8,11 (1,2)	8:9	97,94 (10,31)	108,05 (18,03)	105,94 (14,51)
Children with verbal IQ $<$ 85	17	8,10 (1,1)	13:4	71,76 (7,48)	93,94 (19,79)	80,7 (11,59)

2.3 Methods

The tasks to understand the visual perspective of second levels, to understand the first and second order false beliefs (like “Sally-Anne test” and “Ice-cream test”) and two stories from “Strange story” (deception and “white lie”) [1, 10, 11] were used to assess theory of mind. All the variables of ToM were measured based on dichotomous scale: 0 = the task was not performed correctly; 1 = the task was performed correctly. Overall score of theory of mind was the sum of all tasks performed (The Cronbach's alpha is 0.714).

All participants were tested with a "Reading the Mind in the Eyes" (child version) test to assess their understanding of mental states by the expression of eyes [12].

For assessment of cognitive control, we used the Kogan's task of combining attributes [13] and "Tower of Hanoi". Kogan's task examines child's abilities to focusing, shifting and maintain attention. During this task a child asked to sort cards with different geometric shapes by different colors (with preliminary series when child just counts cards), first – by color, then – by shape and in final series a child has to put them in special table considering both color and shape. The experimenter recorded time for each series and a number of errors in counting and/or sorting. The "Tower of Hanoi" is well-known puzzle, frequently used in psychological research on problem solving. We registered time spent on solving a task and a number of moves.

We took "Child anxiety test" by R. Temple, M. Dorky, B. Aman [14] and "ABC of mood" by N.L. Belopolskaya [15] to estimate the emotional control. We modified "ABC of mood" for investigating purposes. A set of pictures with images of people and animals (a man, a woman, a cat, a bird) with different moods (a joy, an anger, a fear, a grief, a discontent, a complacency) was selected. For assessment of a correctness of emotion naming we presented each picture to a child and asked them about depicted character: "What is his\her mood?" Synonyms (for example, angry, rage, grief, annoyed, etc.) were considered as right answers. After that, we mixed the pictures and asked children to arrange the pictures to piles that in each pile there were images of people and animals with the same mood. Then we asked children to name mood of characters in each pile. It was an estimation of emotion classification. We estimated the correctness of emotion classification by how much it coincides with the classification of the author of the "ABC of mood". In both cases a number of errors was accounted.

The control of actions was assessed by neuropsychological tasks (for reciprocal hand movement, repetition of rhythmic sequence and a task "Fist-Rib-Palm" for execution of a sequence of actions – two sequences for each hand) [16]. Max score was 6.

Wechsler Intelligence Scale for Children (WISC) was used to assess the level of intellectual development of children with special needs. Eight subtests were used, four in each test series, which allowed calculating the Full-scale IQ, Verbal IQ and Performance IQ [17].

For statistical analysis we used Statistica 6.0. And SPSS 23, with chi-quadrat test (χ^2) and Mann-Whitney criterion (U) to determine the differences in the success of performing certain tasks on theory of mind and behavioral control.

3 Results

3.1 ToM's Tasks Performance

Based on the assumption that the verbal intelligence played the role in the development of theory of mind, the aim of this study was to investigate a possible difference in the understanding mental states by children with and without borderline intellectual disorder. It is evident from the results that overall (Fig. 1), there were significant differences in

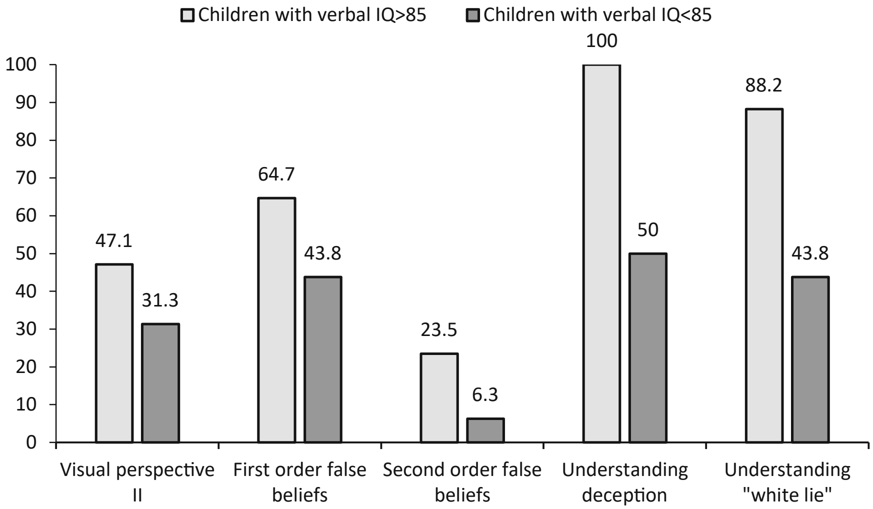

Fig. 1. Results of ToM's tasks performance (%) by children with and without borderline intellectual functioning.

the understanding of deception ($\chi^2 = 11{,}22$, $p = 0{,}001$) and “white lie” ($\chi^2 = 7{,}34$, $p = 0{,}007$) between the two groups of children.

Also, there were found significant differences between children with disabilities with normal and reduced verbal intelligence in the general indicator of the theory of mind ($U = 71.50$; $p = 0.019$) and the indicator of the “Reading the Mind in the Eyes” test ($U = 19{,}50$; $p = 0{,}000$). These results are in line with those of Baker et al. [18], who noted that intelligence does play a significant role in performance on the “Reading the Mind in the Eyes” test. It is apparent that verbal intelligence plays a role both in the cognitive aspect of understanding the mental world (theory of mind), and in the emotional one (recognition of mental states by facial expressions).

3.2 Behavioral control's Tasks Performance

Children with higher verbal intelligence had a larger range of values for most indicators (except for the classification of emotions and neuropsychological tests) (Table 2), which may indicate the heterogeneity of this group of children. Thus, the level of verbal intelligence cannot be considered as a single indicator of children's performance in self-regulation tasks.

Significant differences in behavioral control indicators between children with reduced and normal verbal intelligence were found only in the number of errors when sorting cards by color in the Kogan task. There were also differences at the border of significance in the number of errors when sorting cards by shape in the Kogan task, i.e. children with low verbal intelligence had difficulties with distribution of attention between two processes (counting and sorting by color, counting and sorting by shape). The distribution of attention between three processes simultaneously (count, color, shape) was apparently equally difficult for both groups of children, so no significant differences were

Table 2. Demographical and intellectual characteristics of children.

Scales	IQ > 85 (M (min-max))	IQ < 85 (M (min-max))	p-level
KoganCount, s	47 (14–131)	45 (25–111)	0,828
KoganColour, s	56 (25–292)	55 (33–125)	0,969
KoganForm, s	90 (37–435)	79 (49–199)	0,864
Kogan Color-Form, s	143 (81–657)	141 (41–344)	0,985
KoganCountErr	0 (0–5)	1 (0–5)	0,438
KoganColourErr	0 (0–25)	2 (0–25)	0,017**
KoganFormErr	1 (0–25)	2 (0–25)	0,051*
Kogan Color-Form Err	2 (0–25)	3,5 (0–25)	0,594
TowerTurn	19 (7–49)	15 (7–30)	0,761
TowerTime, s	121 (20–300)	106 (30–206)	0,705
Anxiety, %	42 (21–63)	50 (28–57)	0,059*
EmotionNaming (errors)	6 (0–15)	7 (4–15)	0,353
EmotionClass (errors)	6 (0–13)	7 (0–24)	0,899
Neuropsy	4 (1,5–6)	3,75 (0–6)	0,637

found in this series. The significance of differences also in anxiety reached the borderline values; it was higher in children with low intelligence. This may be due to the children's experience of their failure in learning and social interaction, communication difficulties associated with low verbal intelligence, the difficulty of school adaptation [19].

4 Discussion

The results of the study show that children with special needs 7–11 years old with borderline intellectual functioning have a deficit in the development of the theory of mind compared to their peers without borderline intellectual functioning, while the shortage in self-regulation is weak. Cognitive control is impaired to a greater extent, the accuracy of task performance suffers when children must distribute attention to several attributes. As a tendency, a lack of emotional control is manifested as an increased anxiety in children with low verbal intelligence. These results are in line with data from other studies [20]. Children with borderline intellectual functioning were less likely to understand the communicative intentions of the speaker in a situation of deception and "white lie", and they were less likely to recognize emotions and other mental states by facial expressions. These results are consistent with data from other studies [6, 7, 18]. In general, we found a moderate relation of ToM and verbal IQ and a weak one of verbal IQ and behavior control.

5 Conclusion

In conclusion, we would like to emphasize that our results indicate that primary schoolers with a borderline intellectual functioning have a deficit of social understanding rather than a deficit of self-regulation. In primary school, children enter a new social environment and relationships, and understanding the mental states of another person becoming critically important. The verbal intelligence plays an important role in this process, and the borderline level of verbal intelligence causes difficulties in social understanding. These findings provide important details about the developmental trajectory of self-regulation and theory of mind in children with and without borderline intellectual functioning during middle childhood.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Baron-Cohen, S.: Theory of mind and autism: a fifteen-year review. In: Baron-Cohen, S., Tager-Flusberg, H., Cohen, D. (eds.) Understanding Other Minds: Perspectives from Developmental Cognitive Neuroscience, pp. 3–20. Oxford University Press, Oxford (2000). https://doi.org/10.1016/s0074-7750(00)80010-5
2. Sergienko, E.A., Vilenskaya, G.A.: Kontrol' povedenija – integrativnoe ponjatie psihologicheskoj reguljacii [Behavior control - an integrative concept of psychological regulation]. In: Sergienko, E.A., Zhuravlev, A.L. (eds.) Razrabotka ponjatij sovremennoj psihologii [Development of concepts of modern psychology], pp. 343–378. Publishing house "Institute of Psychology RAS", Moscow (2018). (in Russian)
3. Ackerman, P.L., Beier, M.E., Boyle, M.O.: Working memory and intelligence: the same or different constructs? Psychol. Bul. **131**, 30–60 (2005). https://doi.org/10.1037/0033-2909.131.1.30
4. Schuiringa, H., van Nieuwenhuijzen, M., Orobio de Castro, B., Matthys, W.: Executive functions and processing speed in children with mild to borderline intellectual disabilities and externalizing behavior problems. Child Neuropsychol **23**, 442–462 (2017). https://doi.org/10.1080/09297049.2015.1135421
5. Rajkumar, A.P., Yovan, S., Raveendran, A.L., Russell, P.S.S.: Can only intelligent children do mind reading: the relationship between intelligence and theory of mind in 8 to 11 years old. Behav. Brain Funct. **4**, 51 (2008). https://doi.org/10.1186/1744-9081-4-51
6. Baglio, G., Blasi, V., Sangiuliano Intra, F., Castelli, I., Massaro, D., Baglio, F., Marchetti, A.: Social competence in children with borderline intellectual functioning: delayed development of theory of mind across all complexity levels. Front. Psychol. **7**, 1604 (2016). https://doi.org/10.3389/fpsyg.2016.01604
7. Smogorzewska, J., Szumski, G., Grygie, P.: Same or different? theory of mind among children with and without disabilities. PLoS ONE **13**, e0202553 (2018). https://doi.org/10.1371/journal.pone.0202553
8. Blijd-Hoogewys, E.M.A., van Geert, P.L.C., Serra, M., Minderaa, R.B.: Measuring theory of mind in children. Psychometric properties of the ToM storybooks. J. Autism Dev. Disord. **38**(10), 1907–1930 (2008). https://doi.org/10.1007/s10803-008-0585-3
9. Yang, Hui-Chun., Gray, S.: Executive function in preschoolers with primary language impairment. J. Speech Lang. Hear. Res. **60**(2), 379–392 (2017). https://doi.org/10.1044/2016_JSLHR-L-15-0267

10. Happé, F.G.: An advanced test of theory of mind: understanding of story characters' thoughts and feelings by able autistic, mentally handicapped, and normal children, and adults. Autism Dev. Disord. **24**, 129–154 (1994). https://doi.org/10.1007/bf02172093
11. Hutchins, T.L., Bonazinga, L.A., Prelock, P.A., Taylor, R.S.: Beyond false beliefs: the development and psychometric evaluation of the perceptions of children's theory of mind measure-experimental version (PCToMM-E). Autism Dev. Disord. **38**, 143–155 (2008). https://doi.org/10.1007/s10803-007-0377-1
12. Baron-Cohen, S., Wheelwright, S., Spong, A., Scahill, V., Lawson, J.: Are intuitive physics and intuitive psychology independent? A test with children with asperger syndrome. Dev. Lear. Disord. **5**, 47–78 (2001)
13. Blejher, V.M., Kruk, I.V.: Patopsihologicheskaja diagnostika [Patopsychological diagnostics]. Zdorov'e, Kazan' (1986). (in Russian).
14. Golovej, L.A., Rybalko, E.F.: Praktikum po psihologii razvitija [Practicum on Developmental Psychology]. Rech', Sant-Petersburg (2001).(in Russian)
15. Belopol'skaja, N.L.: Azbuka nastroenija. Jemocional'no-kommunikativnaja igra dlja detej 4–10 let [The ABC of mood. Emotional-communicative game for children 4–10 yr.] Cogito, Moscow (2008). (in Russian)
16. Akhutina, T.V.: Metody nejropsihologicheskogo obsledovanija detej 6–9 let [Methods of neuropsychological examination of children 6–9 years old]. V.Sekachev, Moscow (2016)
17. Filimonenko, Yu.I., Timofeev, V.I.: Test Vekslera: diagnostika struktury intellekta (detskij variant): metodicheskoe rukovodstvo [Wechsler Intelligence Scale for Children. Manual]. Imaton, Moscow (2006). (in Russian)
18. Baker, C.A., Peterson, E., Pulos, S., Kirkland, R.A.: Eyes and IQ: a meta-analysis of the relationship between intelligence and "Reading the Mind in the Eyes." Intelligent **44**, 78–92 (2014). https://doi.org/10.1016/j.intell.2014.03.001
19. Alesi, M., Rappo, G., Pepi, A.: Depression, anxiety at school and self-esteem in children with learning disabilities. Psychol. Abnorm. in Child. **3**, 1–10 (2014). https://doi.org/10.4172/2329-9525.1000125
20. Emerson, E., Einfeld, S., Stancliffe, R.J.: The mental health of young children with intellectual disabilities or borderline intellectual functioning. Soc. Psych. Psychiatric Epidem. **45**, 579–587 (2010). https://doi.org/10.1007/s00127-009-0100-y

Bilingualism and Reserve: Etiology of Successful Aging

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Abstract. In bilingualism research, there is a rapidly growing interest towards potential neuroprotective mechanisms against age-related cognitive decline, supported by dual and multiple language use. In this brief review, we discuss existing evidence, which generally suggests that bilingualism may foster neuroplastic changes resulting in beneficial consequences for the brain both at the structural level and at the functional one during later stages of life. First, we outline the interplay between the neural function and the bilingual experience. We then propose how bilingual and multilingual experience may protect the mind and the brain from the age-related cognitive decline and its consequences. We continue by discussing the notions of cognitive and brain reserve and contextualize existing findings from bilingualism literature with regard to this newly proposed reserve framework. We highlight how bilingualism-induced neural and cognitive changes may pave the way for the development of the neural foundations of reserve: both at the neuroanatomical and at the cognitive levels. We conclude our review by proposing possible models of bilingualism-induced successful aging.

Keywords: Bilingualism · Cognitive reserve · Age-related cognitive impairment

1 Introduction

Average life expectancy is predicted to continue to grow in the coming decades [1]. Alongside the obvious advantages of an extended life span come a number of negative consequences, for example, increase in the occurrence of neurodegenerative disorders in progressively aging population. Unsurprisingly, there is a sense of urgency to search for factors protecting against neurocognitive decline. This sense of urgency is further amplified if one considers the relatively slow pace at which pharmacological research is proceeding.

Several neuroprotective factors have recently been identified including high educational and occupational attainment, physical exercise, and social interactions (for a

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review, see [2]). The search for these and similar factors has been motivated by the remarkable interindividual variability observed in the cognitive aging trajectories. One concept developed to describe and subsume the neuroprotective factors is reserve [3]. It is defined as the discrepancy between the severity of observed brain damage (or age-related deterioration) and the resulting level of cognitive impairment [3]. Reserve is believed to alleviate the cognitive decline via several mechanisms (see below) that allow to prevent – and compensate for – neural damage causing age-related cognitive impairments [4, 5]. The abovementioned lifestyle-related protective factors are thus believed to promote "successful aging" by enhancing the development of reserve. Here, we will review evidence supporting the role of bilingualism in promoting reserve and explore potential neuroanatomical mechanisms supporting this promotion of reserve by means of bilingualism.

1.1 Bilingualism and Successful Aging

Existing evidence suggests that bilingualism supports successful aging in healthy older adults, both at the cognitive and at the neural levels (e.g. [6, 7]; see also [8] for a review). Indeed, the use of multiple languages has been shown to improve executive control (EC) abilities across the lifespan (for a review, see [9]). In particular, there is considerable amounts of evidence supporting these effects in older bilingual adults, who have been shown to outperform their monolingual peers on several EC tasks [10–14].

However, the neurocognitive value of bilingualism is not limited to healthy aging. For example, the onset of mild cognitive impairment (MCI) and dementia symptoms has been shown to be delayed in bilinguals by an average of 4.5 years in both cross-sectional [15–21] and longitudinal studies [22]. However, while existing evidence suggests that bilingualism indeed fosters the development of reserve both in healthy and in pathological aging, the neurocognitive mechanisms underlying this phenomenon remain underexplored. Below, after a short review of existing evidence, we will propose potential neural mechanisms at the basis of bilingualism-induced reserve.

2 Consequences of Bilingualism for Brain and Cognition

The key to the beneficial effects of bilingualism on the mind and brain seems to be the increase in cognitive effort constantly required by dual-language use [23]. Indeed, bilinguals, unlike monolinguals, need to exercise constant control over their two languages to prevent interference and to maintain fluency [24]. The cognitive facility supporting this EC system is referred to as language control, and is rooted in a neural network that overlaps with the domain-general EC network [25]. Due to this substantial overlap, regular use of the language control system should lead to the population-specific enhancement across the EC network – by (1) strengthening the efficiency of connections and (2) increasing the gray and white matter volumes of its sub-components. Thus, bilingualism is thought to affect the brain both at the structural and at the functional levels. Respectively, reserve has been postulated to act via both structural- and functional-related mechanisms, namely, brain reserve (BR) and cognitive reserve (CR).

In brief (see [3–5] for a detailed account), BR has been defined as individual capacity for resilience to age-related deterioration of the neural substrate arising from both innate and environmental (i.e. experienced-induced neuroplasticity) causes. CR, on the other hand, is a compensatory mechanism, acting against age-related cognitive impairment via two different yet interlinked mechanisms. The first is neural reserve (NR), the individual degree of flexibility, capacity, and efficiency of brain networks. The second is neural compensation (NC), the ability to deploy alternative (relatively to healthy subjects) neural/cognitive resources following neural deterioration.

2.1 Bilingualism and Brain Reserve

Extensive evidence suggests that bilingualism supports the developments of BR across the lifespan. Bilinguals have repeatedly been shown to have increased gray matter volumes (GMVs) in a number of key components of the language/executive control network, including the dorsolateral prefrontal cortex [7, 26, 27], inferior parietal lobule [7, 11, 27–30], anterior cingulate cortex [7, 11, 31], temporal pole [32, 33], caudate nucleus [34], thalamus [35], cerebellum [36, 37], putamen [35, 38], and globus pallidus [35]. Bilingualism has also been shown to contribute to the preservation of white matter integrity in the corpus callosum, inferior fronto-occipital fasciculus, uncinate fasciculus [39], and superior longitudinal fasciculus [39, 40].

It is important to note that some of the abovementioned brain areas (e.g., the temporal pole reported in Abutalebi and colleagues' [32] study) are among the first cortical structures to be affected by age-related brain atrophy [41]. Moreover, atrophy in the inferior parietal lobule is related to MCI [42] and to early stages of dementia [43]. Finally, frontal white matter is well known to suffer from age-related deterioration [44, 45]. Therefore, the evidence reviewed above provides an initial indication of bilingualism's role in supporting successful aging.

2.2 Bilingualism and Cognitive Reserve: Neural Reserve and Neural Compensation

Bilingualism has also been shown to foster CR via NR. Functional magnetic resonance imaging (fMRI) studies have reported increased neural efficiency in bilinguals who outperform their monolingual peers on a number of EC tasks while showing less activation of their executive network [6, 31, 46]. Moreover, increased flexibility of bilinguals' EC network has been repeatedly reported with bilinguals activating alternative/more extensive neural pathways to those of monolingual controls while performing executive tasks [47, 48]. Finally, bilingual functioning promotes stronger functional connectivity in older adults, as found in both fMRI [49] and magnetoencephalography [50] investigations.

Existing evidence also assigns an important role to bilingualism in fostering NC. Following its definition, individuals with high NC show better cognitive performance than can be expected given their level of neurodegeneration. In other words, at behaviorally comparable levels of cognitive functioning and dementia severity, individuals with higher NC will show more severe neurodegeneration at the neural substrate level. Indeed, higher degrees of neurodegeneration affecting gray and white matter in regions affected by cognitive aging have been consistently reported for bilinguals compared to the monolingual controls matched for severity of dementia symptoms, signaling higher NC in the former population [51, 52]. Similarly, positron emission tomography (PET) studies showed more severe glucose hypometabolism in frontotemporal brain areas of bilingual dementia patients as compared to the monolinguals matched on disease severity [53, 54].

2.3 Etiology of Bilingualism-Induced Reserve

The interplay between bilingualism-induced BR and CR remains largely understudied. One notable exception [7] compared young and older bilingual and monolingual adults' executive performance and brain network. The results indicated (1) a behavioral executive advantage for senior bilinguals over the monolingual age peers, (2) GMV increases in bilinguals across the EC network's areas as compared to monolinguals, across the whole age span, and (3) a modulatory effect of bilingualism, among older adults, mitigating the GMV/performance relationship. In brief, bilingual seniors showed optimal EC performance irrespectively of executive network's GMV variation (i.e. brain atrophy) while senior monolinguals' performance declined in the face of lower GMVs. The authors interpreted this evidence as a sign of bilingualism-induced NC, as discussed above. Although the study lacked a functional component, it suggested that bilingual experience may foster the development of BR, which in turn may support the establishment of NR and NC. This result has been recently reinforced by a longitudinal study showing bilingualism-induced mitigation of semantic memory loss in the face of enthorinal cortex thinning [55].

There have been some efforts recently in modeling the underlying mechanisms of bilingualism-induced successful aging. Grant et al. [56] hypothesized that the phenomenon may be framed in the context of the posterior-to-anterior shift in aging (PASA) model [57, 58]. PASA model proceeds from the observation that, following age-related decline in task-related posterior neural activation, older adults tend to compensate with increased reliance on activation in frontal brain areas. Based on the above-par integrity of posterior regions, as the temporal pole and inferior parietal lobule [7, 32, 59], and enhanced frontoposterior connectivity [39] observed in senior bilinguals (see section Bilingualism and Brain Reserve above), Grant and colleagues argue that they may be able to postpone such shift thus leading to increased neural resources' availability when performing complex tasks.

Further developing this argument, Grundy et al. [60] proposed the bilingual anterior to posterior and subcortical shift (BAPSS) model. The model is centered around the hypothesis that bilingual expertise would affect the neural activation patterns related to executive task performance, resulting in an activation shift to mainly posterior and subcortical areas when exerting EC. Following evidence from neuroimaging studies of bilingual processing, BAPSS argues that expert bilinguals progressively shift towards automatic, bottom-up executive processing due to their lifelong training of language control. This would lead bilingual older adults to experience less of the typical PASA effect, and, in line with Grant and colleagues' [56] assumptions, to an enhanced availability of neural resources in the face of increasing cognitive load.

Finally, Guzmán-Velez & Tranel [61] offer a cytochemically focused account based on the noradrenergic theory of CR [62]. Reserve-inducing factors (including bilingualism) in this framework are thought to upregulate the noradrenergic system promoting compensatory mechanisms as neurogenesis/synaptogenesis and stimulation of brain-derived neurotrophic factor (BDNF) production as well as mechanisms reducing the impact of dementia, as prevention of amyloid burden formation.

3 Conclusion

Here, we discussed evidence in support of the role of bilingualism in promoting successful aging. Combating age-related cognitive impairment is a priority in the progressively aging world, which dictates the need to maintain the ageing individuals' quality of life and mitigate further increases in public expense. As we witness an impasse in dementia-related pharmacological advances, non-pharmaceutical, cognition- and behavior-based protective factors acquire ever more importance and should thus be give due attention by researchers and public health authorities.

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References

1. Kontis, V., Bennett, J.E., Mathers, C.D., Li, G., Foreman, K., Ezzati, M.: Future life expectancy in 35 industrialised countries: projections with a Bayesian model ensemble. Lancet **389**, 1323–1335 (2017). https://doi.org/10.1016/S0140-6736(16)32381-9
2. Cheng, S.T.: Cognitive reserve and the prevention of dementia: the role of physical and cognitive activities. Curr. Psychiatry Rep. **18**, 1–12 (2016). https://doi.org/10.1007/s11920-016-0721-2
3. Stern, Y.: Cognitive reserve. Neuropsychologia **47**, 2015–2028 (2009). https://doi.org/10.1016/j.neuropsychologia.2009.03.004
4. Steffener, J., Reuben, A., Rakitin, B.C., Stern, Y.: Supporting performance in the face of age-related neural changes: testing mechanistic roles of cognitive reserve. Brain Imaging Behav. **5**, 212–221 (2011). https://doi.org/10.1007/s11682-011-9125-4
5. Barulli, D., Stern, Y.: Efficiency, capacity, compensation, maintenance, plasticity: emerging concepts in cognitive reserve. Trends Cogn. Sci. **17**, 502–509 (2013). https://doi.org/10.1016/j.tics.2013.08.012
6. Gold, B.T., Kim, C., Johnson, N.F., Kryscio, R.J., Smith, C.D.: Lifelong bilingualism maintains neural efficiency for cognitive control in aging. J. Neurosci. **33**, 387–396 (2013). https://doi.org/10.1523/JNEUROSCI.3837-12.2013
7. Del Maschio, N., Sulpizio, S., Gallo, F., Fedeli, D., Weekes, B.S., Abutalebi, J.: Neuroplasticity across the lifespan and aging effects in bilinguals and monolinguals. Brain Cogn. **125**, 118–126 (2018). https://doi.org/10.1016/j.bandc.2018.06.007
8. Bialystok, E., Abutalebi, J., Bak, T.H., Burke, D.M., Kroll, J.F.: Aging in two languages: implications for public health. Ageing Res. Rev. **27**, 56–60 (2016). https://doi.org/10.1016/j.arr.2016.03.003

9. Bialystok, E.: The bilingual adaptation: How minds accommodate experience. Psychol. Bull. **143**, 233–262 (2017). https://doi.org/10.1037/bul0000099
10. Bialystok, E., Poarch, G., Luo, L., Craik, F.I.M.: Effects of bilingualism and aging on executive function and working memory. Psychol. Aging. **29**, 696–705 (2014). https://doi.org/10.1037/a0037254
11. Abutalebi, J., Guidi, L., Borsa, V., Canini, M., Della Rosa, P.A., Parris, B.A., Weekes, B.S.: Bilingualism provides a neural reserve for aging populations. Neuropsychologia **69**, 201–210 (2015). https://doi.org/10.1016/j.neuropsychologia.2015.01.040
12. Incera, S., McLennan, C.T.: Bilingualism and age are continuous variables that influence executive function. Aging Neuropsychol. Cogn. **25**, 443–463 (2018). https://doi.org/10.1080/13825585.2017.1319902
13. Rosselli, M., Loewenstein, D.A., Curiel, R.E., Penate, A., Torres, V.L., Lang, M., Greig, M.T., Barker, W.W., Duara, R.: Effects of bilingualism on verbal and nonverbal memory measures in mild cognitive impairment. J. Int. Neuropsychol. Soc. **25**, 15–28 (2019). https://doi.org/10.1017/S135561771800070X
14. López Zunini, R.A., Morrison, C., Kousaie, S., Taler, V.: Task switching and bilingualism in young and older adults: a behavioral and electrophysiological investigation. Neuropsychologia **133**, 107186 (2019). https://doi.org/10.1016/j.neuropsychologia.2019.107186
15. Bialystok, E., Craik, F.I.M., Freedman, M.: Bilingualism as a protection against the onset of symptoms of dementia. Neuropsychologia **45**, 459–464 (2007). https://doi.org/10.1016/j.neuropsychologia.2006.10.009
16. Craik, F.I.M., Bialystok, E., Freedman, M.: Delaying the onset of Alzheimer disease: bilingualism as a form of cognitive reserve. Neurology **75**, 1726–1729 (2010). https://doi.org/10.1212/WNL.0b013e3181fc2a1c
17. Alladi, S., Bak, T.H., Duggirala, V., Surampudi, B., Shailaja, M., Shukla, A.K., Chaudhuri, J.R., Kaul, S.: Bilingualism delays age at onset of dementia, independent of education and immigration status. Neurology **81**, 1938–1944 (2013). https://doi.org/10.1212/01.wnl.0000436620.33155.a4
18. Perquin, M., Vaillant, M., Schuller, A.-M., Pastore, J., Dartigues, J.-F., Lair, M.-L., Diederich, N.: lifelong exposure to multilingualism: new evidence to support cognitive reserve hypothesis. PLoS ONE **8**, e62030 (2013). https://doi.org/10.1371/journal.pone.0062030
19. Woumans, E., Santens, P., Sieben, A., Versijpt, J., Stevens, M., Duyck, W.: Bilingualism delays clinical manifestation of Alzheimer's disease. Bilingualism. **18**, 568–574 (2015). https://doi.org/10.1017/S136672891400087X
20. Ramakrishnan, S., Mekala, S., Mamidipudi, A., Yareeda, S., Mridula, R., Bak, T.H., Alladi, S., Kaul, S.: Comparative effects of education and bilingualism on the onset of mild cognitive impairment. Dement. Geriatr. Cogn. Disord. **44**, 222–231 (2017). https://doi.org/10.1159/000479791
21. Saidi, L.G.: Bilingual speakers postpone symptoms of cognitive deficit in parkinson's disease. Innov. Aging. **3**, S661–S661 (2019). https://doi.org/10.1093/geroni/igz038.2447
22. Wilson, R.S., Boyle, P.A., Yang, J., James, B.D., Bennett, D.A.: Early life instruction in foreign language and music and incidence of mild cognitive impairment. Neuropsychology **29**, 292–302 (2015). https://doi.org/10.1037/neu0000129
23. Abutalebi, J., Green, D.W.: Neuroimaging of language control in bilinguals: neural adaptation and reserve. Bilingualism. **19**, 689–698 (2016). https://doi.org/10.1017/S1366728916000225
24. Green, D.W.: Mental control of the bilingual lexico-semantic system. Biling. Lang. Cogn. **1**, 67–81 (1998). https://doi.org/10.1017/s1366728998000133
25. Abutalebi, J., Green, D.: Bilingual language production: the neurocognition of language representation and control. J. Neurolinguistics. **20**, 242–275 (2007). https://doi.org/10.1016/j.jneuroling.2006.10.003

26. Stein, M., Federspiel, A., Koenig, T., Wirth, M., Strik, W., Wiest, R., Brandeis, D., Dierks, T.: Structural plasticity in the language system related to increased second language proficiency. Cortex **48**, 458–465 (2012). https://doi.org/10.1016/j.cortex.2010.10.007
27. Olulade, O.A., Jamal, N.I., Koo, D.S., Perfetti, C.A., LaSasso, C., Eden, G.F.: Neuroanatomical evidence in support of the bilingual advantage theory. Cereb. Cortex. **26**, 3196–3204 (2016). https://doi.org/10.1093/cercor/bhv152
28. Mechelli, A., Crinion, J.T., Noppeney, U., O' Doherty, J., Ashburner, J., Frackowiak, R.S., Price, C.J.: Neurolinguistics: structural plasticity in the bilingual brain. Nature. **431**, 757 (2004). https://doi.org/10.1038/431757a
29. Della Rosa, P.A., Videsott, G., Borsa, V.M., Canini, M., Weekes, B.S., Franceschini, R., Abutalebi, J.: A neural interactive location for multilingual talent. Cortex **49**, 605–608 (2013). https://doi.org/10.1016/j.cortex.2012.12.001
30. Heim, S., Stumme, J., Bittner, N., Jockwitz, C., Amunts, K., Caspers, S.: Bilingualism and "brain reserve": a matter of age. Neurobiol. Aging. **81**, 157–165 (2019). https://doi.org/10.1016/j.neurobiolaging.2019.05.021
31. Abutalebi, J., Della Rosa, P.A., Green, D.W., Hernandez, M., Scifo, P., Keim, R., Cappa, S.F., Costa, A.: Bilingualism tunes the anterior cingulate cortex for conflict monitoring. Cereb. Cortex. **22**, 2076–2086 (2012). https://doi.org/10.1093/cercor/bhr287
32. Abutalebi, J., Canini, M., Della Rosa, P.A., Sheung, L.P., Green, D.W., Weekes, B.S.: Bilingualism protects anterior temporal lobe integrity in aging. Neurobiol. Aging. **35**, 2126–2133 (2014). https://doi.org/10.1016/j.neurobiolaging.2014.03.010
33. Olsen, R.K., Pangelinan, M.M., Bogulski, C., Chakravarty, M.M., Luk, G., Grady, C.L., Bialystok, E.: The effect of lifelong bilingualism on regional grey and white matter volume. Brain Res. **1612**, 128–139 (2015). https://doi.org/10.1016/j.brainres.2015.02.034
34. Zou, L., Ding, G., Abutalebi, J., Shu, H., Peng, D.: Structural plasticity of the left caudate in bimodal bilinguals. Cortex **48**, 1197–1206 (2012). https://doi.org/10.1016/j.cortex.2011.05.022
35. Pliatsikas, C., DeLuca, V., Moschopoulou, E., Saddy, J.D.: Immersive bilingualism reshapes the core of the brain. Brain Struct. Funct. **222**, 1785–1795 (2017). https://doi.org/10.1007/s00429-016-1307-9
36. Filippi, R., Richardson, F.M., Dick, F., Leech, R., Green, D.W., Thomas, M.S.C., Price, C.J.: The right posterior paravermis and the control of language interference. J. Neurosci. **31**, 10732–10740 (2011). https://doi.org/10.1523/JNEUROSCI.1783-11.2011
37. Pliatsikas, C., Johnstone, T., Marinis, T.: Grey matter volume in the cerebellum is related to the processing of grammatical rules in a second language: a structural voxel-based morphometry study. Cerebellum **13**, 55–63 (2014). https://doi.org/10.1007/s12311-013-0515-6
38. Abutalebi, J., Rosa, P.A.D., Gonzaga, A.K.C., Keim, R., Costa, A., Perani, D.: The role of the left putamen in multilingual language production. Brain Lang. **125**, 307–315 (2013). https://doi.org/10.1016/j.bandl.2012.03.009
39. Luk, G., Bialystok, E., Craik, F.I.M., Grady, C.L.: Lifelong bilingualism maintains white matter integrity in older adults. J. Neurosci. **31**, 16808–16813 (2011). https://doi.org/10.1523/JNEUROSCI.4563-11.2011
40. Anderson, J.A.E., Grundy, J.G., De Frutos, J., Barker, R.M., Grady, C., Bialystok, E.: Effects of bilingualism on white matter integrity in older adults. Neuroimage **167**, 143–150 (2018). https://doi.org/10.1016/j.neuroimage.2017.11.038
41. Kalpouzos, G., Chételat, G., Baron, J.C., Landeau, B., Mevel, K., Godeau, C., Barré, L., Constans, J.M., Viader, F., Eustache, F., Desgranges, B.: Voxel-based mapping of brain gray matter volume and glucose metabolism profiles in normal aging. Neurobiol. Aging. **30**, 112–124 (2009). https://doi.org/10.1016/j.neurobiolaging.2007.05.019

42. Apostolova, L.G., Steiner, C.A., Akopyan, G.G., Dutton, R.A., Hayashi, K.M., Toga, A.W., Cummings, J.L., Thompson, P.M.: Three-dimensional gray matter atrophy mapping in mild cognitive impairment and mild Alzheimer disease. Arch. Neurol. **64**, 1489–1495 (2007). https://doi.org/10.1001/archneur.64.10.1489
43. McDonald, C.R., McEvoy, L.K., Gharapetian, L., Fennema-Notestine, C., Hagler, D.J., Holland, D., Koyama, A., Brewer, J.B., Dale, A.M.: Regional rates of neocortical atrophy from normal aging to early Alzheimer disease. Neurology **73**, 457–465 (2009). https://doi.org/10.1212/WNL.0b013e3181b16431
44. Pfefferbaum, A., Adalsteinsson, E., Sullivan, E.V.: Frontal circuitry degradation marks healthy adult aging: Evidence from diffusion tensor imaging. Neuroimage **26**, 891–899 (2005). https://doi.org/10.1016/j.neuroimage.2005.02.034
45. Gunning-Dixon, F.M., Brickman, A.M., Cheng, J.C., Alexopoulos, G.S.: Aging of cerebral white matter: a review of MRI findings. Int. J. Geriatr. Psychiatry. **24**, 109–117 (2009). https://doi.org/10.1002/gps.2087
46. Rodríguez-Pujadas, A., Sanjuán, A., Fuentes, P., Ventura-Campos, N., Barrós-Loscertales, A., Ávila, C.: Differential neural control in early bilinguals and monolinguals during response inhibition. Brain Lang. **132**, 43–51 (2014). https://doi.org/10.1016/j.bandl.2014.03.003
47. Luk, G., Anderson, J.A.E., Craik, F.I.M., Grady, C., Bialystok, E.: Distinct neural correlates for two types of inhibition in bilinguals: response inhibition versus interference suppression. Brain Cogn. **74**, 347–357 (2010). https://doi.org/10.1016/j.bandc.2010.09.004
48. Ansaldo, A.I., Ghazi-Saidi, L., Adrover-Roig, D.: Interference control in elderly bilinguals: appearances can be misleading. J. Clin. Exp. Neuropsychol. **37**, 455–470 (2015). https://doi.org/10.1080/13803395.2014.990359
49. Grady, C.L., Luk, G., Craik, F.I.M., Bialystok, E.: Brain network activity in monolingual and bilingual older adults. Neuropsychologia **66**, 170–181 (2015). https://doi.org/10.1016/j.neuropsychologia.2014.10.042
50. De Frutos-Lucas, J., López-Sanz, D., Cuesta, P., Bruña, R., De La Fuente, S., Serrano, N., López, M.E., Delgado-Losada, M.L., López-Higes, R., Marcos, A., Maestú, F.: Enhancement of posterior brain functional networks in bilingual older adults. Bilingualism. **23**, 387–400 (2020). https://doi.org/10.1017/S1366728919000178
51. Schweizer, T.A., Ware, J., Fischer, C.E., Craik, F.I.M., Bialystok, E.: Bilingualism as a contributor to cognitive reserve: evidence from brain atrophy in Alzheimer's disease. Cortex **48**, 991–996 (2012). https://doi.org/10.1016/j.cortex.2011.04.009
52. Gold, B.T., Johnson, N.F., Powell, D.K.: Lifelong bilingualism contributes to cognitive reserve against white matter integrity declines in aging. Neuropsychologia **51**, 2841–2846 (2013). https://doi.org/10.1016/j.neuropsychologia.2013.09.037
53. Kowoll, M.E., Degen, C., Gorenc, L., Küntzelmann, A., Fellhauer, I., Giesel, F., Haberkorn, U., Schröder, J.: Bilingualism as a contributor to cognitive reserve? evidence from cerebral glucose metabolism in mild cognitive impairment and alzheimer's disease. Front. Psychiatry. **7**, 15 (2016). https://doi.org/10.3389/fpsyt.2016.00062
54. Perani, D., Farsad, M., Ballarini, T., Lubian, F., Malpetti, M., Fracchetti, A., Magnani, G., March, A., Abutalebi, J.: The impact of bilingualism on brain reserve and metabolic connectivity in Alzheimer's dementia. Proc. Natl. Acad. Sci. U. S. A. **114**, 1690–1695 (2017). https://doi.org/10.1073/pnas.1610909114
55. Arce Rentería, M., Casalletto, K., Tom, S., Pa, J., Harrati, A., Armstrong, N., Rajan, K.B., Manly, J., Mungas, D., Zahodne, L.: The contributions of active spanish-english bilingualism to cognitive reserve among older hispanic adults living in California. Arch. Clin. Neuropsychol. **34**, 1235 (2019). https://doi.org/10.1093/arclin/acz029.02
56. Grant, A., Dennis, N.A., Li, P.: Cognitive control, cognitive reserve, and memory in the aging bilingual brain. Front. Psychol. **5**, 1401 (2014). https://doi.org/10.3389/fpsyg.2014.01401

57. Davis, S.W., Dennis, N.A., Daselaar, S.M., Fleck, M.S., Cabeza, R.: Qué PASA? the posterior-anterior shift in aging. Cereb. Cortex. **18**, 1201–1209 (2008). https://doi.org/10.1093/cercor/bhm155
58. Dennis, N.A., Cabeza, R.: Neuroimaging of healthy cognitive aging. Handb. Aging Cogn. **3**, 1–54 (2008)
59. Abutalebi, J., Canini, M., Della Rosa, P.A., Green, D.W., Weekes, B.S.: The neuroprotective effects of bilingualism upon the inferior parietal lobule: a structural neuroimaging study in aging Chinese bilinguals. J. Neurolinguistics. **33**, 3–13 (2015). https://doi.org/10.1016/j.jneuroling.2014.09.008
60. Grundy, J.G., Anderson, J.A.E., Bialystok, E.: Neural correlates of cognitive processing in monolinguals and bilinguals. Ann. N. Y. Acad. Sci. **1396**, 183–201 (2017). https://doi.org/10.1111/nyas.13333
61. Guzmán-Vélez, E., Tranel, D.: Does bilingualism contribute to cognitive reserve? Cogn. Neural Perspect. Neuropsychol. **29**, 139–150 (2015). https://doi.org/10.1037/neu0000105
62. Robertson, I.H.: A noradrenergic theory of cognitive reserve: Implications for Alzheimer's disease. Neurobiol. Aging. **34**, 298–308 (2013). https://doi.org/10.1016/j.neurobiolaging.2012.05.019

Perception, Memory, and Higher Cognition

Recognition of Visual Stimuli Which Proceeded by Socially Significant Images: An ERP Study

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Abstract. In everyday life, humans see many visual objects simultaneously. Some of them are important for the current task; others capture our attention due to their great social significance. This study aimed to evaluate the influence of forward masking with photographs of faces and houses on the recognition of target objects and to assess the influence of low spatial frequency filtration (LSF) of a mask.

Twenty participants performed recognition of target man-made objects when the stimuli were preceded by irrelevant images. Behavioral data and event-related potentials (ERPs) were collected. Target stimuli were recognized faster when they were preceded by faces. The amplitude of the early ERP components depended on the mask category as well as LSF transformation. The forward masking by faces enhanced occipital-temporal N50 and frontal P50, but LSF transformation evoked a decrease of the components. The amplitude of the mid-latency N150 and P200 were depended on the spatial frequency more than on the mask category. The LSF-masks increased the amplitude of N150 in the frontal and occipital-temporal areas, and at the same time, it decreased the P200 in the occipital areas. The N150 amplitude in the occipital-temporal areas was higher under masking by faces. We assume that the masking effect evoked by faces was weaker than the effect evoked by houses due to face ability to increase spatial attention. The increased caudal negativity N150 under the LSF mask may be due to increased top-down frontal influences, and also to the greater difficulty of the recognition task.

Keywords: Human · Vision · Perception · Forward masking · Face · Event-related potentials (ERPs) · Spatial attention · Spatial frequency

1 Introduction

The efficient performance of visual behavioral tasks requires the ability to allocate attention to relevant information and to inhibit irrelevant signals. Faces are a unique category of images due to their role in social interaction [1]. They automatically capture visual attention, regardless of the observer's current goals [2, 3]. Faces are not only recognized faster and more accurately than images of other categories but also facilitate recognition of subsequent visual stimuli [4].

Houses are another category of unique complex images common in every-day life. They represent spatial informational and are perceived as landmarks, thus playing an important role in navigation [5]. Therefore faces and houses represent special classes

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of complex images which perception is associated with category-selective areas, the fusiform face area for first ones, and the parahippocampal place area for second ones [6–8].

Traditionally, theories of human visual perception assume a bottom-up hierarchy of ventral areas that perform sequential processing of the visual signals [9]. But recent findings showed that top-down mechanisms might play an important role in visual processing. It was supposed that low spatial frequency (LSF) information about an object is conveyed rapidly to the orbitofrontal cortex (OFC) and is used for the prediction stimulus category [10]. Then the OFC influence on areas of the ventral pathway to activate appropriate visual representation [10].

The aim of the present study was to compare the influence of preceding face and house images on object recognition. Due to the significant role of LSF in object categorization, we also used LSF transformation for face and house masks to assess the role of low-frequency information in the unconscious processing of socially important images.

2 Methods and Materials

2.1 Subjects

Twenty participants (10 females; mean age = 24.9 ± 1.0 years), with normal or correct-to-normal vision, participated in the study. All participants gave their informed written consent before participating in the experiments. The study was approved by the local ethical committee and was performed according to the ethical principles for medical research involving human subjects of the World Medical Association Declaration of Helsinki.

2.2 Stimuli and Procedure

Black-and-white photographs of everyday objects were used as target stimuli; black-and-white photographs of houses and emotionally neutral human faces, as masks (Fig. 1). Face images were retrieved from the Radboud Faces Database, Radboud University Nijmegen [11]. Images of objects and houses were selected from color images available on the Internet and were converted to grayscale. To convert images to LSF versions, they were processed by applying a Gaussian blur with a 3-pixel blurring index to the target stimuli. The image resolution was about 210 × 210 pixels covering 4.5° × 4.5° of visual angle at a viewing distance of 120 cm.

For every category of target man-made objects (a bag, a cap, an iron, etc.) we found four different images. In total, 48 images were created for each of the two experiments, including 32 masks (16 houses and 16 faces) and 16 stimuli. These masks and stimuli were combined to produce 96 unique mask–stimulus pairs, each of which was presented once in the experiment.

Every subject participated in two experiments. In the first one, the subject recognized objects which were preceded by unfiltered mask image, in another experiment we used LSF mask images.

Masks and stimuli were displayed against a white background on a 17 in. CRT monitor with a spatial resolution 800 × 600 pixels and a refresh rate of 60 Hz. E-Prime

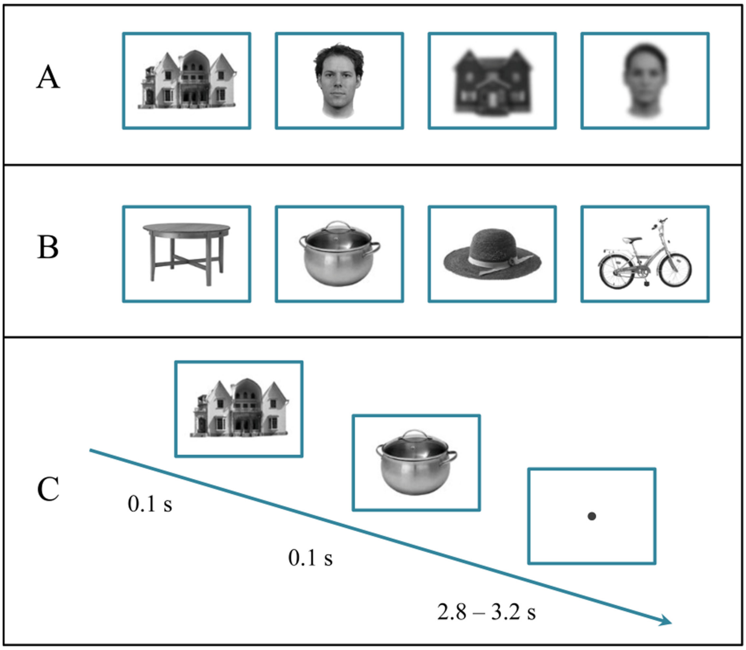

Fig. 1. Examples of masks (A) and stimuli (B). Schematic example of the trial procedure (C).

software (E-Prime Psychology Software Tools Inc., USA) was used to present the images and recorded participant's behavioral responses (accuracy and reaction time).

Mask was presented for 100 ms, a target stimulus was demonstrated for 100 ms immediately after a mask. The interval between trails varied at random from 2.8 to 3.2 s. Subjects were asked to recognize the target image and press the appropriate button on the Serial Response Box keyboard.

2.3 Recording and Data Analysis

ERPs were recorded using a Geodesic electroencephalogram (EEG) system; NetAmps 300 and high-density 128-channel HydroCel Geodesic Sensor net (Electrical Geodesics Inc., USA). The sampling rate was 500 Hz. EEG data were collected using the vertex (Cz) electrode reference.

NetStation 4.5.4 program software (Electrical Geodesics Inc., USA) was used for offline ERP processing. Data were re-referenced to the averaged reference. EEG recordings of each subject were filtered (0.5–45 Hz) and used to isolate the 1100-ms epochs that contained 300-ms intervals before mask presentation and 800-ms intervals after mask presentation. Epochs that contained artifacts were rejected for subsequent analysis.

For every subject, artifact-free EEG epochs (25–45, 36.5 on average) were then used to average the ERPs for correct answers, separately for each mask category and spatial frequency characteristics. Baseline correction was performed using the 300-ms EEG segment before mask presentation.

The amplitudes of the ERP components were measured using NetStation 4.5.4. The adaptive minimum or maximum was found in the component-time window. The amplitudes of the ERP components were averaged over the following symmetrical the right and left electrode clusters: frontal, temporal, and occipital.

For statistical analysis, we applied the repeated measures analysis of variance (ANOVA RM) with category (face and house), spatial frequency (unfiltered and LSF), as within-subjects variables. The factor of the hemisphere (the right and left) was also used as a within-subjects variable for all ERP components and area (occipital and temporal) was used for posterior N50 only. The Greenhouse-Geisser correction for nonsphericity was applied whenever appropriate.

3 Results

3.1 Behavioral Results

Target accuracy (ACC) and mean reaction time (RT) data are presented in Table 1.

For RT, an ANOVA revealed a main effect of category F (1, 19) = 11.85; $p < 0.01$; indicated faster responses when the target image was preceded by face. In terms of accuracy, we found the significant interaction of mask category and spatial frequency F (1, 19) = 6.07, $p < 0.05$. For houses, the unfiltered masks cause less masking effect than LSF house masks. For faces, accuracy was not significantly affected by mask spatial filtering.

Table 1. Mean response time and accuracy (and standard errors of the means) across masking conditions.

Mask	Face	House	LSF face	LSF house
RT, ms	683 (33)	716 (30)	715 (31)	737 (33)
ACC, %	97.7 (0.8)	98.1 (0.6)	98.5 (0.4)	96.7 (0.6)

3.2 ERP Results

Posterior N50. For the amplitude of the posterior N50 component, there were effects of area F(1, 19) = 14.93, $p < 0.001$, spatial frequency F(1, 19) = 28.31, $p < 0.0005$, and category F(1, 19) = 31.84, $p < 0.0005$, and interactions between area and spatial frequency F(1, 19) = 6.85, $p < 0.05$, area and category F(1, 19) = 24.12, $p < 0.0005$, area, spatial frequency and category F(1, 19) = 6.24, $p < 0.05$, and area, category and hemisphere F(1, 19) = 7.27, $p < 0.05$.

The effect of the area was due to the amplitude of the N50 being larger in the temporal areas in comparison with the occipital areas. Masking by house images evoked a decrease of N50 amplitude. The N50 amplitude was significantly higher for unfiltered masks than for LSF masks (Fig. 2).

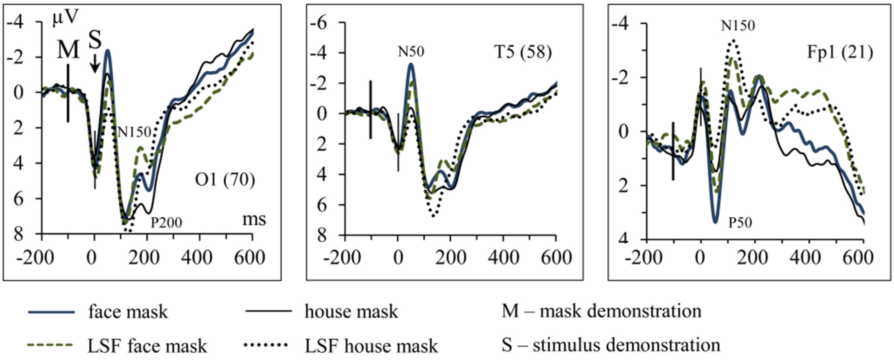

Fig. 2. Grand-averaged ERP waveforms for the different mask conditions recorded at right occipital, right temporal, and right frontal areas.

Posterior N150. In the occipital cluster, an ANOVA revealed significant effects of spatial frequency $F(1, 19) = 7.21$, $p < 0.05$ and category $F(1, 19) = 7.05$, $p < 0.05$. In the temporal cluster, significant effects were observed for the factors spatial frequency $F(1, 19) = 12.84$, $p < 0.01$, and category $F(1, 19) = 5.94$, $p < 0.05$, and the interaction between category and hemisphere $F(1, 19) = 4.91$, $p < 0.05$ was found. The effect of spatial frequency was present because the size of the N150 was larger when the target stimulus was preceded by the LSF mask. The effect of the category was due to the amplitude of the N150 being smaller under the house mask condition. The N150 amplitude observed in the temporal cluster of the left hemisphere at unfiltered face masks was significantly higher than at unfiltered house masks.

Posterior P200. For the amplitude of the occipital P200 component, there were effect of category $F(1, 19) = 20.60$, $p < 0.0005$, and interaction between spatial frequency and category $F(1, 19) = 6.07$, $p < 0.05$. Low-pass filtering of the mask decreased the P200 amplitude. A decrease observed with house masks ($p < 0.0005$) was greater than with face masks.

Anterior P50. In the frontal cluster, an ANOVA revealed significant effects of spatial frequency $F(1, 19) = 4.59$, $p < 0.05$ and category $F(1, 19) = 67.63$, $p < 0.0005$. The face mask produced a greater P50 amplitude compared to the house mask. Low-pass mask filtering decreased the P50 amplitude.

Anterior N150. An ANOVA revealed a significant effect of the spatial frequency $F(1, 19) = 8.22$, $p < 0.01$. Low-pass filtering of the masking images increased the N150 amplitude.

4 Discussion

4.1 RT Depended on Mask Category

Our results demonstrate that images of man-made objects which were preceded by face masks recognized faster than under house masks. Our behavioral data confirmed the assumption that faces capture attention and facilitate the processing of subsequent visual information.

4.2 Early ERP Components

The amplitudes of the early ERP components were significantly affected by the mask category. The increase of the posterior N50 was more pronounced in temporal cortical areas. This component was detected 150 ms after mask presentation and corresponded to the conventional N170, which reflects the encoding of individual face features [12, 13]. The frontal P50 reflects the early processing of the mask and therefore is comparable with the positive P200 component, which is detected 150–200 ms after image presentation [14, 15]. The increased P200 is associated with an allocation of exogenous attention [16].

The amplitudes of the early ERP components also depended on the spatial frequency of the mask. LSF images decreased the posterior N50 and the frontal P50 amplitudes. Several studies showed that the increase of early posterior negativity reflects the processing of the previous irrelevant image object [17, 18]. We conclude that the depth of mask processing was larger in the case of an unfiltered mask because it contains more detailed visual information about the image as compared with an LSF mask. Thus, it was easier to inhibit an irrelevant signal in the case of an unfiltered mask.

4.3 Mid-latency ERP Components

An analysis of the mid-latency ERP components showed the more pronounced dependence of their amplitudes on mask spatial frequency compared with the mask category. LSF masks increased the N150 in the frontal and caudal areas and decreased P200 in the occipital ones. Mu and Li [19] showed the relations of the increased frontal negativity with interference in the processing of low-frequency and high-frequency information. Thus, the larger N150 reflects more pronounced interference from the non-attended LSF information and poorer processing of the stimulus. It was assumed that the increased posterior N150 was associated with influences from higher-level regions which were activated by the preceding low-frequency mask image [20]. The amplitude of the mid-latency posterior component P200 was higher in the condition of forward masking by unfiltered images. It was shown that the higher positivity in this time window indicated efficient inhibition of visual information about distractors [21, 22].

An effect of the mask category was only observed in the case of the N150 component in the posterior cortical regions. The N150 amplitude observed under face masks was larger than under house masks. This result may be associated with increased spatial attention to faces that facilitate the recognition of the following visual stimuli [4].

5 Conclusions

Summing up, socially significant images - faces and buildings - when presented centrally just before the target, show a masking effect, and for faces, this effect is less marked than that of buildings. We suppose that face masks increase the subject's spatial attention and thus facilitate the processing of the subsequent relevant stimulus. LSF transformation enhances the masking, probably by reducing their visibility, which prevents an efficient inhibition of the irrelevant signals. The early ERP components were predominantly affected by the mask category, while the mid-latency components were more sensitive in the spatial frequency.

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References

1. Guyader, N., Chauvin, A., Boucart, M., Peyrin, C.: Do low spatial frequencies explain the extremely fast saccades towards human faces? Vision Res. **133**, 100–111 (2017). https://doi.org/10.1016/j.visres.2016.12.019
2. Lavie, N., Ro, T., Russell, C.: The role of perceptual load in processing distractor faces. Psychol. Sci. **14**, 510–515 (2003). https://doi.org/10.1111/1467-9280.03453
3. Neumann, M.F., Mohamed, T.N., Schweinberger, S.R.: Face and object encoding under perceptual load: ERP evidence. Neuroimage **54**, 3021–3027 (2011). https://doi.org/10.1016/j.neuroimage.2010.10.075
4. Bindemann, M., Burton, A.M., Langton, S.R.H., Schweinberger, S.R., Doherty, M.J.: The control of attention to faces. J. Vision **7**, 1–8 (2007). https://doi.org/10.1167/7.10.15
5. Sala, J.B., Rama, P., Courtney, S.M.: Functional topography of a distributed neural system for spatial and nonspatial information maintenance in working memory. Neuropsychology **41**, 341–356 (2003). https://doi.org/10.1016/s0028-3932(02)00166-5
6. Downing, P.E., Chan, A.W.Y., Peelen, M.V., Dodds, C.M., Kanwisher, N.: Domain specificity in visual cortex. Cereb. Cortex **16**, 1453–1461 (2005). https://doi.org/10.1093/cercor/bhj086
7. Bunzeck, N., Schutze, H., Duzel, E.: Categoryspecific organization of prefrontal response-facilitation during priming. Neuropsychology **44**, 1765–1776 (2006). https://doi.org/10.1016/j.neuropsychologia.2006.03.019
8. Grill-Spector, K., Weiner, K.S.: The functional architecture of the ventral temporal cortex and its role in categorization. Nat. Rev. Neurosci. **15**, 536–548 (2014). https://doi.org/10.1038/nrn3747
9. Grill-Spector, K., Malach, R.: The human visual cortex. Annu. Rev. Neurosci. **17**, 649–677 (2004). https://doi.org/10.1146/annurev.neuro.27.070203.144220
10. Bar, M. Kassam, K.S., Ghuman, A.S., Boshyan, J., Schmid, A.M., Dale, A.M., Hämäläinen, M.S., Marinkovic, K., Schacter, D.L., Rosen, B.R., Halgren, E.: Top-down facilitation of visual recognition. Proc. Natl. Acad. Sci. U.S.A. **103**, 449–454 (2006). https://doi.org/10.1073/pnas.0507062103
11. Langner, O., Dotsch, R., Bijlstra, G., Wigboldus, D.H.J., Hawk, S.T., van Knippenberg, A.: Presentation and validation of the Radboud Faces Database. Cognit. Emotion **24**, 1377–1388 (2010). https://doi.org/10.1080/02699930903485076
12. Nakashima, T., Kaneko, K., Goto, Y., Abe, T., Mitsudo, T., Ogata, K., Makinouchi, A., Tobimatsu, S.: Early ERP components differentially extract facial features: Evidence for spatial frequency-and-contrast detectors. Neurosci. Res. **62**, 225–235 (2008). https://doi.org/10.1016/j.neures.2008.08.009
13. Pesciarelli, F., Sarlo, M., Leo, I.: The time course of implicit processing of facial features: An event-related potential study, Neuropsychology **49**, 1154–1161. https://doi.org/10.1016/j.neuropsychologia.2011.02.003
14. Potts, G.F.: An ERP index of task relevance evaluation of visual stimuli. Brain Cognit. **56**, 5–13 (2004). https://doi.org/10.1016/j.bandc.2004.03.006

15. Daffner, K.R., Alperin, B.R., Mott, K.K., Tusch, E.S., Holcomb, P.J.: Age-related differences in early novelty processing: Using PCA to parse the overlapping anterior P2 and N2 components. Biol. Psychol. **105**, 83–94 (2015). https://doi.org/10.1016/j.biopsycho.2015.01.002
16. Carretie, L., Kessel, D., Garcia-Rubio, M.J., Giménez-Fernández, T., Hoyos, S., Hernández-Lorca, M.: Magnocellular bias in exogenous attention to biologically salient stimuli as revealed by manipulating their luminosity and color. J. Cognit. Neurosci. **29**, 1699–1711 (2017). https://doi.org/10.1162/jocn_a_01148
17. Gibbons, H., Bachmann, O., Stahl, J.: The more you ignore me the closer I get: an ERP study of evaluative priming. Cognit. Affective Behav. Neurosci. **14**, 1467–1484 (2014). https://doi.org/10.3758/s13415-014-0289-4
18. Jost, K., Wendt, M., Luna-Rodriguez, A., Löw, A., Jacobsen, T.: Strategic control over extent and timing of distractor-based response activation. J. Exp. Psychol. Learn. Mem. Cognit. **43**, 326–333 (2017). https://doi.org/10.1037/xlm0000326
19. Mu, T., Li, S.: The neural signature of spatial frequency-based information integration in scene perception. Exp. Brain Res. **227**, 367–377 (2013). https://doi.org/10.1007/s00221-013-3517-1
20. Peyrin, C., Michel, C.M., Schwartz, S., Thut, G., Seghier, M., Landis, T., Marendaz, C., Vuilleumier, P.: The neural substrates and timing of top–down processes during coarse-to-fine categorization of visual scenes: A combined fMRI and ERP study. J. Cognit. Neurosci. **22**, 2768–2780 (2010). https://doi.org/10.1162/jocn.2010.21424
21. Neumann, M.F., Viska, C.G., van Huis, S., Palermo, R.: Similar distraction, but differential suppression, for faces and non-face objects: evidence from behavior and event-related potentials. Biol. Psychol. **139**, 39–46 (2018). https://doi.org/10.1016/j.biopsycho.2018.09.011
22. Del Zotto, M., Pegna, A.J.: Processing of masked and unmasked emotional faces under different attentional conditions: an electrophysiological investigation. Front. Psychol. **6**, 1691 (2015). https://doi.org/10.3389/fpsyg.2015.01691

How Areas of Ventral Visual Stream Interact When We Memorize Color and Shape Information

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Abstract. We studied the role of ventral visual cortex areas in processing color and shape information during memorizing these characteristics. The participants (22 people) were presented with blots of different colors and shapes (9 shapes, 8 colors). There were 3 experimental series in which participants had to memorize shape, color, or both characteristics at once. A control block was also conducted, in which the task was to count the number of the same color images. EEG was recorded, then the brain activity sources were localized. Also, we calculated the connectivity parameters (via Granger causality method). During memorizing colors, we found strong connections between the V3v and hV4 areas. During memorizing the shape, connection between the VO1 areas in both hemispheres was found. When both characteristics were memorized, we found connections between the V3v, hV4, and VO1 areas. In addition, connections were observed between the VO1 and VO2 areas of both hemispheres. We suggested that hV4 and VO1 areas are related to color and shape processing, respectively. In VO2 area all characteristics are integrated into a holistic image of perception.

Keywords: Ventral visual cortex · Visual working memory · Visual perception

1 Introduction

Large amounts of data suggest that various characteristics of visual stimuli are processed by the ventral part of the visual cortex. Although the areas of the brain responsible for the perception of complex objects such as faces are fairly well established, it was more difficult to localize cortex areas that process simpler visual characteristics such as the color and shape of objects. For example, there is conflicting data on the role of the hV4 area (human V4) in visual perception: some studies have found that this area is involved exclusively in the processing of color information [2] or other characteristics of stimuli [10]. Other studies show that the color and shape information is processed in other areas of the ventral visual cortex [12].

We suggest that the reason for this discrepancy is due to the peculiarities of experimental procedures. In most studies, experimental designs are made so that participants perceive stimuli passively, without performing any task. We suppose that perception is an active process that depends on the task being performed by a person at the moment.

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In our study, the participants were given a task in which they were required to select and memorize individual characteristics of visual stimuli. The aim of the study is to identify areas of the ventral visual cortex involved in processing the color and shape of stimuli.

2 Methods

2.1 Participants

We collected data on 22 participants (13 female, 9 male, age 19.6 years, SD = 1.84). All participants were healthy with no history of neurological and/or psychiatric disorders. Each participant had normal or corrected-to-normal visual acuity, and normal color vision. The experiment was considered and approved by the Research Ethics Committee of the Faculty of Psychology, Lomonosov Moscow State University.

2.2 Visual Stimuli and Experimental Design

The participants were presented with the picture of color blot for 400 ms period (there were 8 different shapes and 9 colors). The task was to memorize either the color or shape, or both characteristics together. In the control series, the same stimuli were presented, but the task was to count the number of figures with a certain color (see Fig. 1).

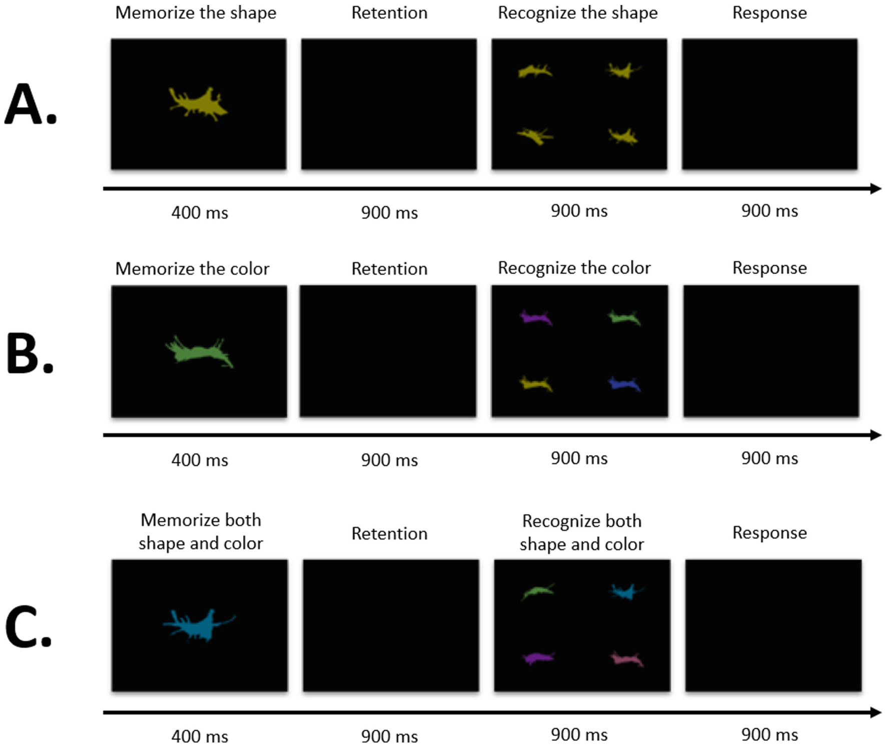

Fig. 1. Design of experiment. A – shape memorizing session, B – color memorizing session, and C – both shape and color memorizing session.

2.3 EEG Methods

EEG was recorded (19 channels, 10–20% system) and evoked potentials (ERP) were calculated for presenting an image with a figure in each of the series. Based on the results obtained, the sources of brain activity were localized via Brainstorm [11] using the dSPM algorithm [3]. For further analysis, we selected 8 areas of the ventral visual cortex: V3v (VP), hV4, VO1, and VO2 in both hemispheres. Coordinates of areas boundaries according to Wang et al. [13] were adapted for Brainstorm. Using the Granger causality estimation method [9], causal connections between these areas of the ventral visual cortex were calculated.

3 Results

We obtained causal connections between 8 areas of the visual cortex: V3v, hV4, VO1 and VO2 in both hemispheres (see Fig. 2).

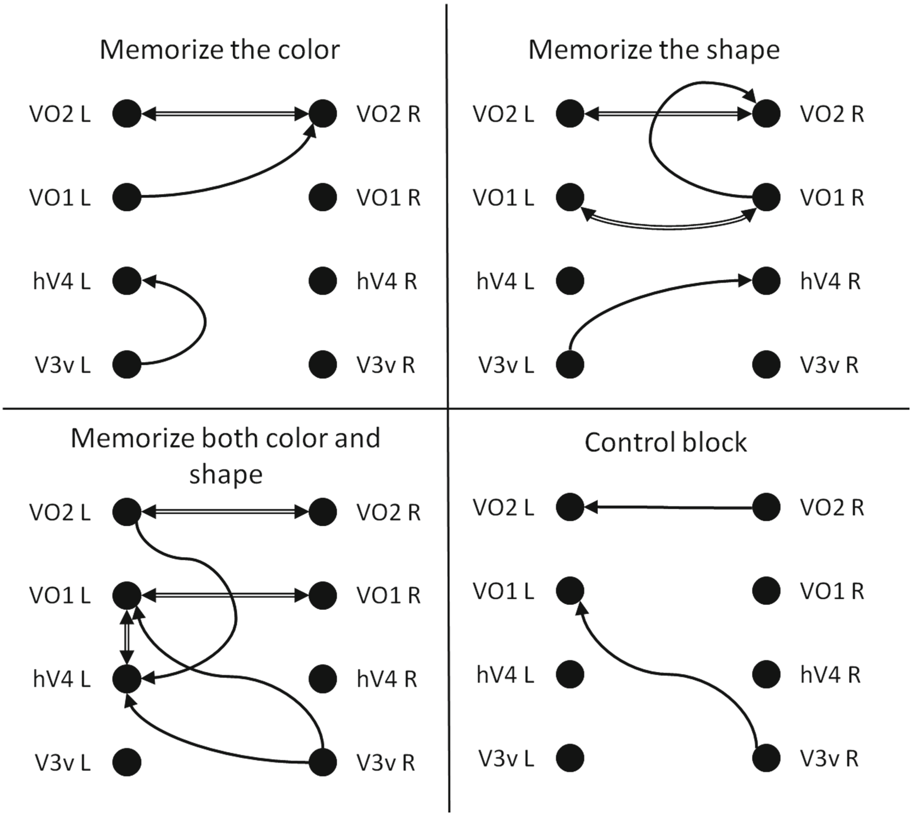

Fig. 2. Granger causal connections between the areas of ventral visual cortex for experimental sessions and the control block. “L” and “R” mean “left” and “right”, respectively. The line with one arrow indicates unidirectional connections, double line with two arrows – bidirectional connections.

In the control block we found connections between V3v (right hemisphere) and VO1 (left hemisphere), and unidirectional connection between VO2 areas.

The color memorizing session shows bidirectional connections between VO2 areas, and unidirectional ones between V3v and hV4 (left), VO1 (left) and VO2 (right) areas.

In the shape memorizing session, there are unidirectional connections between V3v (left) and hV4 (right), VO1 and VO2 (right) areas, and bidirectional connections between VO1 and VO2 areas in both hemispheres.

When participants were to memorize both characteristics were, we found an integrative pattern of activation. There are bidirectional connections between VO1 and VO2 (left and right), hV4 and VO1 (left) areas, and unidirectional ones between V3v (right) and hV4 and VO1 (left) areas.

We can distinguish several patterns of causal connections. Memorizing color information requires connections between V3v, hV4 and VO1 areas; shape information—between V3v, VO1 and VO2 areas. Memorizing both visual characteristics involves all these activity patterns.

We found that visual information comes from V3v area to hV4 and VO1 areas in each experimental series, because the stimulus has color and shape characteristics. If the task is "to memorize the color", participants will switch attention from the whole stimulus to its color. That leads to increasing the level of hV4 activation and the level of connections with other areas. Under other conditions we can observe the same patterns.

4 Discussion

In a series in which participants had to memorize the color shade of stimuli (both separately and in combination with the shape), the activation of hV4 area was observed immediately after the activation of the V3v (VP) area. Human fMRI experiments have shown that V3v area neurons respond to chromatic stimuli [7]. Recently, it was proved that V4 area neurons (in primates) form a "hue preference map" [5]. It can be assumed that the human V4 (hV4) performs a similar function and integrates the color information received from V3v area.

When participants had to memorize the shape of stimuli, there were revealed strong connections between VO1 areas of both hemispheres. We suggest that connection can be associated with shape information processing. We assume that these visual cortex areas integrate information about the shape of the stimulus from both semifields of the visual field. In support of this assumption, the activity of V3v is also observed in the perception of illusory contours [6] and contours of geometric shapes [8].

We revealed that in a series in which both color and shape were required to be memorized, bidirectional connections between hV4 and VO1 were found. This data is well explained by hypothesis that hV4 is responsible for integrating information about color, and VO1 integrates information about shape of the stimuli. It is likely that when these two characteristics are processing, there is an interaction between these areas.

Finally, both the experimental and control series show activation of VO2 areas in both hemispheres. There are unidirectional (in control series) and bidirectional (in all other series) connections between these areas. In the literature there is a little amount of data which allows us to establish a functional role of these areas, and the available data is quite contradictory. Thus, according to the hypothesis of Goddard and Mullen [4], neurons in the VO2 are responsible for separating color from achromatic contrast in these areas. Wang et al. [14] suggest that this area of the ventral visual cortex has large fields of attention modulation for face and house images. It can be cautiously assumed that VO2 is rather related to the perception of stimuli as complete familiar objects. Thus, our experimental design with ERP, as well as the experimental designs described in the literature, where similar VO2 activation was observed, suggest multiple presentations of similar stimuli. Accordingly, bidirectional connections between these areas of two hemispheres may indicate the integration of information from both semifields, which is necessary for object recognition. In addition, this assumption is indirectly supported by the close connection of the VO2 area with the parahippocampal cortex, which plays an important role in the recognition process [1].

5 Conclusion

Our study clarifies the role of ventral visual cortex in color and shape perception of objects. We assume that the hV4 area is related to the integration of color information, and the VO1 area is related to the integration of information about the shape of objects. In addition, the activity of the VO2 area is probably associated with the formation of a holistic image of perception that combines all the important characteristics of the stimulus for the observer.

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References

1. Aminoff, E.M., Kveraga, K., Bar, M.: The role of the parahippocampal cortex in cognition. Trends Cog. Sci. **17**(8), 379–390 (2013). https://doi.org/10.1016/j.tics.2013.06.009
2. Bannert, M.M., Bartels, A.: Human V4 activity patterns predict behavioral performance in imagery of object color. J. Neurosci. **38**(15), 3657–3668 (2018). https://doi.org/10.1523/JNEUROSCI.2307-17.2018
3. Dale, A.M., Liu, A.K., Fischl, B.R., Buckner, R.L., Belliveau, J.W., Lewine, J.D., Halgren, E.: Dynamic statistical parametric mapping: combining fMRI and MEG for high-resolution imaging of cortical activity. Neuron **26**(1), 55–67 (2000). https://doi.org/10.1016/S0896-6273(00)81138-1
4. Goddard, E., Mullen, K.T.: fMRI Representational similarity analysis reveals graded preferences for chromatic and achromatic stimulus contrast across human visual cortex. Neuroimage **215**, 116780 (2020). https://doi.org/10.1016/j.neuroimage.2020.116780
5. Liu, Y., Li, M., Zhang, X., Lu, Y., Gong, H., Yin, J., Chen, Z., Qian, L., Yang, Y., Andolina, I.M., Shipp, S., Mcloughlin, N., Tang, S., Wang, W.: Hierarchical representation for chromatic processing across macaque V1, V2, and V4. Neuron **108**(3), P538–550.E5 (2020). https://doi.org/10.1016/j.neuron.2020.07.037
6. Montaser-Kouhsari, L., Landy, M.S., Heeger, D.J., Larsson, J.: Orientation-selective adaptation to illusory contours in human visual cortex. J. Neurosci. **27**(9), 2186–2195 (2007). https://doi.org/10.1523/JNEUROSCI.4173-06.2007

7. Mullen, K.T., Thompson, B., Hess, R.F.: Responses of the human visual cortex and LGN to achromatic and chromatic temporal modulations: an fMRI study. J. Vis. **10**(13), 1–9 (2010). https://doi.org/10.1167/10.13.13
8. Salmela, V.R., Henriksson, L., Vanni, S.: Radial frequency analysis of contour shapes in the visual cortex. PLoS Comput. Biol. **12**(2), 1–8 (2016). https://doi.org/10.1371/journal.pcbi.1004719
9. Seth, A.K., Barrett, A.B., Barnett, L.: Granger causality analysis in neuroscience and neuroimaging. J. Neurosci. **35**(8), 3293–3297 (2015). https://doi.org/10.1523/JNEUROSCI.4399-14.2015
10. Seymour, K., Clifford, C.W., Logothetis, N.K., Bartels, A.: Coding and binding of color and form in visual cortex. Cereb. Cortex **20**(8), 1946–1954 (2010). https://doi.org/10.1093/cercor/bhp265
11. Tadel, F., Baillet, S., Mosher, J.C., Pantazis, D., Leahy, R.M.: Brainstorm: a user-friendly application for MEG/EEG analysis. Comput. Intel. Neurosc. **2011**, 1–3 (2011). https://doi.org/10.1155/2011/879716
12. Wade, A.R., Brewer, A.A., Rieger, J.W., Wandell, B.A.: Functional measurements of human ventral occipital cortex: retinotopy and colour. Philos. Trans. R. Soc. Lond., B, Biol. Sci., **357**(1424), 963–973 (2002). doi: https://doi.org/10.1098/rstb.2002.1108
13. Wang, L., Mruczek, R.E., Arcaro, M.J., Kastner, S.: Probabilistic maps of visual topography in human cortex. Cereb. Cortex **25**(10), 3911–3931 (2015). https://doi.org/10.1093/cercor/bhu277
14. Wang, B., Yan, T., Ohno, S., Kanazawa, S., Wu, J.: Retinotopy and attention to the face and house images in the human visual cortex. Exp. Brain Res. **234**(6), 1623–1635 (2016). https://doi.org/10.1007/s00221-016-4562-3

The Effectiveness of Metacognitive Hints in Insight Problem Solving

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Abstract. One of the difficulties in research of insight problem solving is that insight solutions are hard to control consciously. Moreover, participants cannot verbally report about problem solving [14] or evaluate their progress to the answer [11]. In this study we assumed that metacognitive hints could enhance an insight solution effectiveness. The hints may be helpful to participants' progress monitoring, understanding of contradictions and conflicts in insight problems. To test this hypothesis, we conducted the experiment where participants had to solve the Five-Square problem under one of two conditions: a) control – experimenter periodically gave supportive statements to participants (for example, "You will succeed", "You can do it"); b) experimental – experimenter periodically gave metacognitive hints to participants (for example, "What prevents you from solving the problem?", "What else can you use?"). We compared the number of solvers who successfully solved the problem within 15 min in each group. As a result, we found that the insight problem is more likely to be solved in the condition with metacognitive hints than in the condition with supportive statements. The result indicates that an incentive to conflict analysis plays a greater role in insight problem solving compared to the motivation to solve.

Keywords: Insight · Insight problem solving · Metacognition · Metacognitive hints

1 Introduction

The study of insight problem solving is one of the complex and controversial challenges in modern psychology of thinking. One of the difficulties in insight problems is an inaccessibility of solving processes for an observer. The inaccessibility manifests as an inability to monitor a solution progress [1], an inability to give a verbal report about the progress [2], and a participants' immunity to verbal hints [3]. From this perspective insight solution occurs unconsciously, uncontrollably, and largely spontaneously [4]. However, there are striking evidences that information is available to consciousness during insight problem solving [5, 6]. Such information can be used as a source of knowledge by metacognitive processes [7], i.e., processes that track solution progress.

In a recent literature, two views on the role of metacognitive monitoring in insight problem solving can be distinguished. The first view belongs to adherents of the nothing

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special approach, who consider mechanisms of insight and algorithmic solutions as identical. They suppose that metacognitive monitoring of progress to the goal state in insight problems should proceed according to the same principles as in algorithmic problems. For example, a use of metacognitive progress-monitoring heuristic in the classical insight problems was shown [8–10]. The use of the heuristic in the nine-dots and the eight-coins problems is available due to the fact that these problems have sufficient requirements for the goal state and it is only required to find a path to achieve the goal. The second view belongs to adherents of the specific approach and deals with problems, in which the goal state is not given or the goal requirements are unclear to the solver. The metacognitive monitoring in these problems can be very difficult due to the lack of feedback and, as a result, the monitoring is limited. The main information source for metacognitive processes is emotional signals. In particular, Aha! experience (an accompanying feeling for the emergence of a solution or hypothesis) can be considered as a signal from unconsciousness to consciousness that the problem solution has been found [11]. The two indicated theoretical views about the role of metacognitive monitoring in problem solving management are not opposite, but they are probably aimed at explaining different problems and various difficulties in their solution.

The key evidence of the important role of metacognitive processes in insight problem solving is the solver's ability to use preliminary metacognitive training. A number of studies have shown that the training (to pay attention to obstacles and barriers in the problem space; to identify a set of initial solver assumptions) improves the efficiency of spatial insight problems [6]. For this purpose, the authors used various questions aimed at the activation of metacognition. For example, "What strategies have you tried? Why?", "What are you trying to do?", etc. Another work [5] also demonstrated the possibilities of metacognitive training, but at this time to increase the effectiveness of verbal insight problems. It was shown that verbal insight problems are better solved after participants have been trained to look for inconsistencies in the problem representation. The effectiveness of such training is associated not only with a conscious attitude to the problem solving, but with a training to detect conflicts.

These studies not only show the importance of metacognitive training, but also reveal the key role of conflict detection and contradiction analysis in insight problem solving. The importance of conflict detection is indirectly indicated by recent data about the brain correlates of creativity and insight. A number of studies of brain activity in insight problems indicate a significant activity of anterior cingulate cortex, namely ACC [12]. Activity of ACC accompanies the unexpected failures detection and, possibly, provides the search and detection of conflicts and contradictions [13, 14]. It is important to note that ACC activity is observed in insight problems, but is not observed in creativity [12].

Thus, we suggest that metacognitive processes are useful for increasing the efficiency of insight problem solving. Their role is primarily associated with an increase of the solver's attention to the contradictions and conflicts in the problem. However, it should be noted that some studies show the impossibility of building a complete and adequate metacognitive model for the insight problem. For example, differences between insight and algorithmic in solution monitoring were found [1]. Participants could carefully monitor their solution progress in algorithmic problems, measuring a feeling-of-warmth. But during the solution of insight problems, the participants were not able to adequately assess their solution progress. Another work obtained the similar data [15]: participants showed a divergence between objective and subjective measurements of the impasse.

2 Experiment

The aim of this study is to test the role of metacognition in insight problem solving. We suppose that metacognitive hints allow participants to monitor their solution progress. The main function of monitoring is increasing the solution effectiveness. The metacognition compensates the incompleteness of problem representation and reveals the contradictions and inconsistencies in it [16]. The positive role of metacognitive hints will be manifested both in an increase of successful attempts in the experimental group and in a decrease in the solution time in the experimental group compared to the control group.

3 Method

3.1 Participants

Participants were 60 persons: the control group – 30 persons (21 women), aged 18–53 years ($M = 22.7$, $SD = 7.09$); the experimental group – 30 persons (22 women), aged 18–34 years ($M = 21.2$, $SD = 4.03$) All participants were tested individually, took part voluntarily, and were not paid for their participation.

3.2 Stimuli

As an insight problem we used the five-square problem [17], in which participants should move three sticks to reduce the number of five squares to four squares of equal size (see Fig. 1). The problem was presented to the participants on the table. Square sides were made from counting sticks of the same color. The initial state of the problem was presented for the participants; they did not see building process. The participants were instructed aloud. The experimenter could repeat the problem instruction at the request of the participant.

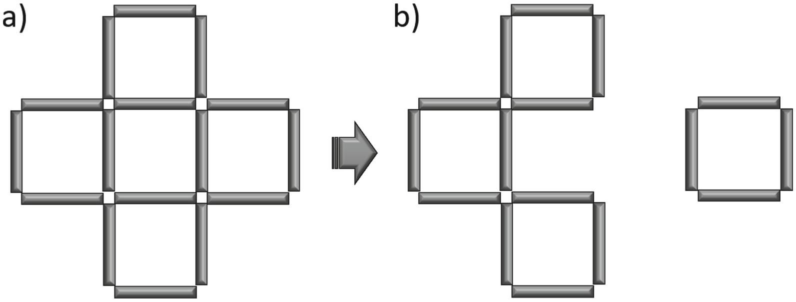

Fig. 1. The five-square problem (a) – initial problem state, (b) – one of the correct solutions.

3.3 Procedure

The participants were tested individually. The solution time limit was 15 min. The time was measured by a stopwatch. A start was a moment when participants reported understanding of the instruction. A finish was a moment when participants found the solution and was certain of its correctness. The participants were randomly assigned to one of the two groups:

1) experimental group that receives a metacognitive hint from the experimenter every minute during problem solving. Metacognitive hints were phrases such as “What prevents you from solving the problem”, “What else can you use?”, “Is there a conflict in the problem?”, “Are there any unusual elements in the problem?”, “What do you want to achieve?”, “What should be in the solution final?”, “Do you have any internal constraints that do not allow you to solve the problem?”, “Maybe you overlook anything?”.

2) control group that receives supportive statement from the experimenter also every minute. The control group received supportive statements to control the factor of participant distraction from the solution process. The following phrases were used as supportive statements: “Please, try again”, “You will succeed”, “The problem at first seems difficult for all participants”, “You need to make a little more effort”, “You can do it”, “You have all the necessary knowledge”, “You are doing well”, “Feel free to make hypotheses”.

The order of phrases presentation was random, but it was corrected in the light of participant’s remarks in the problem solving process.

4 Results

We used the Chi-square method with Yates correction to compare the number of successful (when the problem was solved) and unsuccessful (when the problem was not solved) attempts in the control and experimental groups. The Yates correction was introduced, because the value of one cell of the contingency table does not exceed 10, but not less than 5. The method revealed a significant difference between the distribution of successful (control group – 5, experimental – 13) and unsuccessful (control – 25, experimental – 17) attempts in the control and experimental groups, $\chi^2 = 3.889, p = .049$, *Cramer’s* $V = 0.017$.

We used the independent sample t-tests to compare the solution time. We found significant difference of the total solution times of successful and unsuccessful attempts (time of unsuccessful attempt is 900 s) between the control ($M = 840$, $SD = 171$) and experimental ($M = 709.4$, $SD = 261.8$) groups, $t(49.94) = 2.288, p = .026, r = 0.275$. However, the comparison of the solution times only in successful attempts using the Mann-Whitney test did not reveal the difference between the control ($M = 540$, $SD = 277.5$) and experimental ($M = 460$, $SD = 216.4$) groups, $U(\mathrm{N}_{\mathrm{control}} = 5, \mathrm{N}_{\mathrm{experimental}} = 13) = 25, z = -0.739, p = .46$.

5 Discussion

Based on the obtained data, we can conclude that metacognitive hints significantly influence the probability of insight solution comparing to the supportive statements in the control group. The main function of supportive statements was participants' motivation to continue problem solving, while metacognitive hints induced analysis of problem difficulties, detection of contradictions and ambiguities in representation. The result indicates that the inducement to conflict analysis plays a greater role in problem solving in comparison with the motivation to find the answer. We assume that the result is associated with the fact that metacognitive hints are a kind of external tool for assessing and monitoring problem progress.

Metacognitive hints allow solvers not only analyzing problem conditions, but also analyzing their representation and solution processes. In particular, such hints can be used to search for sources of difficulty in the problem; search for conflict elements in the initial representation; search for representation components that are flexible or change resistant. All of this demonstrates the possibility of conflict detection and conflict analysis in the insight as tools for representational change.

Unfortunately, our results only barely pass the threshold of significance after applying the Yates correction, and the effect size is not large enough. Nevertheless, we consider the data as confirmation of our hypothesis and plan to conduct similar experiments about the role of metacognitive hints in insight problem solving.

6 Conclusions

In conclusion, we found that conflict analysis in the problem representation increase the effectiveness of insight problems. Metacognitive hints could be the base for metacognitive monitoring. The monitoring allows the solver to consciously track his own mistakes and distortions in insight problem solving and to receive additional feedback about solution processes. Thus, high-level processes in insight problems can be effective and our data demonstrate the possibility of conflict analysis as a mean of representational changing in the insight.

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References

1. Metcalfe, J., Wiebe, D.: Intuition in insight and noninsight problem solving. Memory Cog. **15**(3), 238–246 (1987). https://doi.org/10.3758/BF03197722
2. Schooler, J.W., Ohlsson, S., Brooks, K.: Thoughts beyond words: when language overshadows insight. J. Exp. Psychol. Gen. **122**(2), 166–183 (1993). https://doi.org/10.1037/0096-3445.122.2.166
3. Weisberg, R.W., Alba, J.W.: An examination of the alleged role of "fixation" in the solution of several "insight" problems. J. Exp. Psychol. Gen. **110**(2), 169–192 (1981). https://doi.org/10.1037/0096-3445.110.2.169
4. Seifert, C.M., Meyer, D.E., Davidson, N., Patalano, A.L., Yaniv, I.: Demystification of cognitive insight: Opportunistic assimilation and the prepared-mind hypothesis. In: Sternberg, R., Davidson, J. (eds.) The Nature of Insight, pp. 65–124. MIT Press, Cambridge (1994)

5. Patrick, J., Ahmed, A., Smy, V., Seeby, H., Sambrooks, K.: A cognitive procedure for representation change in verbal insight problems. J. Exp. Psychol. Learn. **41**(3), 746–759 (2015). https://doi.org/10.1037/xlm0000045
6. Walinga, J., Cunningham, J.B., MacGregor, J.N.: Training insight problem solving through focus on barriers and assumptions. J. Creative Behav. **45**(1), 47–58 (2011). https://doi.org/10.1002/j.2162-6057.2011.tb01084.x
7. Klein, G.: The Power of Intuition: How to Use Your Gut Feelings to Make Better Decisions at Work. Knopf Doubleday, New York (2004)
8. Chronicle, E.P., MacGregor, J.N., Ormerod, T.C.: What makes an insight problem? the roles of heuristics, goal conception, and solution recoding in knowledge-lean problems. J. Exp. Psychol. Learn. Mem. Cogn. **30**(1), 14–27 (2004). https://doi.org/10.1037/0278-7393.30.1.14
9. MacGregor, J.N., Ormerod, T.C., Chronicle, E.P.: Information processing and insight: a process model of performance on the nine-dot and related problems. J. Exp. Psychol. Learn. **27**(1), 176–201 (2001). https://doi.org/10.1037/0278-7393.27.1.176
10. Ormerod, T.C., MacGregor, J.N., Chronicle, E.P.: Dynamics and constraints in insight problem solving. J. Exp. Psychol. Learn. **28**(4), 791–799 (2002). https://doi.org/10.1037/0278-7393.28.4.791
11. Valueva, E.A., Ushakov, D.V.: The signaling model of insight: from historical preconditions to empirical predictions. In: Juravlev, A.L., Ushakov, D.V., Holodnaya, M.A. (eds.) The Contemporary Studies of Intelligence and Creativity, pp. 15–48. IP RAS, Moscow (2015). (in Russian)
12. Dietrich, A., Kanso, R.: A review of EEG, ERP, and neuroimaging studies of creativity and insight. Psy. Bull. **136**(5), 822–848 (2010). https://doi.org/10.1037/a0019749
13. Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.D.: Conflict monitoring and cognitive control. Psy. Rev. **108**(3), 624–652 (2001). https://doi.org/10.1037/0033-295X.108.3.624
14. Botvinick, M., Nystrom, L.E., Fissell, K., Carter, C.S., Cohen, J.D.: Conflict monitoring versus selection-for-action in anterior cingulate cortex. Nature **402**(6758), 179–181 (1999). https://doi.org/10.1038/46035
15. Vladimirov, I.Y., Markina, P.N.: Objective and subjective impasse in insight problem solving. Vestnik YArGU. Seriya Gumanitarnye nauki. **3**, 76–80 (2017). (in Russian)
16. Duncker, K.: On problem-solving. Psy. Mono. **58**(5), 1–13 (1945)
17. Katona, G.: Organizing and Memorizing: Studies in the Psychology of Learning and Teaching. Columbia University Press, New York (1940)

Effects of Online Repetitive Transcranial Magnetic Stimulation on the Frequency of Insights During Anagram Solving

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Abstract. Insight is the sudden unpredictable appearance of a problem's solution. The solution of anagrams is one of the tasks available for studying insight. Repetitive transcranial magnetic stimulation (rTMS) allows the detection of a causal relationship between the activity of a cerebral cortex area and the studied cognitive phenomenon. During online-rTMS, the presentation of a short train of stimuli causes a so-called "virtual lesion" - a disruption of the task performance in which this area is involved. We aimed to study online effects of rTMS over left and right dorsolateral prefrontal cortex (DLPFC) on insight solution of anagrams. Healthy volunteers aged 18 to 55 years who did not have contraindications for magnetic resonance imaging (MRI) and rTMS were included. Each volunteer underwent 3 sessions of rTMS of left DLPFC, right DLPFC and Vertex (Control region) in a randomized order with intersession interval not less than 48 h. The presentation and solving of anagrams was synchronized to the rTMS train. During each session, 35 anagrams were presented with the intertrain intervals not less than 26 s. We assessed the total number and frequency of insight problem solving, mean duration of an insight solution and the percentage of correct answers. The data of 16 healthy volunteers were analyzed. No significant differences were observed depending on the stimulation zone when comparing the studied parameters for the three stimulation protocols and in pairwise comparisons between them. These results may be associated with a high degree of interindividual variability of the insight rate and a relatively low total number of insights. Further studies in this area are needed patients.

Keywords: Insight · Aha!-moment · Creativity · Repetitive transcranial magnetic stimulation · Online effects · Dorsolateral prefrontal cortex

1 Introduction

Insight is the sudden and unpredictable appearance of a problem's solution. Insight is usually contrasted with two other ways of problem solving – analytical solution and

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memory retrieval, and is thought to be associated with creativity and creative thinking. This explains a significant interest in studying the neural bases of this phenomenon and exploring possibilities of its modulation. The solution of anagrams is one of the tasks available for studying insight, in which, compared to "classical insight tasks" such as the nine-dot problem and the eight-coin problem, it is possible to apply not only the insight-based but also the analytical solution strategy, which allows the computation of the insight rate. Repetitive transcranial magnetic stimulation (rTMS) is a method of noninvasive brain stimulation (NIBS) using an alternating magnetic field to excite neurons [1]. rTMS allows the detection of a causal relationship between the activity of a certain area of the cerebral cortex and the studied cognitive phenomenon. Two main approaches are used in cognitive studies: online-rTMS and offline-rTMS. In both cases, one modulates brain activity using magnetic stimuli and evaluates the effects of this modulation. However, in online-rTMS, the stimulation effect is assessed directly during the stimulation, while in offline-rTMS - after the stimulation. Online-rTMS applied during task performance is a widely used approach to disrupt brain regions that are involved it task processing. During online-rTMS, the presentation of a short train of stimuli causes a so-called "virtual lesion" - a temporary and reversible dysfunction of the stimulated area of the brain immediately at the moment of stimulation and, accordingly, a disruption of the task performance in which this area is involved. To our knowledge, no studies of the insight phenomenon using the online-rTMS approach have been published yet. Previous studies discussed the role of right prefrontal cortex in insight problem solving [2]. At the same time, studies using another NIBS method, transcranial direct current stimulation, showed that anodal stimulation of the left DLPFC can modulate insight problem solving [3–5]. Our aim was to study online effects of navigated rTMS over left and right DLPFC on insight solution of anagrams. Conscious awareness.

2 Method

2.1 Subjects

24 volunteers (19 women, age 18.0 [18.0; 23.5] years) were screened for participation in the study. All participants were right-handed according to the Edinburgh Handedness Inventory. All procedures performed in the study were in accordance with the ethical standards of the Ethics Committee of the Research Center of Neurology (reference number 2–4/19 from 20.02.2019) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from the 24 volunteers.

Inclusion criteria for participation in this study:

- age of 18–55 years;
- normal or corrected-to-normal vision;

Exclusion criteria:

- MRI contraindications, e.g., implanted cardiac devices, claustrophobia, pregnancy, and others according to the guidelines [6];

- intake of drugs acting on the central nervous system;
- history of neurologic or psychiatric disorders;
- severe chronic diseases.

Three volunteers were excluded at the screening stage. One volunteer dropped off the study due to loss of interest, three more volunteers dropped off due to logistical difficulties. 17 participants completed the study protocol.

2.2 Neuromodulation

All participants underwent MRI to obtain structural data and import it into the NBS eXimia Nexstim neuronavigation TMS system (Nexstim, Finland). The MRI acquisitions were performed on a 3T Siemens MAGNETOM Verio scanner. Anatomic images were obtained using a 3D-T1-gradient echo sequence (T1-MPR) and consisted of 176 sagittal slices (TR = 1900 ms, TE = 2.47 ms, slice thickness = 1.0 mm, voxel size 1.0 × 0.977 × 0.977 mm^3, FOV = 250 mm).

Each volunteer underwent 3 sessions of rTMS of left DLPFC, right DLPFC and Vertex (control region) in a randomized order with intersession intervals not less than 48 h. The targets within the right and left DLPFC were 5 cm forward from the "hot spot" of the abductor pollicis brevis muscle representation of the corresponding hemisphere. The area of the vertex was determined by structural MRI. The following stimulation protocol was used: frequency - 10 Hz, duration of one train - 4 s, stimulation intensity - 90% of the resting motor threshold measured by the Rossini-Rothwell algorithm [7].

2.3 Task

Russian language anagrams with 5–8 letters were presented on a display and synchronized to rTMS trains by Trigger Station (BrainTrends, Italy). The structure of a single anagram presentation is shown in Fig. 1.

At the first stage, an anagram was presented for 9 s without stimulation. If the subject solved it within 9 s and pressed the button "solved", the subject would be asked about the first letter of the answer, which was followed by the display of the correct answer. If the subject did not solve the anagram within the first 9 s, one train of 10-Hz rTMS lasting 4 s was performed followed by 4 more seconds of anagram presentation. If the subject found the correct solution (during stimulation or within 4 s after), the subject would be requested to answer the following questions:

1) Did the solution come by insight? Yes/No;
2) Select one of three ways of reaching the solution: instant solution/unsuccessful search followed by a sudden solution emergence/search resulting in finding the solution;
3) Select the first letter of the answer: A/B/C;
4) Select the last letter of the answer: A/B/C.

After these questions, as well as in the case when the subject did not solve the anagram, the correct answer was demonstrated. The next anagram was presented in no less than 22 s after that, so as to fulfill the safety requirements [8] regarding the number of stimuli per unit time. During each session, 35 anagrams were presented.

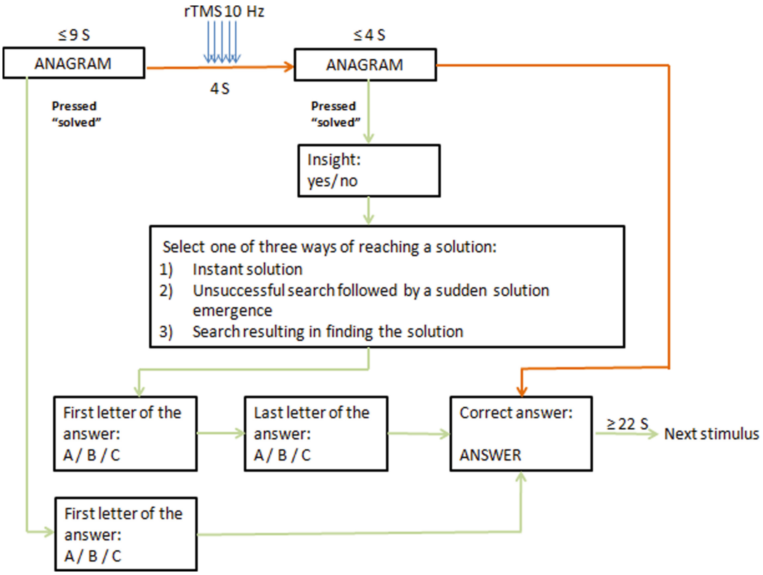

Fig. 1. Repetitive TMS-synchronised paradigm for the anagram solving problem. Green lines correspond to a button press; red lines correspond to transitions due to elapsed time. The rTMS train is shown by blue arrows.

2.4 Data Analysis

Statistical analysis was performed using MATLAB R2017a (Mathworks, Natick, MA, USA). Safety and tolerability was evaluated after each session using in-house questionnaires. We assessed the total number and frequency of insight problem solving, mean duration of an insight solution and the percentage of correct answers obtained by any of the two strategies. Since all the parameters were distributed non-normally (Shapiro-Wilk test) we applied non-parametrical statistic tests: Friedman's test was used to compare results between protocols; pairwise comparisons of the protocols were performed using the sign test (Wilcoxon's test excluded based on a visual assessment of distribution symmetry).

3 Results

No serious adverse events were reported during rTMS. All solutions of one subject fit into the first 9 s of anagram presentation, so rTMS was not performed at all, and the obtained data were excluded. Thus, the data of 16 healthy volunteers were analyzed. Data from volunteers who had at least one insight in each session (a total of 7 people) was used for analyzing the time spent on an insight solution. On average, during one session, the volunteers experienced 2–3 insights, and they spent an average of 12 s on each insight solution (Table 1).

Table 1. Investigated parameters of insight solution in three stimulation conditions. Data are presented as the median and quartiles Me [LQ; HQ].

Parameter/Protocol	Left DLPFC	Right DLPFC	Vertex
Total number of insight problem solutions	2,5 [0;3]	1,5 [0,5;3,5]	2 [0,5;4]
Frequency of insight problem solving	0,27 [0;0,63]	0,35 [0,06;0,64]	0,47 [0,06;0,63]
Percentage of correct answers	0,63 [0,3;1]	0,6 [0,18;0,79]	0,67 [0,44;0,71]
Mean duration of an insight solution, s	12,0 [11,4;13,5]	12,4 [11,4;12,6]	12,3 [11,8;13,5]

We observed great interindividual variability in insight rates, without a clear tendency towards higher or lower average rates in any of the protocols (Fig. 2).

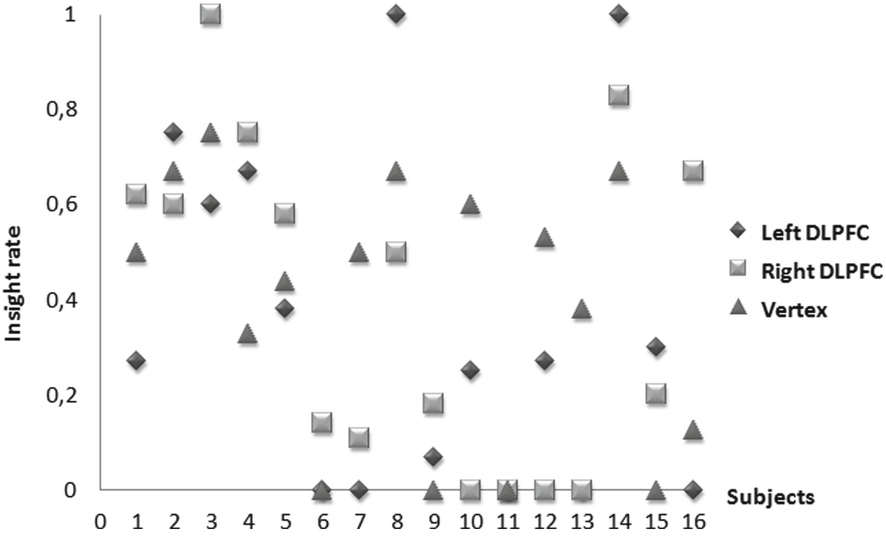

Fig. 2. Frequency of insight problem solving during the stimulation of the three studied brain areas.

No significant differences were found between the stimulation zones when comparing the studied parameters for the three stimulation protocols (Friedman test) and in pairwise comparisons between them (sign test).

4 Discussion

In our study, we tested whether left or right DLPFC has a causal role in insight problem solving by assessing the online effects of navigated rTMS on anagram solving. We did not find significant effects on the frequency of insight solving as well as its speed and the overall rate of correct solutions. These results may be associated with a high degree of interindividual variability and the relatively low total number of insights. One of the main limitations of our study was the subjectivity of determining the problem-solving strategy. Although the self-report approach is thought to be reliable and is widely used in studies of insight [9], its obvious disadvantages are the difficulty and possible inaccuracies in the distinction between insight and analytical solutions. Our data failed to reinforce previous obtained results from Cerruti et al. [5], Metuki et al. [4] and Zmigrod et al. [10] who showed an increase in insight problem solving by anodal tDCS of the left dorsolateral prefrontal cortex. However, it should be noted that the authors used CRA (Compound Remote Associate) problem solving as an insight task and we used anagram solving. In addition, the role of the DLPFC appears to be complex and involve various aspects of the insight and creative thinking, such as the integration of semantically distant information, creative choice of ideas and convergent thinking [11]. The heterogeneity of NIBS effects depending on the choice of the task is also discussed. Chi RP and Snyder AW [12] showed the enhancement of non-verbal insight by stimulating anterior temporal lobes (ATL). At the same time Aihara et al. [13] found that anodal tDCS of the right anterior temporal lobe did not significantly affect performance in either verbal or non-verbal insight tasks. Finally, a basic difference in the approaches to assessing NIBS effects between our research and all the mentioned studies should be noted. The cited authors [3–5, 10–13] used an offline approach when the effects are assessed after the end of stimulation. In our study, we used an online approach when the effects are assessed during the stimulation thus allowing a more accurate assessment of causality. Future rTMS studies may explore different areas reported to be involved in creative thinking, as well as the effects of different stimulation protocols.

5 Conclusions

We did not find significant effects on the frequency of insight solving as well as its speed and the overall rate of correct solutions and thus did not reinforce study results obtained in previous studies using NIBS. In conclusion we would like to note that despite the negative results obtained in our pilot study, further research in this area is warranted, in particular, the study of different insight tasks using multiple approaches including functional MRI, electroencephalography (EEG) and event-related potential (ERP) studies. Our group is planning to perform an experiment studying offline effects of rTMS on insight problem solving.

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References

1. Valero-Cabré, A., Amengual, J.L., Stengel, C., Pascual-Leone, A., Coubard, O.A.: Transcranial magnetic stimulation in basic and clinical neuroscience: a comprehensive review of fundamental principles and novel insights. Neurosci. Biobehav. Rev. **83**, 381–404 (2017). https://doi.org/10.1016/j.neubiorev.2017.10.006
2. Aziz-Zadeh, L., Kaplan, J.T., Iacoboni, M.: "Aha!": The neural correlates of verbal insight solutions. Hum. Brain Mapp. **30**(3), 908–916 (2009). https://doi.org/10.1002/hbm.20554
3. Weinberger, A.B., et al.: Using transcranial direct current stimulation to enhance creative cognition: interactions between task, polarity, and stimulation site. Front Hum. Neurosci. **16**, 11, 246 (2017). https://doi.org/10.3389/fnhum.2017.00246.
4. Metuki, N., Sela, T., Lavidor, M.: Enhancing cognitive control components of insight problems solving by anodal tDCS of the left dorsolateral prefrontal cortex. Brain Stimul. **5**(2), 110–115 (2012). https://doi.org/10.1016/j.brs.2012.03.002
5. Cerruti, C., Schlaug, G.: Anodal transcranial direct current stimulation of the prefrontal cortex enhances complex verbal associative thought. J. Cogn. Neurosci. **21**(10), 1980–1987 (2009). https://doi.org/10.1162/jocn.2008.21143
6. ACR Committee on MR Safety: Greenberg, T.D., Hoff, M.N., Gilk, T.B., Jackson, E.F., Kanal E., et al.: ACR guidance document on MR safe practices: updates and critical information 2019. J Magn Reson Imaging. **51**(2), 331–338 (2020). https://doi.org/10.1002/jmri.26880.
7. Rothwell, J.C., Hallett, M., Berardelli, A., Eisen, A., Rossini, P., Paulus, W.: Magnetic stimulation: Motor evoked potentials. The International Federation of Clinical Neurophysiology. Electroencephalogr. Clin. Neurophysiol. Suppl. **52**, 97–103 (1999)
8. Rossi, S., Hallett, M., Rossini, P.M., Pascual-Leone, A., et al.: Safety of TMS Consensus Group. Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. Clin. Neurophysiol. **120**(12), 2008–2039 (2009). https://doi.org/10.1016/j.clinph.2009.08.016.
9. Laukkonen, R.E.; Tangen, J.M.: How to detect insight moments in problem solving experiments. Front Psychol. **9**, 282:1–282:5 (2018). https://doi.org/10.3389/fpsyg.2018.00282.
10. Zmigrod, S., Colzato, L.S., Hommel, B.: Stimulating creativity: modulation of convergent and divergent thinking by transcranial direct current stimulation (tDCS). Creat. Res. J. **27**, 353–360 (2015). https://doi.org/10.1080/10400419.2015.1087280
11. Lucchiari, C., Sala, P.M., Vanutelli, M.E.: Promoting Creativity Through Transcranial Direct Current Stimulation (tDCS). A Critical Review. Front Behav Neurosci. **12**, 167 (2018). https://doi.org/10.3389/fnbeh.2018.00167
12. Chi, R.P., Snyder, A.W.: Facilitate insight by non-invasive brain stimulation. PLoS ONE **6**(2), e16655 (2011). https://doi.org/10.1371/journal.pone.0016655
13. Aihara, T., Ogawa, T., Shimokawa, T., Yamashita, O.: Anodal transcranial direct current stimulation of the right anterior temporal lobe did not significantly affect verbal insight. PLoS ONE **12**(9), e0184749 (2017). https://doi.org/10.1371/journal.pone.0184749

The Mirror Neuron System Activity is Higher with Personal Direct Interaction

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Abstract. The mirror neurons are involved in learning, empathy, and social interactions. The mirror neuron system (MNS) is activated when observing, presenting, and performing social gestures, so the MNS projects the action seen, determines its purpose, emotion, and motivation of the person. The most commonly used paradigm in MNS researches is to demonstrate biological movements using a video clip, although initially the mirror properties of neurons were discovered during a personal demonstration. As an indicator of the MNS activity, we used the level of EEG mu-rhythm suppression in the central areas of the scalp when performing certain tasks. We found differences in the MNS activation when demonstrating movement in person or when using a video clip. The mu rhythm suppression was significantly greater in the higher alpha range (10.5–13 Hz) in central and parietal areas during observation, imagination, and execution in paradigm with a personal demonstration. This indicates that the MNS is more active in personal social interaction, as opposed to video clip mode. Since one of the functions of mirror neurons is associative learning in childhood, our discovery may indicate poor quality of learning from video clips and online.

Keywords: Mirror neuron system · Mu suppression · Personal demonstration

1 Introduction

1.1 Mirror Neurons Discovering

Mirror neurons were discovered in 1996 by Italian scientists in experiments on the motor cortex of monkeys [1]. Rizzolatti with Colleagues conducted a study on the localization of motor neurons when they placed electrodes in the ventral premotor cortex of the monkey. During each experiment, the researchers showed the monkey by themselves what to do and then allowed the monkey to repeat that motion. It turned out that particular neurons responded identically when the experimenter showed the action, and when the monkey performed it. So a mirror neuron is a neuron that fires both when one acts and observes the same action performed by another one. At the same time, Rizzolatti showed the importance of understanding the purpose of the action and the physical ability to repeat it for activation of the mirror neurons [2]. Further studies have already been conducted in humans using indirect methods such as fMRI and EEG, which allows to identify the increase in the mirror neurons system (MNS) activity.

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1.2 Mirror Neurons Functions

One of the theories of the MNS origin reports [3] that the mirror neurons appear in infancy during associative learning and are intermediaries between sensory and motor systems. So, the first function of the mirror neurons is learning through imitation. The second important function of mirror neurons is the ability to perceive and understand the actions and emotions of other people in social communication [4–7]. So, the mirror neurons play a key role in the processes of learning, imitation, and perception. Apparently, the MNS helps to accommodate the emotional mood of the interlocutor, to understand his motivation and goals. Thus mirror network is a key mechanism in social behavior.

1.3 Mirror Neuron System Research Methods

If we talk about methods of studying the MNS, in addition to neuroimaging methods, EEG with functional samples is also widely used. This method does not allow us to identify the localization of the MNS activity, however, it allows us to identify the moment and degree of the MNS activation by reducing the mu-rhythm. The mu-rhythm or sensorimotor rhythm of the EEG is associated with motor activity and reduces its power when observing or performing motor movements, i.e. just when the mirror system is activated. Thus, mu-rhythm can serve as an indicator of the MNS activity in various tasks [8]. Not so long ago, in invasive experiments, it was shown that mirror neurons modulate the amplitude of the mu rhythm [9].

The typical scheme of the MNS experiment is recording EEG during observation and repeating of biological movement when mirror neurons work. Our scientific team has conducted the MNS researches since 2015 using various types of demonstrating stimulus material. The first studies of the MNS were conducted using a personal direct demonstration of hand movement by an experimenter [10], like in the original Rizzolatti's experiment. Subsequent studies were conducted using a mounted video clip, where the same hand movement was shown to the subject on the monitor screen [11]. Then we realized that mu-suppression was higher in our experiments with a personal demonstration of hand movement. This fact led us to a new study of the activation force of the mirror neuron system in different paradigms of biological motion demonstration. This research seems to be very topical in the field of the fact that social interaction is forced to switch to online mode in the modern world. The question remains how much this will affect the quality of communication and understanding of each other.

2 Methods

2.1 Ethics Statement

The research methods were approved by the ethical committees of the Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences and the Research and Clinical Center for Neuropsychiatry of Moscow Healthcare Department.

2.2 Experimental Design

EEG recording was performed at resting state with open eyes (baseline) and during the implementation of tasks that activate the MNS – "observation", "imagination" and "execution". The motor task was clenching the right hand. The first paradigm was a personal direct demonstration of motor movements by the experimenter. In this case, the experimenter sat opposite the subject, and the subject first observed the clenching of the experimenter's hand, then imagined and repeated this movement. The second paradigm was to use a mounted video clip with visualization of the same motor movement at the same task sequence. Each active task in both paradigm lasted 10 s. There were pauses between tasks when the experimenter reminded what to do next. Paradigms were ranked among the subjects.

2.3 Participants

The participant group consisted of 37 healthy subjects aged 20 to 37 years, all right-handed without psycho-neurological disorders: 17 subjects (11 women, 6 men, average age 27 years) with personal demonstrating, 20 subjects (14 women, 6 men, average age 29 years) with using a video clip. The experiment took place in the same room, the experimenter was the same, the procedure for preparing for the experiment was exactly the same for both groups of subjects. The exclusion criteria were the following: left-handedness; low amplitude resting-state EEG ($<20\ \mu V$); strong alpha resting-state activity ($>150\ \mu V$); alcohol and drug addiction; diabetes; chronic neurological diseases.

2.4 Data Processing and Analysis

EEG recording was performed using an EEG-21/26 encephalograph analyzer "MTD ENCEPHALAN 131–03", (19 electrodes according to the 10–20 system, monopolar relative to the combined ear electrodes A1 and A2) at rest with open eyes (baseline) and during the tasks. Data was sampled at 256 Hz with filter settings of 0.5 to 60 Hz in DC acquisition mode with impedances kept below 10 kΩ. EEG recordings were processed by spectral correlation analysis based on fast Fourier transform (FFT) over 3 frequency bands: alpha1 (8–10.5 Hz) and alpha2 (10.5–13 Hz). To identify the sensorimotor rhythm changes we analyzed C3, C4, Cz (central), P3, P4, Pz (parietal) electrodes, furthermore, we verified O1 and O2 (occipital) electrodes to exclude visual alpha rhythm suppression during the experiment.

Statistical comparison was made with the logarithmic powers of EEG rhythms relative to baseline. The paradigm of repeated measurements (observation, imagination, execution) with the factors "brain location" (central, parietal, occipital) and "group" (personal demonstration or using video clip) were used. Statistical analysis was performed using an ANOVA, and Tukey's test for post-hoc analysis was used to determine pairwise differences (StatSoft© Statistica 8).

3 Results

After FFT analysis, power values were obtained in the alpha1 and alpha2 frequency sub-bands for each electrode in three active tasks and the baseline. Natural logarithms of the spectral power in each of the tasks relative to the baseline were calculated. We performed an ANOVA of the relative logarithmic powers separately for the alpha1 and alpha2 ranges. Note that when we talk about rhythm suppression in central and parietal areas, we mean sensorimotor mu rhythm, considering in two sub-bands: 8–10.5 Hz called alpha1 band and 10.5–13 Hz called alpha2 band. When we consider changes in these two sub-bands in occipital electrodes, we mean changes in the visual alpha rhythm verifying the level of visual attention.

3.1 Changes in the Alpha1 Band

ANOVA with repeated measures didn't show significant effect of factors interaction R1*group*location. Current effect was F(4, 660) = 2.04, p = 0.09. One can see mu rhythm suppression in alpha1 frequency band only in the "observation" task in central and parietal areas (see Fig. 1). There was no mu suppression in the "imagination" and the "execution" task in 8–10.5 Hz frequency range.

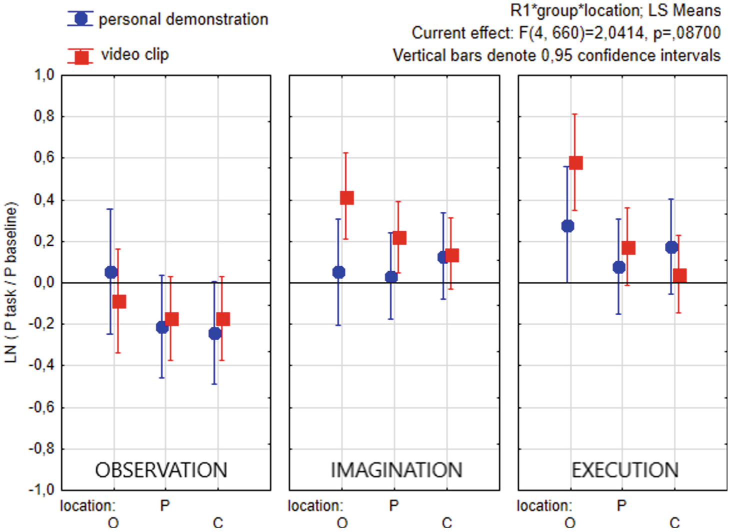

Fig. 1. Relative changes in the alpha1 range in occipital (O), parietal (P) and central (C) regions during the implementation of three tasks (observation, imagination, and execution) - in two groups of subjects: by a personal demonstration (blue circles) and using a video clip on the monitor screen (red squares). The baseline values are equal to zero.

3.2 Changes in the Alpha2 Band

At the same time we received a significant effect of factors interaction R1*group*location in alpha2 frequency band: F(4, 660) = 3.03, p = 0.02. Post-hoc Tukey's test showed significant differences ($p < 0.02$) between a degree of rhythm suppression in groups with different types of stimulus demonstration (see Fig. 2). One can see that the mu suppression occurred in the “observation” and the “imagination” tasks only in the group that was shown the movement in person, moreover, the suppression occurred only in parietal and central areas of scalp. The mu suppression in the “execution” task occurred in both groups in central areas only.

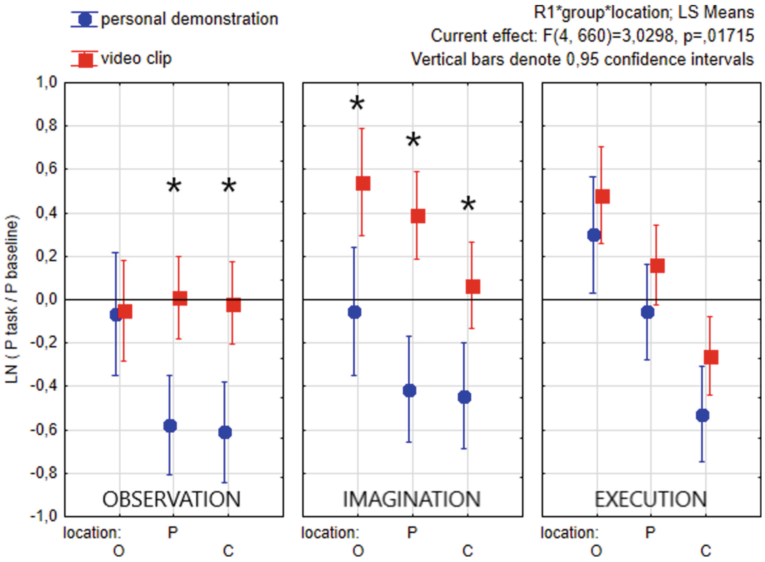

Fig. 2. Relative changes in the alpha1 range in occipital (O), parietal (P) and central (C) regions during the implementation of three tasks (observation, imagination, and execution) - in two groups of subjects: by a personal demonstration (blue circles) and using a video clip on the monitor screen (red squares). The baseline values are equal to zero. * - significant pairwise differences between groups (post-hoc Tukey’s test).

4 Discussion

4.1 Changes in Upper Alpha Band

According to some data, the upper and lower ranges of alpha or mu rhythm may have different functional significance [12]. So we divided the standard range of alpha activity of 8–13 Hz into two sub-ranges: alpha1 and alpha2 (see the Sect. 2 “Methods”). It was found that the decrease in the mu-rhythm power in the central areas in all three tasks was revealed only in the frequency range of 10.5–13 Hz (which corresponds to the range of alpha2) and only in subjects to whom the stimulus material was demonstrated directly by the experimenter. Since the degree of the mu suppression can be estimated by the degree of the MNS activation, it can be argued that the MNS activity was higher only in the group of subjects who were personally shown the hand movement. It can also be concluded that the rhythm functionally associated with the MNS activation is in the upper alpha2 range. These results are in good agreement with recent work that simultaneously recorded the activity of the premotor cortex neurons MUA, LFP, and EEG in monkeys when observing and performing grasping movements, and the demonstration was performed directly by the experimenter [9]. Authors found that the activity of neurons in the premotor cortex significantly correlated with an increase in the LFP gamma rhythm and a decrease in EEG power in the range of 10–20 Hz, i.e., the upper alpha and lower beta rhythms.

4.2 Occipital Alpha Rhythm and Visual Attention

To find out whether the decrease in alpha-band power during tasks is associated with visual information perception or increased concentration, we compared the desynchronization of alpha-band power in various areas of the cortex, including the visual (occipital leads). Some researchers reported that in the "observation" tasks, the power of not only the mu rhythm in the central regions, but also the alpha rhythm in the occipital regions decreased [13–15]. At the same time, the power suppression in the occipital regions in alpha band directly related to visual attention. In such cases this alpha suppression in the occipital regions leads to distrust of the mu-rhythm suppression in the central regions, since visual alpha can be mixed in. There was no decrease in rhythm power in the occipital areas during all active tasks. In our study, when demonstrating hand compression live, there was a significant decrease in the mu power in the central and parietal regions only (the motor and the sensorimotor regions of the cortex, which functionally corresponds to the perception and projection of movement) without visual alpha mixed in.

4.3 Demonstration Type Effect

In this study for the first time, a comparative analysis of the MNS activity using various methods of stimulus material presentation was demonstrated. The results indicated that the decrease in mu-rhythm and, accordingly, the MNS activation were significantly higher with personal demonstration of hand movement. We can only assume that in a personal demonstration the activation threshold of mirror neurons decreases, or the modulation of the mu rhythm occurs in a larger volume. It is interesting that the presence of an opponent (a social context) has a prolonged effect on the MNS. We revealed more activation not only in the observation task, but also in subsequent tasks (imagination and execution) when the participant didn't watch the experimenter's motion.

Is the discussed result of detecting more mu-rhythm suppression with personal demonstration can be related to the effect of the experimenter's presence and the feeling of control? In experiments with both groups, the same experimenter was present and prepared. During the demonstration of the hand clenching using the monitor, the same experimenter was also present in the room at that moment, but was not in the field of view of the subject. The subjects at that moment felt his presence and understood that the experimenter was continuing their work in close proximity to them. However, the moment of personal direct interaction during the EEG recording was excluded in case of video-clip demonstration. We believe that it is the lack of social contact in the perception of movement (primarily in the task "observation") was the cause of the differences in the mu rhythm suppression. The results of this work serve as a prerequisite for new MNS research, which will aim to identify the effect of "live" social interaction in comparison with the online format.

5 Conclusions

In conclusion, we would like to emphasize that we have found differences in the MNS activation when using two different methods of stimulus material demonstrating – personally by the experimenter and using a video clip. A decrease in mu-rhythm power was observed in all three tasks only in the upper frequency range (10.5–13 Hz), in the central regions, and only in the group that was demonstrated live. Moreover, the presence of an opponent affected the results not only in the observation task, but also in the other two tasks. The results of this comparative analysis allow us to hypothesize that the mirror neuron system is more active during "live" social contact. Thus, it can be assumed that social contacts via video communication, for example, online, do not significantly involve the MNS in the work. In this regard, non-verbal contact, the understanding of the emotional background of the interlocutor can significantly deteriorate, and the learning process can be worse implemented. To test this hypothesis, additional studies are planned with the most identical conditions for demonstrating stimuli live and on the monitor screen.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Gallese, V., Fadiga, L., Fogassi, L., Rizzolatti, G.: Action recognition in the premotor cortex. Brain **119**, 593–609 (1996). https://doi.org/10.1093/brain/119.2.593
2. Grafton, S., Arbib, M., Fadiga, L., Rizzolatti, G.: Localization of grasp representations in humans by positron emission tomography. Exp. Brain Res. **112**, 103–111 (1996). https://doi.org/10.1007/BF00227183
3. Cook, R., Bird, G., Catmur, C., Press, C., Heyes, C.: Mirror neurons: from origin to function. Behav. Brain Sci. **37**, 177–192 (2014). https://doi.org/10.1017/S0140525X13000903
4. Berntson, G., Cacioppo, J.: Social Neuroscience. Psychology Press, New York (2005). https://doi.org/10.4324/9780203496190
5. Iacoboni, M.: Understanding others: Imitation, language, empathy. Perspect. Imitation Cogn. Neurosci. Soc., Sci. (2005)
6. Carr, L., Iacoboni, M., Dubeau, M.C., Mazziotta, J.C., Lenzi, G.L.: Neural mechanisms of empathy in humans. Proc. Natl. Acad. Sci. **100**, 5497–5502 (2003). https://doi.org/10.1073/pnas.0935845100
7. Mikulan, E.P., Reynaldo, L., Ibáñez, A.: Homuncular mirrors: misunderstanding causality in embodied cognition. Front. Hum. Neurosci. **8** (2014). https://doi.org/10.3389/fnhum.2014.00299
8. Fox, N.A., Yoo, K.H., Bowman, L.C., Cannon, E.N., Ferrari, P.F., Bakermans-Kranenburg, M.J., Vanderwert, R.E., Van IJzendoorn, M.H.: Assessing human mirror activity with EEG mu rhythm: a meta-analysis. Psychol. Bull. **100**, 5497–5502 (2016). https://doi.org/10.1037/bul0000031
9. Bimbi, M., Festante, F., Coudé, G., Vanderwert, R.E., Fox, N.A., Ferrari, P.F.: Simultaneous scalp recorded EEG and local field potentials from monkey ventral premotor cortex during action observation and execution reveals the contribution of mirror and motor neurons to the mu-rhythm. Neuroimage **175**, 22–31 (2018). https://doi.org/10.1016/j.neuroimage.2018.03.037

10. Lebedeva, N.N., Karimova, E.D., Karpichev, V.V., Maltsev, V.Y.: The mirror system of the brain on observation, performance, and imagination of motor tasks – neurophysiological reflection of the perception of another person's consciousness. Neurosci. Behav. Physiol. **49**, 714–722 (2019). https://doi.org/10.1007/s11055-019-00791-3
11. Lebedeva, N.N., Karimova, E.D., Burkitbaev, S.E., Maltsev, V.Y., Guekht, A.B.: Features of the Operation of the Mirror Neuron System in Patients with Affective Disorders. Neurosci. Behav. Physiol. **49**, 1054–1060 (2019). https://doi.org/10.1007/s11055-019-00837-6
12. Bazanova, O.M., Vernon, D.: Interpreting EEG alpha activity. Neurosci. Biobehav. Rev. **44**, 94–110 (2014). https://doi.org/10.1016/j.neubiorev.2013.05.007
13. Ensenberg, N.S., Perry, A., Aviezer, H.: Are you looking at me? Mu suppression modulation by facial expression direction. Cogn. Affect. Behav. Neurosci. **17**, 174–184 (2017). https://doi.org/10.3758/s13415-016-0470-z
14. Hobson, H.M., Bishop, D.V.M.: The interpretation of mu suppression as an index of mirror neuron activity: Past, present and future. R. Soc. Open Sci. **4**, 160662 (2017). https://doi.org/10.1098/rsos.160662
15. Karakale, O., Moore, M.R., Kirk, I.J.: Mental Simulation of Facial Expressions: Mu Suppression to the Viewing of Dynamic Neutral Face Videos. Front. Hum. Neurosci. **13**, (2019). doi: https://doi.org/10.3389/fnhum.2019.00034

Gender Differences in Object and Spatial Inattentional Blindness Under Working Memory Load

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Abstract. Inattentional blindness is observed when a visible object is not noticed because attention is focused elsewhere. It is an open question whether inattentional blindness is related to working memory load. In this study, subjects performed a demanding visual task under various levels of visual working memory load. In the last trail of the visual task, an unexpected object was presented in one of four shapes and in one of four locations. The subjects were asked if they have seen something unusual. If yes, they were asked to judge the shape and location of the unexpected object. It was found that working memory load induced inattentional blindness but this was observed only in men. Men generally noticed more unexpected objects than women. Generally, men judged the location of the unexpected object better than women at all working memory load levels. Women better judged the shape of the unexpected object at low working memory load. In women, shape and location identification worked in parallel while in men they differed. This points to the existence of two types of attention – spatial attention and object attention – which may work differently in men and women.

Keywords: Working memory · Inattentional blindness · Object attention · Spatial attention · Gender difference

1 Introduction

Inattentional blindness is the failure to notice an unexpected object when attention is focused elsewhere and loaded with something else [1]. The study of this phenomenon is relevant for various spheres, for example, the usability of computer interfaces, safe driving, and others. Technically, this phenomenon can be an indicator of attention effectiveness. According to many researches, one of the main causes of inattentional blindness is load on subject's working memory (WM) [2, 3]. Specifically, if visual-spatial WM is loaded, some researches show that the probability of noticing an unexpected object is lowered [4, 5]. But there are also conflicting results. Seegmiller et al. [6] found no relationship between working memory and noticing of an unexpected gorilla. Also, in Bredemeier and Simons [7] neither tracking task nor working memory load predicted

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the noticing of an unexpected object. Thus, there is still need for more data on the relationship between WM load and inattentional blindness.

Considering inattentional blindness, it is interesting to compare the recognition of different characteristics of stimuli. First, attention ("object attention") can be focused on the visual characteristics of the stimulus, i.e. shape, color, size, etc. Second, attention ("spatial attention") can be used to notice the location of an object. As a rule, indicators of object and spatial attention are different. For instance, they are characterized by different types of eye movements (saccades and fixations) [8]. This can be explained by separation of the ventral and dorsal pathways of the visual cortex, which are responsible for the perception of the "what" and "where" systems [9]. This corresponds to the idea of attention as a multi-level structure that includes different mechanisms.

It is assumed that different types of attention prevailed at different stages of human evolutionary development. Its earliest form was spatial attention. It is responsible for determining the location of objects. It also includes the fixation of moving objects. In some cases the reaction of spatial attention to movement is so fast that the object does not have time to be identified [10]. It is spatial attention which is associated with the "where" system. Object attention emerged in later stages of development. It is responsible for identifying objects, their shape, color, size, and so on. This type of attention assumes the participation of WM resources, as well as more complex and conscious forms of perception than with spatial attention. It is object attention that is associated with the "what" system.

Inattentional blindness may affect object and spatial recognition of a stimulus in different ways. In this study, we focus on gender differences in inattentional blindness under WM load with respect to spatial and object recognition of an unexpected stimulus. Based on rather primitive evolutionary considerations, we assumed a different degree of inattentional blindness in male and female It is an open question whether males and females differ in attention capacity. While previous research did not find gender differences in inattentional blindness [3], a recent study find a substantial effect of gender, with men noticing the unexpected object more often than women [11]. In addition, we suggested gender differences in how WM load affects inattentional blindness and in the recognition of object and spatial characteristics.

2 Material and Methods

2.1 Participants

Participants were 160 students (71 males, 89 females), students of Moscow universities, with normal or corrected-to-normal vision. The experiment complied with Declaration of Helsinki and was approved by the local ethics committee of the Lomonossov Moscow State University.

2.2 Materials

In our experiment, we compared the ability to spot the critical stimulus and to identify the shape and location of the critical stimulus with low and high level of visual WM load. One group of participants remembered the color of one object, and the second group - the colors of the four objects. Thus, we controlled the level of visual WM load: low or high. We chose four colors because there is a hypothesis that four objects lead to high visual-spatial WM load. Then the participants performed a series of visual tasks (line length comparisons). During the last task, an unexpected critical stimulus appeared. We compared the ability of participants to spot this object and determine its shape and location.

Figure 1 illustrates procedure of the experiment. At first, the participants remembered the colors of objects. One group of participants remembered the color of one square (300 × 300 pix), and another group – of four squares (size of one object 200 × 200 pix). This task (200-ms showing duration and 200-ms perceptual mask duration) allowed us to vary the low and high level of visual WM load. After that there was the task to compare the length of two lines (blue and yellow, size 700 × 700 pix, 10 s presentation duration). The answer was given using the keyboard. In our research, this task was distracting and we did not process this data. The participants were instructed to answer as quickly as possible, using the key "left" if they thought that blue line is longer, and "right", if yellow. The keyboard has been marked with stickers. Next was shown the perceptual mask (the gray background) with duration of 200 ms. Then the participants saw again one or four objects of different colors. They answered if colors match or do not match with those that they saw on the first slide. The duration of this test was regulated by clicking the key. The participants were instructed to click the key "5", if the colors are the same, and "7", if they are not the same. The keyboard has also been marked with stickers.

2.3 Procedures

The participants performed a total of 10 trials. The first 3 consisted of practice trials, followed by 7 experimental trials that were identical to the practice trials. In the last (1oth) trial for comparing the length, an unexpected critical stimulus (100 × 100 pix, black arrow of one of the four forms) was presented for 10 s (duration of the whole trial) 35° away from the fixation point in one of the four corners of the display. The participants were not informed of the presentation of this stimulus. Detection of the critical stimulus was measured after experiment by a series of questions presented on the computer screen. The first question assessed whether the participants had seen anything unusual during the trial. The participants responded by selecting yes or no, using separate keyboard presses. The second question asked the participants to select which form of stimulus they might have seen among 4 possible forms. The third question asked the participants to select in which of the four corners the critical stimulus had appeared. Critical stimulus detection was considered successful (without "inattentional blindness") if the participants reported "yes" to the presence of the unexpected stimulus. Correctly selection of stimulus form and location reflected efficiency of object and spatial attention.

The total duration of the experiment was approximately 16 min. All responses and clicks were saved in the program "PsychoPy2". Incorrect answers to the questions about form and location of the stimulus were took for inattentional blindness in determining the form or location of stimulus. We assume that the object could be noticed but its visual and location characteristics could not be processed by perceptual systems.

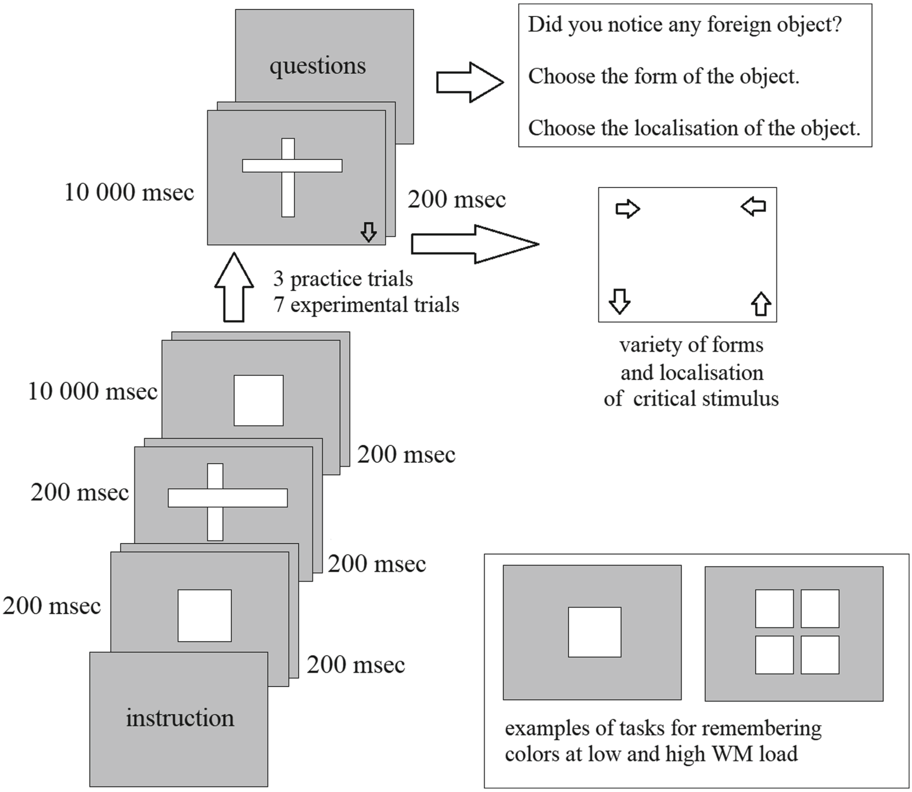

Fig. 1. The procedure and time-course of the experiment.

3 Results

As can be seen from Fig. 2, men were better at the identification of an unexpected stimulus than women. This effect was reduced to the identification of the location of the unexpected stimulus only (spatial attention). There were no gender differences in the identification of the unexpected object's shape (object attention). In the male sample, inattentional blindness was observed significantly more often with high WM load than with low WM load, $\chi2(1, 43) = 4.51$, $p = .022$. However, we found no significant differences in inattentional blindness under different WM loads in the female sample, $\chi^2(1, 45) = 0.92$, $p = .338$. Women were more likely to identify the shape at low WM loading than at high WM load, $\chi2(1, 45) = 3.962$, $p = .047$. There was no effect of WM load on object shape detection in men sample, $\chi2(1, 43) = 0.270$, $p = .603$. We also didn't find significant effect of WM loading on location detection in men, $\chi2(1, 43) = 0.767$, $p = .381$, and in women, $\chi2(1, 45) = 1.968$, $p = .161$. In addition, we found that women's object and spatial attention systems worked mostly in concert, $\chi2(1, 45) = 6.3$, $p = .012$. In men sample they work inconsistently at any WM loading, $\chi2(1, 43) = 1,1$, $p = .294$.

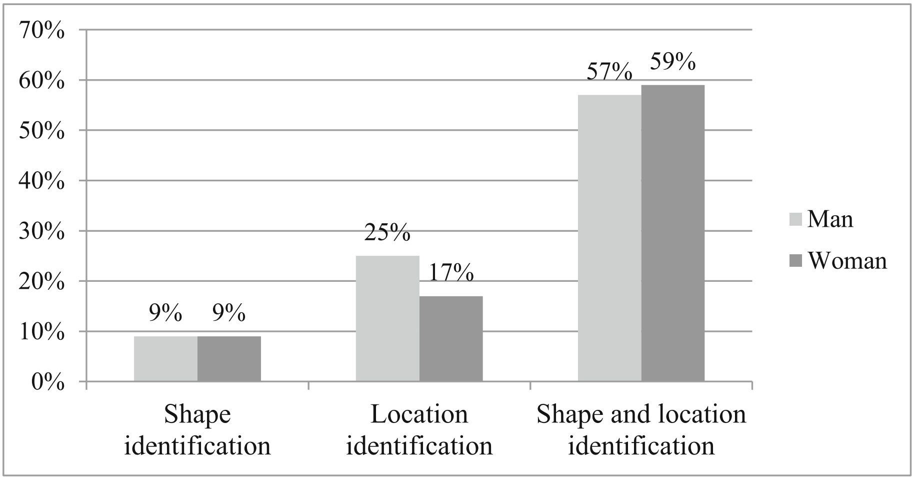

Fig. 2. The percentage of children that passed the +2 and +3 theoretical and empirical criteria.

4 Discussion

Our evidence shows that the high WM loading led to obvious decrease in the visual attention effectiveness in the male sample, that is, "inattentional blindness" occurred more often. However, men identified the location of the unexpected object. We tried to explain these results according to the evolutionary point of view. Men in general are more able to recognize unexpected extraneous objects (spatial attention), since they were required to pay a high level of attention in the early stages of human development.

Comparing the interaction of object and spatial attention systems, we found that these systems work in concert in women. In men, locations were identified more often than shape, which is illustrated in Fig. 2. It is assumed that men's attention can generally fix an object faster than women's [12]. Thus, in men, different attention systems are mismatched, since spatial attention has a higher speed than object attention [11]. Based on the fact that women recognize the spatial characteristics of an object at the same probability as its shape, we assumed that their object attention "keeps up" with the spatial one. This results in a consistent operation of the two systems.

It can be noted that the participants generally recognized the location better than the shape at any level of WM loading. 87% of the participants who identified the shape of the object correctly identified its location. However, only 73% of the participants who identified the object's location were able to identify its shape. Thus, spatial attention is more successful in most cases. These conclusions confirmed that the localization is primary in relation to the identification of object characteristics. Identifying the location of an object requires less awareness/higher level processing than identifying object characteristics. This means that increasing the WM load does not reduce the ability to detect a location as much as the ability to consciously identify a form. It is, of course, related to the fact that we loaded the visual part of visual-spatial WM in our experiment.

5 Conclusion

The present study showed an effect of WM load on inattentional blindness, which could be reduced to a specific effect in the males. Males were generally better than women in the noticing of an unexpected object. This gender difference was primarily observed for the localization of the unexpected object. Shape identification was specifically adversely affected by WM load in women. The results point to the existence of two attention systems. One is spatial attention responsible for the quick localization of objects including unexpected ones. The other is object attention responsible for object's shape (or other visual characteristics') identification. These systems are differently developed in men and women. There seems to be gender specificity in WM load effects on these two systems of attention. Gender differences discovered in our study can have evolutionary origin.

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References

1. Mack, A., Rock, I.: Inattentional Blindness. MIT Press, Boston (1998)
2. Macdonald, J.S.P., Lavie, N.: Load induced blindness. J. Exp. Psychol. Hum. Percept. Perform. **34**, 1078–1091 (2008). https://doi.org/10.1037/0096-1523.34.5.1078
3. Hannon, E.M., Richards, A.: Is inattentional blindness related to individual differences in visual working memory capacity or executive control functioning. Perception **39**, 309–319 (2010). https://doi.org/10.1068/p6379
4. Fougnie, D., Marois, R.: Executive working memory load induces inattentional blindness. Psychon. Bull. Rev. **14**(1), 142–147 (2007). https://doi.org/10.3758/bf03194041
5. De Fockert, J., Bremner, A.: Release of inattentional blindness by high working memory load: Elucidating the relationship between working memory and selective attention. Cognition **121**(3), 400–408 (2011). https://doi.org/10.1016/j.cognition.2011.08.016
6. Seegmiller, J., Watson, J., Strayer, D.: Individual differences in susceptibility to inattentional blindness. J. Exp. Psychol. Learn. Mem. Cogn. **37**(3), 785–791 (2011). https://doi.org/10.1037/a0022474
7. Bredemeier, K., Simons, D.: Working memory and inattentional blindness. Psychon. Bull. Rev. **19**, 239–244 (2012). https://doi.org/10.3758/s13423-011-0204-8
8. Velichkovsky, B.M., Korosteleva, A.N., Pannasch, S., Helmert, J.R., Orlov, V.A., Sharaev, M.G., Velichkovsky, B.B., Ushakov, V.L.: Two Visual systems and their eye movements: A fixation-based event-related experiment with ultrafast FMRI reconciles competing views. STM (Modern Technol. Med.) **11**(4), 7–18 (2019). https://doi.org/10.17691/stm2019.11.4.01
9. Milner, A.D., Goodale, M.A.: The Visual Brain in Action. Oxford University Press, Oxford (1995)
10. Velichkovsky, B.M.: Cognitive Science: The Foundations of Epistemic Psychology. Smysl/Academia, Moscow (2006).(in Russian)
11. Kreitz, C., Furley, P., Memmert, D., Simons, D.J.: Inattentional blindness and individual differences in cognitive abilities. PLoS ONE **10**(8), e0134675 (2015). https://doi.org/10.1371/journal.pone.0134675
12. Colzato, L.S., Pratt, J., Hommel, B.: Estrogen modulates inhibition of return in healthy human females. Neuropsychologia **50**, 98–103 (2015). https://doi.org/10.1016/j.neuropsychologia.2011.11.003

Effect of ‘Dry’ Immersion on Visual Illusions

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Abstract. The ‘dry’ immersion (DI) is the well-known model of gravitational unloading used for studying the physiological effects of space flights on Earth. The prolonged muscle unloading is similar to its effect on the muscles unloading in microgravity. The changes in the vestibular system activity due to the sensory disintegration processes have also appeared. Here we summarized our findings of the influence of the 5-day and 21-day DI on the estimation of neutral stimuli and onto the strength of the Muller-Lyer and Ponzo visual illusions. The responses were registered in verbal and motor domains. The DI influence on the sensorimotor tasks was more pronounced than on the verbal one. It was shown that the strength of Muller-Lyer illusion registered by tracing and grasping tasks was modulated strongly by the DI time-course. It tended to decrease during DI while the use of a ‘Penguin’ suit that provided axial load or high-frequency myostimulation of muscles of both legs had restored its strength to the pre-DI level. We propose that hyperactivation of the dorsal pathway of visual processing can be one possible reason for such result patterns.

Keywords: Dry immersion · Visual illusions · Dorsal pathway

1 Introduction

Typically, the influence of microgravity on the physiological properties of muscles and tissues is studied. However, microgravity also affects the central mechanisms of movement coordination and some cognitive mechanisms [1, 2]. The absence of normal gravity disturbs the vestibular system function. Simultaneously, the human brain already cannot use the gravity vertical for building the reference frames. It seems that these lead to the restructuring of different pathways of visual processing. Namely, the dorsal stream receives the additional load. This load, in turn, results in some peculiarities of visual processing.

One way to study the functioning of the dorsal and ventral stream is to measure the strength of visual illusions. Since Agliotti had performed his experiments [3] and Milner and Goodale suggested the idea of comparison grasping and verbal answer for visual illusions [4], many other studies were made with the help of various visual illusions (Ebbinghaus, Muller-Lyer and Ponzo) to support or to deny the effect of verbal and

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motor estimation mismatch. Grasping is not the only way for motor estimation of the object size. Tracing also can be used: the participant moves his finger across the line, from the start to the endpoint.

The datasets obtained from the space flights are small, and the experiments' performance during the flights meets several difficulties. The parabolic aircraft flights allow studying the cognitive performance only during short microgravity periods (about 20 s). The geometric visual illusions were less frequent [5] and the reaction times to complex tasks decreased [6] in this condition that needs further investigations.

One of the models used on Earth for microgravity studies is the 'dry' immersion (DI). During DI, the volunteers are laying on the rubber textile in the bath filled with comfortably warm water. The prolonged muscle unloading is similar to its effect on the muscles unloading in microgravity. The vestibular system activity changes due to the prolonged constancy of the laying position also appeared. DI's effects on the eye and hand movements are similar to those observed in real microgravity [7]. The DI is also used in the medical treatment of Parkinsonism. A course of the 7-day DI had decreased the Parkinsonism symptoms, especially the motor symptomatic [8].

Meanwhile, the influence of the DI on visual perception *per se* is rarely investigated. Here we summarized the main findings of our works performed on the different DI groups with visual illusions [9–12]. The participants had to respond to the presented stimuli either verbally or by tracing hand movements or grasping hand movements. The aim of using different response modalities was to activate the different visual streams, dorsal or ventral one, to a different extent.

2 Methods

Three groups of volunteers, six men in each, participated in the 5-day DI. The volunteers of the (IM + L)-5 group were wearing a suit 'Penguin' providing axial load four hours per day during DI. The volunteers of the (IM + HFMS)-5 group were subjects of everyday high-frequency myostimulation (HFMS) of mm. *Quadriceps femoris*, *triceps surae*, and *tibialis anterior* of both legs. The volunteers of the IM-5 group were not exposed to any influence other than DI. One group of ten volunteers, IM-21, participated in the 21-day DI. They were also not exposed to any other influence than DI. All volunteers were admitted to participation in the experiment by an expert medical commission. They signed Informed Consent to participate in the study following the Helsinki Declaration of Human Rights. Research procedures were preliminarily reviewed and approved by the Biomedical Ethical Commission of IBMP RAS.

The stimulus consists of a pair of equal to each other horizontal segments. In the case of neutral stimulus, they were flanked by small vertical segments. In the case of the Muller-Lyer illusion, arrows that point in different directions flanked them. In classical Ponzo illusion, the central horizontal segments were surrounded by converging lines to the left and the right. The stimuli were presented by blocks of the same type having central segments of different lengths. For verbal response, the stimuli were presented on display or printed on A4 paper. For tracing, the stimuli were presented on the sensory monitor (iiyama, Japan), allowing us to register the finger touching or presented in A4 paper. In the latter case, the registration was performed using an electromagnetic system

(Ascension Technology Corporation, Burlington, Vermont, USA). The IM-21 group additionally performed the grasping task. For this task, the stimuli were constructed from the plastic shafts that allow executing real grasp; the registration was performed using an electromagnetic system (Ascension Technology Corporation, Burlington, Vermont, USA). For tracing, the start and the endpoint of the touching of the sensory screen were registered. For grasping, the maximum of the grip aperture on the trajectory of hand movement was detected. The strength of the effect was calculated as a ratio between differences in measured values for the upper and lower segments and the segment's length by itself.

At the verbal task, the volunteer had to say which of the central segments is larger than the other one and to estimate the percentage difference. At the tracing task, the volunteer had to move the index finger of his leading hand at first across the upper central segment and then across the lower one. At the grasping task, firstly, the volunteer grasped the upper central segment with his leading hand and, secondly, the lower one. The experimental trials were performed before DI, after DI, and three times during DI: at day 1, 3, and 5 of 5-day DI; at day 3, 10, and 20 of 21-day DI. During all trials, the volunteers were half laying in the bath (during DI) or on the bed (before and after DI).

3 Results

It appeared that the DI by itself does not influence much the results of the verbal task. The estimates of neutral stimuli were correct. Typically, both illusions' strength was slightly but significantly higher than zero at first measurements before the DI. After that, it stayed on the same level or decreased down to zero due to learning processes. Presumably, the verbal response's illusions' weakness is associated with more conscious control of the volunteers than for ordinary participants, due to both an unusual lying position and unusual research conditions. It is worth noting that in the microgravity during parabolic flight, the visual illusions measured with verbal response were also diminished [5].

The DI influence on the sensorimotor tasks was more pronounced. The strength of the Ponzo illusion had become negative; that is, the volunteers overestimated the lower central segment relative to the upper one. It can be assumed that volunteers perceived their index finger moving along the segments as the distractor at a higher than usual level of conscious control. It is known that point distractors located on the central segments of stimuli can change the illusion sign. The Muller-Lyer illusion's strength was positive, which might suggest that these two illusions originate in the visual system's different levels. Such a possibility was indicated in [13]: these two visual illusions were classified into distinct global classes.

The estimates of neutral stimuli were correct during 5-day DI. Meanwhile, the underestimation of the upper central segment was observed on the tenth day of the 21-day DI in relation to values obtained before DI for the grasping task and on the twentieth day of the 21-day DI in relation to its third day for the tracing task.

The strength of the Muller-Lyer illusion was modulated strongly by the DI. For the IM-5 group, its strength decreased at DI and then increased after DI relative to the DI's fifth day. For the (IM + HFMS)-5 group, its strength did not change during DI; but after DI, its strength increased relative to the DI's third day. It can be assumed that HFMS increases the afferent flow in conditions of its deficit during DI, thus normalizing the dorsal and ventral visual pathways’ interaction. For the (IM + L)-5 group, its strength during DI did not change significantly. Furthermore, its strength measured at trials performed when the volunteers wear a ’Penguin’ suit was higher in relation to the trials performed on the same day before the volunteers put on this suit. Presumably, the axial weight loading on various body segments, created with rubber straps, diminished the DI effect of gravitational unload.

For the IM-21 group, the dynamics of the Muller-Lyer illusion strength was more complicated. At the tracing task, it decreased in the first half of the DI. Then, on the twentieth day, it increased relative to the before-DI measurements. Then, after DI, it decreased again down to zero. At the grasping task, the Muller-Lyer illusion’s strength decreased on the third day of the DI. Then, on the tenth day, it increased relative to the third day. Then it decreased again down to zero. Thus, in comparing IM-5 and IM-21 groups, the volunteers tried to compensate for the visual processing changes during DI. However, the compensatory effect had disappeared in the second half of the prolonged DI.

4 Discussion

To our knowledge, cognitive experiments are rarely performed in space missions. The exceptions are the mental rotation studies that led to contradictory results [1]. It was shown the difficulty of performing mental transformations that requires a perception of the position in the space of one’s own body or its parts in microgravity. Presumably, such a task needs the egocentric coordinate system that is proper for the dorsal pathway. The same may be said for orientation illusions experienced by the astronauts at the beginning of the flight, then their strength decreased, but they continued to be present when the cosmonauts were in the dark or had their eyes closed [14]. The mental representation of the vertical dimension of flat objects and volumes is also altered [15]. In such a situation, the perception of illusory objects that induce the incorrect estimation of size, depth, and so on in normal gravity can be changed.

Visual illusions are a powerful tool for studying the features of visual processing. They are used to study visual impairments in both altered states of the subject, caused, for example, by sensory deprivation [16] or physical exhaustion [17], and in various diseases, for example, in schizophrenia [18], autism spectrum disorders and developmental dyslexia [19]. It was shown that the motor responses to visual stimuli activate the dorsal pathway more than the verbal ones [4]. However, our results had shown the persistence of the Muller-Lyer illusion in the dorsal pathway. In this aspect, they contradict the original hypothesis proposed in [4]. However, they are in line with other works providing pieces of evidence of the existence of different illusions in the dorsal pathway [20, 21]. We propose that the change of the Muller-Lyer illusion strength observed in our experiments reflects the restructuring of visual processing during DI, namely, the shift of the balance of activation to the dorsal pathway. This proposal is supported by an observed in DI decrease of EEG activity of the brain’s left hemisphere that is more related to the ventral pathway processing [22]. The increase of contrast sensitivity in the low spatial frequency range on the third day of the DI and after the DI was registered in the same IM-21 group by the visocontrastometry [23]. This finding indicates the dorsal pathway's involvement in the adaptation to the DI conditions process and supports our hypothesis.

The peculiarities of the illusory object evaluation by patients are associated with disorders in the dorsal pathway. It is assumed that patients with schizophrenia have a deficiency in the dorsal flow [18]. For example, in the study of the grip, the modified Ebbinghaus illusion's strength when it was estimated statically by the grip aperture did not differ from that in healthy subjects. The authors suggest that such a response activates the ventral pathway. In contrast, the strength of the modified Ebbinghaus illusion during grasping was higher than that of healthy subjects. The authors suggest that this type of response normally activates the dorsal pathway. Conversely, in schizophrenia, the strength of the illusion increases due to a decrease in dorsal flow activity. As in DI as in schizophrenia, there are differences in the work of the dorsal (activated by motor tasks), but not the ventral (activated by verbal response) flow of visual information processing. EEG data of cosmonauts when solving navigation problems also indicate functional reorganization of feedback in the dorsal, but not ventral pathway [24].

5 Conclusions

The Muller-Lyer and Ponzo visual illusions were studied during 5-day and 21-day DI in 4 groups of volunteers. It was shown that the DI influence was more substantial on the motor than to the verbal response. The strength of the Muller-Lyer illusion was modulated to the greatest extent. It tended to decrease during DI while high-frequency myostimulation or axial loading suit restored the illusion's expected strength. One of the reasons for such a pattern of the results observed can be the hyperactivation of the dorsal pathway of visual processing.

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References

1. Grabherr, L., Mast, F.W.: Effects of microgravity on cognition: the case of mental imagery. J. Vestib. Res. **20**, 53–60 (2010). https://doi.org/10.3233/VES-2010-0364
2. McIntyre, J., Lipshits, M.: Central processes amplify and transform anisotropies of the visual System in a test of visual–haptic coordination. J. Neurosci. **28**, 1246–1261 (2008). https://doi.org/10.1523/JNEUROSCI.2066-07.2008
3. Aglioti, S., DeSouza, J.F., Goodale, M.A.: Size-contrast illusions deceive the eye but not the hand. Curr. Biol. **5**, 679–685 (1995). https://doi.org/10.1016/s0960-9822(95)00133-3
4. Milner, D., Goodale, M.: Visual brain in action. Oxford University Press, Oxford (1995)
5. Villard, E., Garcia-Moreno, F.T., Peter, N., Clement, G.: Gravity affects the preferred vertical and horizontal in visual perception of orientation. NeuroReport **16**, 1395–1398 (2005). https://doi.org/10.1097/01.wnr.0000174060.34274.3e
6. Wollseiffen, P., Vogt, T., Abeln, V., Struder, H.K., Stuckenschneider, T., Sanders, M., Claassen, J.A.H.R., Askew, C.D., Carnahan, H., Schneider, S.: Neuro-cognitive performance is enhanced during short periods of microgravity. Physiol. Behav. **155**, 9–16 (2016). https://doi.org/10.1016/j.physbeh.2015.11.036

7. Kornilova, L.N., Naumov, I.A., Glukhikh, D.O.: Visual-manual tracking during a five-day dry immersion. Aviacosm. Ecol. Med. **45**, 8–12 (2011)
8. Meigal, A., Gerasimova-Meigal, L.I., Saenko, I.V., Subbotina, N.S., Tret’yakova, O.G., Chernikova, L.A.: The effect of “dry” immersion as microgravity analogue on neurological symtoms in Parkinsonism. Aviacosm. Ecol. Med. **51**, 53–59 (2017)
9. Lyakhovetskii, V.A., Karpinskaya, V., Sosnina, I.S., Tomilovskaya, E.S.: Effect of 21-day dry immersion on the sensorimotor evaluation of the Ponzo and Muller-Lyer illusions during grasping Aviacosm. Ecol. Med. **54**, 58–63 (2020). https://doi.org/10.21687/0233-528X-2020-54-4-58-63
10. Lyakhovetskii, V.A., Sosnina, I.S., Zelenskiy, K.A., Karpinskaya, V., Tomilovskaya, E.S.: Influence of the course of the high frequency electric myostimulation during 5-day dry immersion on the perception of illusions. J. Evol. Biochem. Physiol. **56**, 638 (2020). https://doi.org/10.31857/S0044452920070888. (in Russian)
11. Sosnina, I.S., Lyakhovetskii, V.A., Zelenskiy, K.A., Karpinskaya, V.Ju., Tomilovskaya, E.S.: Effect of 21-day dry immersion on the Ponzo and Muller-Lyer illusions. Hum. Physiol, in Print (2021).
12. Sosnina, I.S., Lyakhovetskii, V.A., Zelenskiy, K.A., Karpinskaya, V.Ju., Tomilovskaya, E.S.: Influence of 5-day «dry» immersion on strength of Ponzo and Muller-Lyer illusion. Zh. vyssh. nervnoy deyatel’nosti im. I.P. Pavlova **68**, 313–326 (2018). https://doi.org/10.7868/S004446771803005X
13. Coren, S., Girgus, J.S., Erlichman, H., Hakstian, A.R.: An empirical taxonomy of visual illusions. Percept. Psychophys. **20**, 129–137 (1976). https://doi.org/10.3758/BF03199444
14. Kornilova, L.N., Tarasov, I.K.: Orientational illusions in weightlessness. Aviacosm. Ecol. Med. **30**, 17–23 (1996)
15. Clément, G.: Using your head: cognition and sensorimotor functions in microgravity. Gravitational Space Biol. **20**, 65–78 (2007)
16. Suzuki, Y., Fujii, K., Onizawa, T.: Studies on sensory deprivation: IV. Part 6. Effects of sensory deprivation upon perceptual function. Tohoku Psychologica Folia **24**, 24–29 (1965).
17. Lybrand, W.A., Andrews, T.G., Ross, S.: Systemic fatigue and perceptual organization. Am. J. Psychol. **67**, 704–707 (1954). https://doi.org/10.2307/1418495
18. King, D.J., Hodgekins, J., Chouinard, P.A., Chouinard, V.A., Sperandio, I.: A review of abnormalities in the perception of visual illusions in schizophrenia. Psychon. Bull. Rev. **24**, 734–751 (2017). https://doi.org/10.3758/s13423-016-1168-5
19. Gori, S., Molteni, M., Facoetti, A.: Visual illusions: an interesting tool to investigate developmental dyslexia and autism spectrum disorder. Front. Hum. Neurosci. **10**, 175 (2016). https://doi.org/10.3389/fnhum.2016.00175
20. Bruno, N., Franz, W.H.: When is grasping affected by the Muller-Lyer illusion? a quantitative review. Neuropsychologia. **47**, 1421–1433 (2009). https://doi.org/10.1016/j.neuropsychologia.2008.10.031
21. Uccelli, S., Pisu, V., Riggio, L., Bruno, N.: The Uznadze illusion reveals similar effects of relative size on perception and action. Exp. Brain. Res. **237**, 953–965 (2019). https://doi.org/10.1007/s00221-019-05480-8
22. Kirenskaya, A.V., Novototskii-Vlasov, V.Yu., Tomilovskaya, E.S., Kozlovskaya, I.B.: The effects of simulated microgravity on characteristics of slow presaccadic potentials. Hum. Physiol. **32**, 131–139 (2006). https://doi.org/10.1134/S0362119706020022
23. Shoshina, I.I., Sosnina, I.S., Zelenskiy, K.A., Karpinskaya, V., Lyakhovetskii, V.A., Pronin, S.V.: The contrast sensitivity of the visual system in “dry” immersion conditions. Biophysics **65**, 681–685 (2020). https://doi.org/10.1134/S0006350920040211
24. Cheron, G., Leroy, A., Palmero-Soler, E., De Saedeleer, C., Bengoetxea, A., Cebolla, A.-M., Vidal, M., Dan, B., Berthoz, A., McIntyre, J.: Gravity influences top-down signals in visual processing. PLoS ONE **9**(1), e82371 (2014). https://doi.org/10.1371/journal.pone.0082371

Auditory Mechanisms for Analyzing Conspecific Movement

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Abstract. The aim of this functional magnetic resonance imaging (fMRI) study was to identify human brain multimodal areas that are sensitive to auditory information about the direction of footsteps. Our analysis with multimodal area mask revealed that the direction of conspecific sound movement could be decoded from fMRI response patterns in the both hemispheres (Supra-marginal Gyrus, posterior division Right and Left; Middle Temporal Gyrus, posterior division - hMT/V5). Sounds of approaching footsteps and foot-steps-in-place also caused various activation of the cortex, which was found only in the right hemisphere (Supramarginal Gyrus, posterior division; Angular Gyrus and Precuneus). These findings provide further evidence for the multimodal areas that are the key in supporting motion perception.

Keywords: Spatial hearing · Motion perception · Conspecific signal perception · FMRI · Multimodal integration

1 Introduction

In the problem of motion perception, the processing of conspecific motion sounds is a particular interest. These sounds accompany a person throughout life. It is likely that their analysis is performed by the same brain regions as any other movement. In the study [1], the sounds of human footsteps were assigned to emotionally neutral sound sources, and no differences were found in the emotional perception of approaching and retreating footsteps. Thus, there is no clear reason to suggest that the sounds of footsteps will trigger the activity of cortex areas involved in the processing of emotions.

Studies of auditory motion analysis performed in recent years indicate that parallel mechanisms of motion and static spatial processing co-exist within the auditory dorsal pathway [2–4]. However, the direction-selective processing of auditory information is the subject of a long discussion and the areas that perform it are still the subject of search. A possible candidate for such selectivity may be multimodal areas at the junction of the temporal, parietal, and occipital cortex, which are anatomically extension of the dorsal

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auditory pathway. The aim of our work was to identify differences in the activation of multimodal cortex regions in response to the sounds of approaching and retreating human footsteps also steps-in-place.

2 Methods

The fMRI study was conducted with the participation of 22 healthy adult subjects (19–33 years old) with normal hearing. The experiment was approved by the ethics committee of the NRC Kurchatov Institute. Stereo recordings of approaching and retreating steps, as well as steps-in-place, were used as sound stimuli. The rhythm of steps was 133 per minute, the speed of movement when approaching and moving away was about 1.6 m/s. Sequences of 45 s each were formed from 6-s fragments of the audio recording of steps. The study was performed on a Magnetom Verio 3T MR imager (Siemens, Germany) using a 32-channel head coil. The subjects were instructed to passively listen to the sounds of footsteps presented in headphones with active noise reduction Optoacoustic. The paradigm of the experiment included the task of studying the activity of brain areas when three types of stimuli were presented four times in pseudo-random order (approximation, deletion, and in-place steps). Group maps were formed on the basis of the obtained individual maps of the subjects using the Gauss random field theory. When analyzing the activity of multimodal zones based on the AAL Atlas (automatic anatomy labeling), masks of multimodal zones were created, including MT/V5, Precuneus, Angular Gyrus, and Supramarginal Gyrus regions.

The contrast of interest was the difference between the approaching footstep condition and the step-in-place state condition, we called this contrast: “approaching footsteps - step-in-place footsteps”. And in case of the difference between the approaching footstep condition and the retreating footstep condition, we called this contrast correspondingly: “approaching footsteps - retreating footsteps”.

3 Results

Three cortical multimodal regions of right hemisphere were revealed when searching for areas involved in auditory movement processing ($P < 0.001$, corrected, Fig. 1 and Table 1). Comparison of activity for sound of approaching steps and steps in place revealed differences in the right hemisphere in the areas of the Angular Gyrus (50 –48 16, $t = 4.93$), the Supramarginal Gyrus (38 –6 38 $t = 3.85$) and in the Precuneus (8 –68 44, $t = 4.29$). Hence, activation patterns in these areas contained information about sound-source motion.

Our region-of-interest-based analysis identified also three cortical regions whose activation patterns contained directional information ($P < 0.001$, corrected, Fig. 2 and Table). According to the group analysis, when comparing activities to sounds of approaching and retreating human steps a difference was found in the left hemisphere in the Supramarginal Gyrus (–52 –48 10 $t = 4.68$), and in the right hemi-sphere – both in the Supramarginal Gyrus (64 –36 18 $t = 4.50$). Thus, similar volume and fairly symmetrical location of both activation areas were shown. Another activation area was revealed in the MT/V5 region of right hemisphere (64 –34 2 $t = 4.72$). Its size was significantly larger

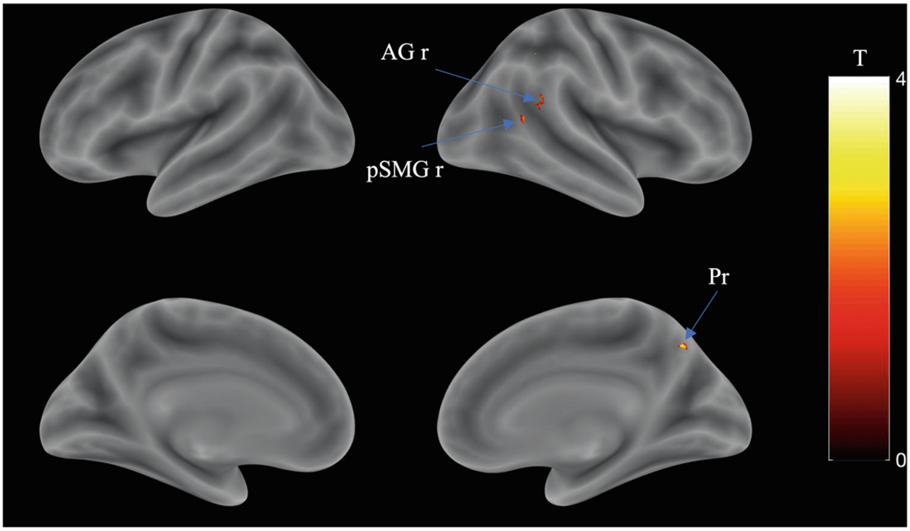

Fig. 1. Topography of the brain activation areas found as result group statistical analysis when contrasting approaching footsteps auditory perception to steps-in-place, displayed on flat cortex template. See Table for the detailed characteristics of these areas. AG: Angular Gyrus; Pr: Precuneus Cortex; pSMG: Supramarginal Gyrus, posterior division. R or L stands for right or left hemisphere. M-scores for all children.

Table 1. Table captions should be placed above the tables.

Side region	MNI coordinates				Cluster size
	x	y	z	t	
Approaching steps – steps-in-place contrast					
AG r (Angular Gyrus Right)	50	−48	16	4.93	22
Precuneous r (Precuneus Cortex)	8	−68	44	4.29	14
pSMG r (Supramarginal Gyrus, posterior division Right)	38	−46	38	3.85	4
Approaching steps - retreating steps contrast					
pMTG r (Middle Temporal Gyrus, posterior division Right)	64	– 34	2	4.72	40
pSMG l (Supramarginal Gyrus, posterior division Left)	– 52	– 48	10	4.68	8
pSMG r (Supramarginal Gyrus, posterior division Right)	64	– 36	18	4.50	9

than the other two cortex areas. Therefore, all three types of steps caused significantly different activation of multisensory zones specialized for spatial orientation.

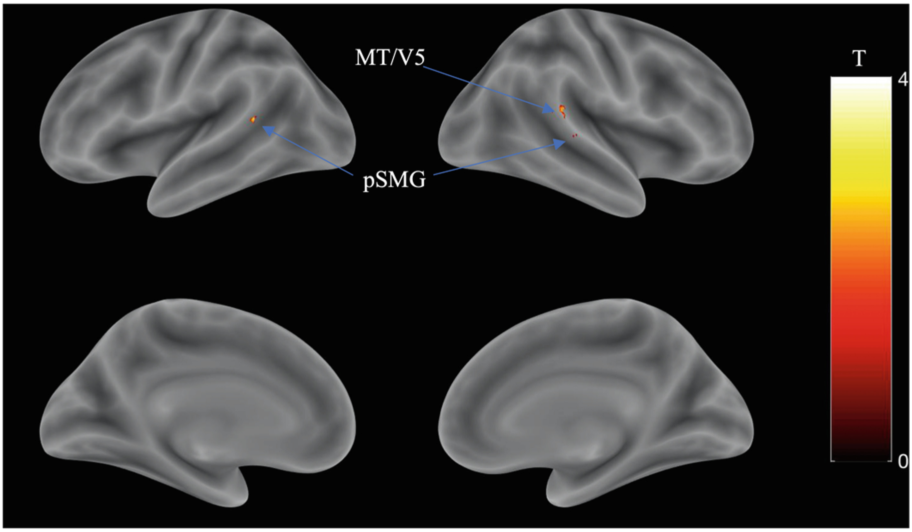

Fig. 2. Group statistical maps for approaching steps - withdrawing steps conditions

4 Discussion

Accordingly, our results conspecific motion sounds in human caused different activations when moving forward and moving in place. The differences were shown at multimodal areas in the right hemisphere. It is well known that fMRI has failed to show any significant motion-specific activity in primary auditory areas [5]. Along with that auditory motion-specific areas described in the study of the nonprimary auditory cortex of awake monkeys using fMRI have been found to extend on the inferior bank of the STG (equivalent of the superior bank of the temporal sulcus), in the vicinity of visual motion areas, and visual experiment in the study revealed also a small overlap between auditory and visual motion-selective areas in this region [2]. Therefore, the identification by us of cortex areas specific to the movement in Angular Gyrus, in the Supramarginal Gyrus and in the Precuneus do not appear to be unexpected.

It seems to be of importance that all the differences in activity were detected in the right hemisphere. The fact indicates the hemispheric lateralization of the auditory orientation function, which is widely dis-cussed according to neurophysiologic data [4, 6]. The fundamental asymmetry in auditory spatial processing between the left and right hemispheres is consistent with findings of specific sound lateralization deficits in patients with callosotomy, which also indicate a stronger reliance of the left hemisphere on the callosal transfer of auditory spatial information form the right hemisphere than vice versa [7]. Note that we have studied the movement along the radius, and not along the azimuth, as in all the works mentioned above. The similarity of the results may additionally indicate two essential moments: first, a single representation for different coordinates of space; and second, the role of binaural cues in distance performance. Their detailed consideration requires a further research.

In contrast to the hemispheric localization of movement, its direction processing (comparison approaching steps versus retreating steps) evoked bilateral differences in activity in the Supramarginal Gyrus and, additionally, in the right pMTG. Note that the sizes of the areas were almost equal, while differences in the right pMST placed near to MT/V5 were found on a significantly larger number of voxels. Bilateral symmetric and unilateral more volumetric activity differences with localization in a separate cortex area may indicate two different mechanisms for analyzing movement information.

5 Conclusion

The visual area V5 is known to be multimodal and is activated by tactile stimulation [8]. An increase in the activity of this area with the sounds of conspecific information about the approach compared to the removal can indicate a restructuring multimodal cortex processing, because in the near future information about contact with a moving object will appear in the peripersonal space.

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References

1. Tajadura-Jiménez, A., Väljamäe, A., Asutay, E., Västfjäll, D.: Embodied auditory perception: the emotional impact of approaching and receding sound sources. Emotion **10**(2), 216–229 (2010). https://doi.org/10.1037/a0018422
2. Poirier, C., Baumann, S., Dheerendra, P., Joly, O., Hunter, D., Balezeau, F.: Auditory motion-specific mechanisms in the primate brain. PLoS Biol. **15**(5), (2017). https://doi.org/10.1371/journal.pbio.2001379.
3. Chaplin, T., Rosa, M., Lui, L.: Auditory and visual motion processing and integration in the primate cerebral cortex. Front. Neural Circuits **12**(93) (2018). https://doi.org/10.3389/fncir.2018.00093.
4. Grzeschik, R., Böckmann-Barthel, M., Mühler, R., Verhey, J.L., Hoffmann, M.B.: Direction-specific adaptation of motion-onset auditory evoked potentials. Eur. J. Neurosci. **38**(4), 2557–2565 (2013). https://doi.org/10.1111/ejn.12264
5. Krumbholz, K., Schönwiesner, M., Ruebsamen, R., Zilles, K., Fink, G., Cramon, D.Y.: Hierarchical processing of sound location and motion in the human brainstem and planum temporale. Eur. J. Neurosci. **21**, 230–238 (2005). https://doi.org/10.1111/j.1460-9568.2004.03836.x
6. Shestopalova, L.B., Petropavlovskaia, E.A., Vaitulevich, S., Nikitin, N.I.: Hemispheric asymmetry of ERPs and MMNs evoked by slow, fast and abrupt auditory motion. Neuropsychologia **91**, 465–479 (2016)

7. Hausmann, M., Corballis, M., Fabri, M., Paggi, A., Lewald, J.: Sound lateralization in subjects with callosotomy, callosal agenesis, or hemispherectomy. Brain Res. Cogn. Brain Res. **25**, 537–546 (2005). https://doi.org/10.1016/j.cogbrainres.2005.08.008
8. Wacker, E., Spitzer, B., Lutzkendorf, R., Bernarding, J., Blankenburg, F.: Tactile motion and pattern processing assessed with high-field fMRI. PLoS ONE **6**(9) (2011). https://doi.org/10.1371/journal.pone.0024860.

Domains of Eye-Tracking Research

Probability of Visually Perceiving Emotional Expression During Saccade is Rising, not Being Suppressed

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Abstract. Subjects were required to perform a horizontal reactive saccade towards a laterally misplaced cross. A photoimage of a human face with a basic emotional expression was flashed either perisaccadically or intrasaccadically, with a step size of 2 frames. A stably rising facial expression identification rate during the course of a saccade spanning 10 dva is shown. No evidence of a saccadic suppression with this type of stimulus is found, at least not for all of them. Performance metrics for identificaiton rate are reported. Possible unintended procedural artifacts are discussed. Spatial frequency analysis is held. Evidence for continuous, uninterrupted perceptive process during rapid eye movements is shown. Comparison with classic papers of 1970's given. Interaction of luminance, spatial frequency, angular distance, chromaticity and angular size factors is suggested. It is shown that psychophysical (visual) features of the stimulus used are likely to be most predetermined for correct identification with given temporal (and functional) constraints. Shape of contour, spatial frequency distribution, skin texture and facial features, optimal angular size are yet to be determined, but evidence is shown that a special type of stimulus has to be developed and generated to control this issue.

Keywords: Saccadic suppression · Postsaccadic blanking · Face recognition · Eyetracking · Naturalistic validity

1 Introduction

Recent studies suggest there is a continuous perception process across saccade. Seminal papers theorized that rapid gaze shift triggers a special physiological mechanism which suppresses the vision, which is afterwards resumed and seamlessly appended. Saccadic suppression is what makes the visual environment seen as a stable world during gaze shifts. Breaking the environment continuity illusion, e.g. by means of target gap (see [1]) cancels the effect of suppression and makes even the brightest stimuli identified above chance. The hypothesis proposed by Bridgeman et al. [2] suggests 'tag assignment' takes place instead of compensation and/or visual map comparison. Only the presence of visual properties is stored, not positions.

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As shown by multiple evidence, higher relative luminance (*contrast ratio* of stimulus to background) actually provokes stronger suppression. Naturally, higher spatial frequencies require higher relative luminance for the same detection rate (see Fig. 4). It is of paramount importance to know while choosing image database for the experiment, if stimuli are equiluminant or not. If so, its intrasaccadic detection is, in fact, not subject for suppression (see evidence in [3]).

The study by Deubel et al. [1] (experiment 3) yields interesting results, none of which are obvious: the longer duration perisaccadical stimulus has, the lower identification rate is; whilst pure intrasaccadical ones are correctly identified almost 100% of the time. The disappearance itself (of the stimulus image) provokes visual analysis of the area in question (information not normally used postsaccadically), whilst continuous stimulus, and sometimes, absolutely steady (see Yarbus' experiments with absolutely stabilized retinal projections), actually, makes it sub-threshold.

Most modern research papers seek answers to practically valuable questions: whether a person can detect a flashing dot during saccade; how much will it be displaced visually; if, at all, motion properties of a saccade are affected [4]; how much is direction [5] of a moving target misinterpreted in perisaccadic interval. A study by Panouillères et al. investigates interaction of gaze speed and perturbing stimuli during saccades [4]. The study showed that adaptive saccade shortening is easier reached (16% gain), while adaptive saccade lengthening is rare (7% gain). Remarkably, a concave spherical screen was used for stimulus exposition, yielding a perfect setup for controlling angular speed and gaze focusing issues, not possible with flat screen setups. It was also shown that perturbing stimulus is ignored when presented during peak speed phase, but affects the saccade offset position when presented during deceleration phase. In our present study, we could not control the stimulus onset time so precisely (trial-to-trial fluctuation due to uncontrollable vertical scan phase of CRT display), and could not bin the results due to insufficient data (because of very high data corruption rate). Overall, the study shows that saccadic suppression phenomena 'does not prevent brief visual information delivered in-flight from being processed'. Authors also report that kinematics of saccades changed (peak velocity decreased) compared to control condition.

But few studies, to our knowledge, utilize natural stimulus so far [6]. Therefore, we address a different class of problem: whether a person can identify a *human face* flashed during saccade for as low as 13.9 ms. And if so, if she can correctly identify which basic emotion the face depicts. It is worth noting that naturalistic stimuli may or may not contain chromatic variations specific to this kind of visual objects (e.g. human faces), depending on image databased used. This class of stimuli is not subject to saccadic suppression and may, in fact, even yield enhanced detection rates during saccades due to spatial frequencies which are better suited for perception when eye speeds are high (e.g. V-shaped contrast sensitivity curve in [3]).

2 Methods

Participants. 32 subjects with normal or corrected-to-normal vision participated (22 female); age 18.6 ± 0.7; students, naïve as to goals and procedure of experiment; 35% of trials were rendered as valid (1164 out of 3354 in total); each subject completed 45 ±

28 valid trials. Participants were dark-adapted, lasting from briefing to initial eyetracker calibration. All procedures complied with Declaration of Helsinki and were approved by the local ethics committee of Moscow State University of Psychology and Education, project id №28-5-20, date 22 June, 2020.

Apparatus. SMI HiSpeed tower-mounted eyetracker operating at 1250 Hz monocularly, with a chin-rest. Color-calibrated (gamma-linearized) ViewSonic G90fB CRT display operating at 144 Hz refresh rate; 800 × 600 px. Head distance was 57 cm. A custom software was controlling the stimulus machine, and the onset/offset moments were recorded in real-time and synchronized with the data feed by means of phototransistor attached to a white strobe nearby the screen edge (which was covered by a piece of cardboard).

Stimulus. 7 color photos of an adult male face expressing basic emotions plus a neutral one (maximum luminance $= 79.8$ cd/m^2). Stimulus size 3.47×5.93 dva. Log relative luminance of stimuli $= 0.24$ (75% gray background, 46.3 cd/m^2). Maximum spatial frequency 2 cpd. Luminance of foveal glare was not measured [7].

We have conducted spatial frequency analysis of images by means of filtering with Gabor patches of varying size and orientation. Because the eye made a horizontal saccade towards the target cross, we assess spatial frequency in horizontal direction, and as such, we applied vertically oriented Gabor patches (Fig. 1) to images. As can be seen, stimuli have 7 spatial cycles in horizontal direction (this is the maximum Gabor filtering possible before gratings become distorted, unclear and/or blend together, which can be checked by thresholding the result (not shown here, for clarity)). Therefore, we conclude that images presented during the experiment have approximately 2 cycles per degree spatial frequency (while they still also have 0.57 and 0.86 cpd, the dominant one is 2, considering the size of fovèa relative to stimulus size). Notice, this calculation assumes the visual subsystem samples image along gaze trajectory uniformly, i.e. each retina ‘pixel’ has equal weight as all others, which is a coarse approximation of actual physiological sampling process.

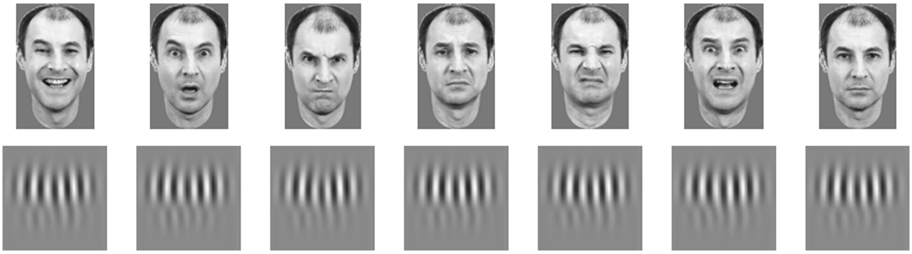

Fig. 1. Luminance bitmaps of stimulus images, together with their corresponding vertically oriented Gabor features; order same as in Table 1; angular size of stimulus was 3.5×5.9 dva, yielding approximately 2 cpd dominant spatial frequency, as can be deducted from the bottom row

It is worth noting that all stimuli photos were smoothly stripped of background (notice the neck was trimmed with a half-circular mask (Fig. 1), and therefore, no unnaturally sharp edges (except the ones stimulus contained itself) were present anywhere within visual field (plus rectangular borders of the screen and the cardboard attached (see Apparatus). Rest of the room was completely dark, relative to screen illumination. Hence, Ss could not show rising visual thresholds during saccades due to structured background (see [8] for reference). Nevertheless, fixation cross ($54'$ of visual angle in both directions) was in fact a sharp border containing several straight lines (black; $5'26''$ of visual angle thick) and right angles. As shown in previously cited paper, suppression dominates 'smearing' in presence of sharp edges (moving contours). If sharp contours are absent (0.375–3.0 cpd spatial frequency; see [6]), no suppression should occur.

Procedure. A short briefing was held prior to calibrating the eyetracker. Subjects were given directions to shift their gaze from the fixation cross to the target cross as soon as they notice the displacement. They were told that either before or after that, they are going to see a human face, and their objective is to assess the perceived localization and emotional expression. No explanations were given for the goal of experiment except that it records the eye movements and studies visual perception. Reactive saccades were required to be performed by Ss. Position judgement and expression identification were held under no time pressure.

It has been stated that temporal gap of the test object forces visual subsystem to reassess target position during saccade. 'The gap should begin (or end) during the period of saccadic suppression for the enhancement to appear', [1, p. 994]. The study was not designed with temporal gap in mind. However, two sources of stimulus blanking actually exist. First, the vertical scan phase of computer display was neither controlled nor accounted for. The vertical scan is itself continuous, and exposes frames progressively. Considering we have not implemented VSync capability (meaning some of trials consisted of bottom part of the stimuli presented, then a time gap of approximately 5.41 ms, then the top part of the stimuli finally gets drawn), unintended intrasaccadic blanking took place. Importantly, detection rate may in fact be conditioned by this apparatus artifact. Second target gap, introduced in close proximity to saccade offset (see Fig. 2), was caused by unanticipated consequence of the programmed procedure itself. The displaced fixation cross (the one acting as an initial saccade target for naïve Ss) also vanished when the test stimulus vanished, effectively meaning that postsaccadic target blanking was in place (see [1]). Target blanking facilitates perception of stimulus displacement, and, probably, identification, too.

Analysis. Eyetracking data was first analysed to remove any trials where the eye-movement did not match the required trial protocol: the stimulus duration must fall within 1–2 display frames range; stimulus onset time relative to saccade must fall within $-200 - +200$ ms. Mean gaze properties: saccade latency 143 ± 30 ms; duration 48 ± 13 ms; amplitude 9.9 ± 2.1 dva; average velocity 196 ± 57 dva/s; peak velocity 407 ± 116 dva/s. *R 4.0* was used for statistical analysis and plotting [9].

3 Results

Our study shows the identification rate of human face expression is actually rising during saccade, not being suppressed. Average F1 score = 0.77 (Table 1), which coincides with

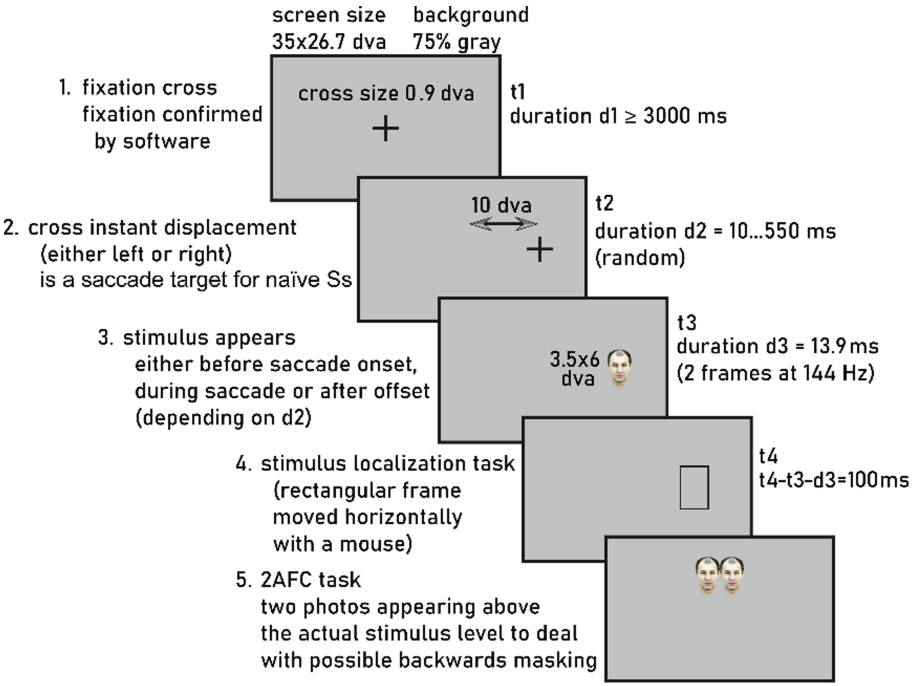

Fig. 2. Time flow of experiment setup; naturalistic stimulus is presented for 2 display frames (including decay time) during perisaccadic proximity range (−200 − + 200 ms from saccade onset). Notice the target cross is covered with the test image, then stimulus vanishes and there is no target cross anymore; meaning there is a target gap going on before the saccade ends (the screen is blanked with gray background between stages 3 and 4 until t4 begins)

our previous study of pure intrasaccadic identification of same stimulus [10]; statistical test for accuracy (Table 2) chi sq. = 348, $p < 0.001$; statistical test for detection rate and stimulus expression, chi sq. = 36.52; $p < 0.001$. No significant connection was found for expression of alternative choice.

Table 1. Performance metrics grouped by stimulus expression

	Joy	Surprise	Anger	Sadness	Disgust	Fear	Neutral
Precision	.81	.79	.78	.74	.73	.77	.79
Recall	.84	.81	.80	.68	.74	.87	.67
F1	.83	.80	.79	.71	.73	.82	.72

It can be seen (Fig. 3) that detection rate begins constantly rising after saccade onset, and reaches its maximum at the moment of saccade offset (a line with gray ribbon). Notice, according to the procedure, the stimulus always appeared 10° displaced, either left or right. That means angular distance to the image was smaller for trials with stimulus

Table 2. Cross-table of identification rate for stimulus/alternative expression of 2AFC task

Stimulus expression								
Alternative	Joy	Surprise	Anger	Sadness	Disgust	Fear	Neutral	Mean
Joy		.85	.92	.83	.77	.71	.80	.82
Surprise	.86		.90	.61	.76	.86	.71	.80
Anger	.85	.79		.71	.82	.96	.72	.80
Sadness	.84	.85	.79		.62	.82	.54	.75
Disgust	.96	.91	.65	.63		.94	.50	.75
Fear	.73	.70	.82	.59	.64		.76	.71
Neutral	.80	.76	.74	.69	.78	.96		.79
Mean	.84	.81	.80	.68	.74	.87	.67	.77

beginning after the saccade onset (study not balanced with naturalistic conditions in mind).

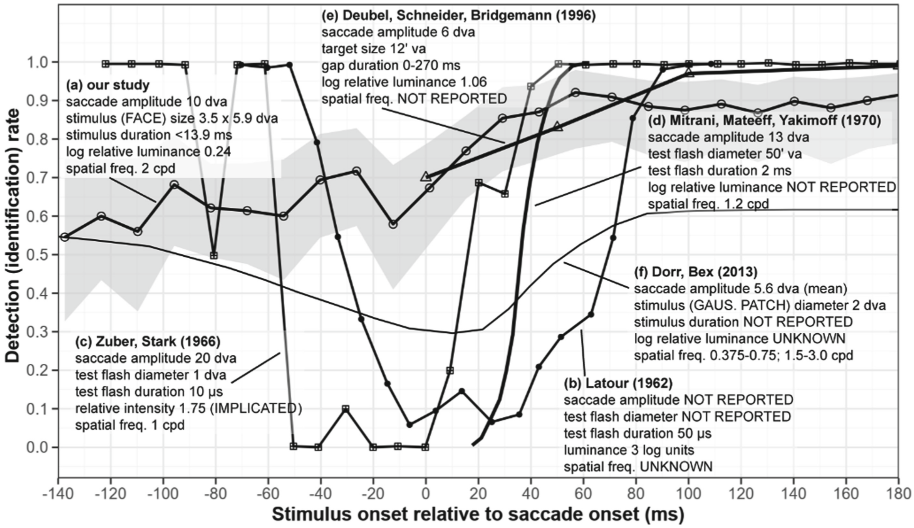

Fig. 3. Detection rates of various stimuli types during saccade (and in temporal proximity), with previous studies' data reproduced and superimposed (scale unified; units converted), with saccade and stimulus physical properties annotated; **a** present study; conducted with naturalistic stimulus; notice most cited papers conducted detection tasks, while ours is a 2AFC identification task; gray ribbon demarcates 95% confidence interval; **b** Latour [12]; detection task conducted with test flashes of sub-threshold duration (50 microseconds); stimulus size and spatial frequency cannot be derived from reported data; suppression reported as long as −40 ms before saccade onset; **c** Zuber, Stark [11]; detection task; notice duration is in microseconds; **d** Mitrani et al. [13]; seminal paper which stated the importance of spatial frequency and structured background for detection tasks; **e** Deubel et al. [1]; direction identification task; **f** Dorr, Bex [6]; direction identification task

Detection rate as a function of luminance is plotted in Fig. 4. As can be seen, lower relative luminance guarantees higher detection rate (which is clearly stated in [15]), given low enough spatial frequency. Our data suggests we have the least luminous stimulus so far, which may or may not be typical for this kind of stimulus. For [15], inverted values given for sake of comparison, because the original paper used additive flashes (always less luminous than the background) superimposed on screen, yielding negative relative luminance values. Notice the steepness of the detection curve, indicative of lowest suppression with these physical conditions. Lederberg utilised a specific type of test flash, spanning 4 by 10° of visual angle and flashed additively on semitransparent screen from behind. Therefore, those results are barely comparable, although the curves are very similar.

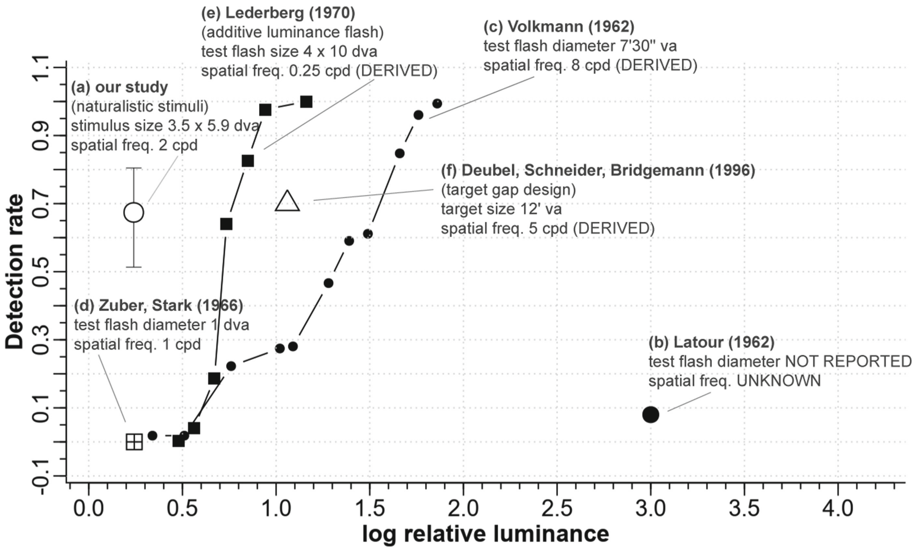

Fig. 4. Detection rate at saccade onset as a function of log relative luminance (We *assume* the authors of cited papers calculated log relative luminance as $\log_{10}(A/B)$, given A is luminance of stimulus, B is luminance of background.); data from different studies reproduced; **a** present study; 0–13.9 ms time range (43 trials) relative to saccade onset taken; whiskers denote 95% confidence interval; **b** Latour [12]; **c** Volkmann [7]; data for left and right-sided saccades pooled; Ss averaged; **d** Zuber, Stark [11]; authors report the test flash intensity (not luminance, therefore plotting for reference only) together with retinal smear causes saccadic suppression with given conditions; **e** Lederberg [15]; **f** Deubel et al. [1]; precise dual Purkinje eyetracking was utilized together with target gap design, yielding a detection rate similar to our identification rate

4 Discussion

It can be seen that positive detection rates during saccades were registered at least 3 times before (Fig. 4). Moreover, Mitrani et al. have shown that ‘*saccadic suppression* is not saccadic but merely depends on the motion of the entire visual pattern on the retina' [8, p. 1161]. Nevertheless, some researchers state that the retinal 'smear' is not important, because suppression actually begins earlier, 80 ms before saccade [16]. Deubel et al. [1] conducted their study with brighter, but much smaller targets (not photos) and fundamentally different type of stimulus (gap durations for target displacement, amplitude 0.33 dva, direction varies). This study yields a curve most similar to ours. Rising intrasaccadic detection rate can be seen. It shows that impairing stimulus during saccade, in fact, facilitates visual perception by breaking the continuity illusion and provoking immediate reassessment of visual environment. Authors report display phosphorus decay time of 10 ms; mean saccade duration = 25 ms.

Notice, test flash studies were conducted with very short durations, orders of magnitude lower than ours. Also, notice how the curve from Mitrani et al. [13] coincides with the rightmost part of Zuber's curve (with a shift of some 20 ms), which is not noticeable until plotting scales unified. In their successive paper [8], they have shown that the brighter the test flash is, the more suppressed it gets. Moreover, suppression rises even more (x3.7) after introducing structured background, while the least luminous (−0.48 log relative units) flashes are not suppressed even with highly structured background, which coincides with results by Volkmann [7]. See also [14], conducted in absolute darkness. As may be hypothesized, detection rate above chance reported in [1] became possible thanks to high relative luminance (1.06 log units in experiment 1; 1.56 log units in subsequent series). Lederberg [15] openly states that medium-luminous flashes are suppressed the most, and the dim ones cannot have color identified correctly, while the brightest ones are both correctly identified by color and detected by presence. Chromatic properties of naturalistic stimulus have been studied by Richards [16] and Lederberg [15]. Both report that blue hues are suppressed the least, and require lower relative luminance for the same detection rates, while green hues require the highest luminance. Evidently, these facts indicate that perisaccadic suppression is a product of contrast-velocity interaction, rather than a mere effect of spatial properties of stimulus and/or saccade velocity.

Also, target blanking during saccade is a special experiment design which facilitates the visual perception, breaking the possible suppressive process. Volkmann's curve intersects with Deubel's stimulus by luminance value, but it has somewhat smaller test flash diameter. Notice that increasing relative luminance finally makes detection possible (see Fig. 4). A study by Zuber and Stark [11] was conducted with test flashes of known size and luminance. Long-size saccades were provoked. Suppression begins −80 ms before saccade onset, and reaches maximum −40 — −20 ms before saccade onset (Fig. 3). Luminance not reported. Notice, relative intensity reported for microsaccades, not saccades. A steep suppression curve was carried out. But steady rising also occurs nearby saccade onset. Also notice that Zuber's test flash luminance is close to ours (*relative intensity* reported as 1.75), but smaller size and/or spatial frequency do not allow for reliable detection rates at the moment of saccade onset. A very similar curve was acquired by Latour [12] several years earlier, but stimulus size and spatial frequency were not reported. Classic saccadic suppression study by Latour utilised very bright test flashes. It is possible that merely the luminance of the test flash in Latour's study determined absolute suppression nearby saccade onset. Compare this to Lederberg's paper with significantly less luminous stimulus.

A remarkable gaze-contingent study was held by Dorr and Bex [6], with naturalistic video-stimulus. Test object was a patch of different spatial frequency smoothly injected into the source signal (Gaussian pyramid decomposition) and offset by 2 dva from the current gaze position in variable direction. Whole system latency is reported <26 ms. Authors report perisaccadic compression of space for cases when saccade direction matches test object displacement direction. The detection rate curve of this study differs by gain significantly, and the stimulus is barely comparable to others.

5 Conclusion

We have demonstrated that with given conditions, photos of human face depicting emotions are not subject to saccadic suppression, not before, not during saccade, and that angular distance to the stimulus is still a determinant for visual identification, even during saccade with top speeds already reached. Different emotional expressions yielded varying detection rates. Exact psychophysical properties determining the detection levels are yet to be investigated, but it can be stated that overall spatial frequency (holistic) of all faces is nearly same. Therefore, a detailed spectral analysis should be conducted, accounting for angular sizes, luminance spectra and visible spatial frequencies during eye movements (saccadic trajectory-centered approach). Moreover, gaze velocity should be considered separately for each trial. One of the most important variables to control in further investigations is the baseline level. In presented study we assumed that baseline for all stimuli is equal and uniform. i.e. equals 0.5. It may possibly turn out that joy, for instance, actually has a higher baseline level, and neutral expression has a baseline significantly lower than 0.5.

Although stimulus onset and offset times had been proof-checked by a custom phototransistor sensor, there is still a small possibility that CRT display phosphorus is being responsible for the phenomena reported. If the decay time is higher or equal to 2 more frames, then it means in some trials participants actually had possibility to perceive the stimulus face while being fixating their gaze already. To address this issue, in the upcoming study we are going to utilize an LCD display with 240 Hz refresh rate and 1 ms gray-to-gray refresh time, with a VSync capability enabled and multiple-diode sensor attached to both top and bottom screen edges (to address the issue of lower part of the stimulus being presented before the upper one, with a blanking gap inside). We are also going to conduct a whole new run with geometric face-alike shapes instead of actual photos, in order to investigate if naturalistic properties of the image play a crucial part for visually perceiving the face.

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References

1. Deubel, H., Schneider, W.X., Bridgeman, B.: Postsaccadic target blanking prevents saccadic suppression of image displacement. Vis. Res. **36**, 985–996 (1996). https://doi.org/10.1016/0042-6989(95)00203-0
2. Bridgeman, B., van der Heijden, A.H.C., Velichkovsky, B.: A theory of visual stability across saccadic eye movements. Behav. Brain Sci. **17**, 247–292 (1994). https://doi.org/10.1017/s0140525x00034361
3. Burr, D.C., Morrone, M.C., Ross, J.: Selective suppression of the magnocellular visual pathway during saccadic eye movements. Nature **371**(6497), 511–513 (1994). https://doi.org/10.1038/371511a0
4. Panouillères, M.T.N., Gaveau, V., Debatisse, J., et al.: Oculomotor adaptation elicited by intra-saccadic visual stimulation: Time-course of efficient visual target perturbation. Front. Hum. Neurosci. **10**, 91 (2016). https://doi.org/10.3389/fnhum.2016.00091
5. Szinte, M., Carrasco, M., Cavanagh, P., Rolfs, M.: Attentional trade-offs maintain the tracking of moving objects across saccades. J. Neurophys. **113**(7), 2220–2231 (2015). https://doi.org/10.1152/jn.00966.2014
6. Dorr, M., Bex, P.J.: Peri-saccadic natural vision. J. Neurosci. **33**(3), 1211–1217 (2013). https://doi.org/10.1523/JNEUROSCI.4344-12.2013
7. Volkmann, F.C.: Vision during voluntary saccadic eye movements. J. Opt. Soc. Am. **52**(5), 571–578 (1962). https://doi.org/10.1364/JOSA.52.000571
8. Mitrani, L., Mateeff, S., Yakimoff, N.: Is saccadic suppression really saccadic? Vis. Res. **11**(10), 1157–1161 (1971). https://doi.org/10.1016/0042-6989(71)90119-2
9. R Core Team: R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria (2020). https://www.R-project.org/
10. Barabanschikov, V.A., Zherdev, I.Y.: Visual perception of facial emotional expressions during saccades. Behav. Sciences. **9**(12), 131–143 (2019). https://doi.org/10.3390/bs9120131
11. Zuber, B.L., Stark, L.: Saccadic suppression: Elevation of visual threshold associated with saccadic eye movements. Exp. Neurol. **16**(1), 65–79 (1966). https://doi.org/10.1016/0014-4886(66)90087-2
12. Latour, P.L.: Visual threshold during eye movements. Vis. Res. **2**(3), 261–262 (1962)
13. Mitrani, L., Mateeff, S., Yakimoff, N.: Temporal and spatial characteristics of visual suppression during voluntary saccadic eye movement. Vis. Res. **10**, 417–422 (1970). https://doi.org/10.1016/0042-6989(70)90122-7
14. Krauskopf, J., Graf, V., Gaarder, K.: Lack of inhibition during involuntary saccades. Am. J. Psychol. **79**(1), 73–81 (1966). https://doi.org/10.2307/1420709
15. Lederberg, V.: Color recognition during voluntary saccades. J. Opt. Soc. Am. **60**(6), 835–842 (1970). https://doi.org/10.1364/JOSA.60.000835
16. Richards, W.: Visual suppression during passive eye movement. J. Opt. Soc. Am. **58**(8), 1159–1160 (1968). https://doi.org/10.1364/JOSA.58.001159

Eye Movements and EEG During Reading as Markers of Interest

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Abstract. Interest as a positive emotion is closely related to the ability to process new information and/or better consolidate the information which has already been perceived, increase in attention to what one is interested in, and indicators of processing, learning, and motivation [1]. Here we aim to identify oculomotor and electroencephalographic correlates, which could serve as predictors of a locus of interest based on the travel locations perception. Thirty-eight (38) healthy volunteers took part in the study (people aged between 18 and 27, the average age was 22 ± 0.4 years, 14 males and 24 females). Eye movements were registered simultaneously with monopolar EEG using a standard 10/20 system (O1, O2, T3, T4, P3, P4, C3, C4, F3, F4). Participants were watching at the slides describing eight different places of interest in Russia. After seeing each slide, volunteers said whether the information shown to them arouse their interest or not. As each text was shown twice in different forms, statistical analysis, taking into account changes in answers about interest, was conducted. The fixation during the first demonstration was longer in case of interest, and doubts in answers also made the fixation duration longer. Saccade amplitudes showed the opposite trend. The electrical activity in the theta-band in frontal channels increased, compared to resting state in case of interest; however, if a participant said that he or she was not interested, there was an even larger increase. Therefore, eye movement and EEG characteristics reflect a subjective assessment of interest when reading information.

Keywords: Eye tracking · Eye movements · EEG · Reading · Theta-band · Interest

1 Introduction

Interest as a positive emotion is connected with the ability to perceive new information and/or to better understand the already consolidated information. It is related to an increased attention to a subject, information processing, comprehension of the subject, learning, and motivation [1]. Interest may be described as an emotion [2, 3], emotional schema [2, 4], or affect [1]. Interest is considered to take into account aesthetics [5], marketing [6], and education [1]. In all these spheres text construes an important part

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of informational content as part of advertising, website content, educational books, literature in various spheres, etc.

Eye movements performed during reading reflect cognitive processes related to comprehending and interpreting a text [7] understanding lexis [8] and syntax [9]. Readability of a text, word frequency, and features related to age and professional competence influence eye movements [7, 8, 10]. The above-mentioned works allow suggesting that eye movements may reflect interest considered as an emotional schema [2] during reading. Additional information (such as pictographs or images) may also modulate eye movement parameters [11]. Emotional state and preferences regarding subjects were extensively studied using EEG, however, there are only a few works including interest [12]. No multimodal research of interest during reading using EEG and eye-tracking has been conducted.

The purpose of the work is to investigate eye movements and EEG parameters related to the subjective assessment of interest during reading.

2 Methods

Thirty-eight healthy volunteers aged between 18 and 27 (14 male and 24 female with an average age of 22 ± 0.4 years) took part in the study. The whole procedure was performed meeting the bioethical standards of the Declaration of Helsinki. Eye movements were registered using a patented system [13]. The monopolar EEG was registered simultaneously, based on the 10/20 system (O1, O2, T3, T4, P3, P4, C3, C4, F3, F4) (Mitsar-EEG 202 system, Russia), against a “summed ears” electrode and “summed ground” electrodes, in Cz and Pz positions.

Descriptions of tours were chosen as a material for research since they arise positive emotions. Overall, eight texts describing places of interest in Russia that were provisionally divided into two groups were used. One way of presenting included only the text with a title, while the other contained additional information in the form of pictographs (16 stimuli, four blocks with four stimuli each). The research scheme is given in Fig. 1.

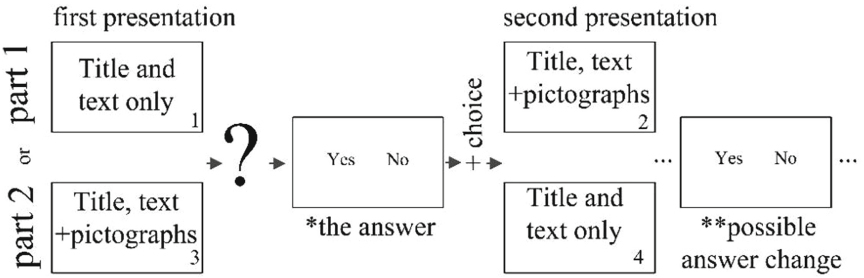

Fig. 1. A research scheme for blocks (1–4) of stimuli, with four texts in each block presented in a row. When the answers marked with * and ** on the scheme were correlated, four groups of answers were compiled taking into account doubts: “interesting”, “interesting” (replaced by “uninteresting”), “uninteresting”, “uninteresting” (replaced by “interesting”).

Calibration was carried out before every four texts, and after that, it was suggested that a person select a version which he or she liked best. In the next four presentations, the same texts were used, but the form of organizing information was different. The order of presenting groups of materials, forms of presentation, texts within a block, location of possible answers, and location of pictographs changed in a pseudorandom manner. After each presentation, there appeared the following question on a screen: “Are you interested in the presented information?”.

Texts were standardized in terms of readability and number of symbols using Flesch-Kincaid, SMOG, and ARI tests adapted for the Russian language. After recording the background EEG for a minute with eyes opened, the respondents were instructed to look through the material and to answer a question about their interest afterward. There were no explicit instructions about looking through the whole material or reading the text thoroughly or for specific information.

Statistical data processing was carried out using RStudio and Matlab, with the unpaired Wilcoxon rank-sum test (W) and the Kruskal-Wallis test (H). To analyze EEG indicators, the first 15 s, starting from the presentation of stimuli with artifacts deleted in advance, were used. Relative changes in indicators were calculated compared to a resting state with open eyes (control) using the following formula:

$$x = \frac{x_n}{x_0} \times 100\% \tag{1}$$

where x_n is the indicator value in the current presentation, and x_0 is the background value for a particular volunteer.

Eye movement indicators were analyzed taking into account the specific areas of interest – a text, a heading, and five pictographs with additional information. Blinking and fixations outside the studied part of the visual field were excluded from the analysis. The eye movement parameters were analyzed during the entire period of reading a text fragment. Fixation durations shorter than 80 and longer than 800 ms were filtered to exclude fixations not related to reading [7]. Besides, high-amplitude saccades when a person moved the gaze at a new line were excluded.

3 Results

A positive answer to the question about interest in content during the first presentation is characterized by an increase in the spectral power in the theta-band of EEG (4–8 Hz) compared to the control but is less intensive compared to a negative answer. During reading the material, such an increase with a positive answer amounted to 12% in F3, 13% in F4, and 30% in T3. In case of a negative answer, it totaled 34%, 30%, and 40% for F3, F4 and T3 channels respectively ($WF3 = 13041$, $WF4 = 13022$, $WT3 = 12718$, $n = 303$, $p < 0.05$). At the same time, it is quite impossible to predict a subsequent change in the answer based on the spectral power in the theta rhythm range during the first demonstration, only the F4 lead showed differences at the level of $p < 0.05$ ($H = 8.14$, $df = 3$, $n = 303$) considering situations of doubt. After repeated reading, the theta-band spectral power reflects the change in the answer both to a positive and negative one, which had already occurred ($n = 608$, $df = 3$) in the following channels:

F4 ($H = 17.0$, $p < 0.001$), T3 ($H = 11.0$, $p < 0.05$), T4 ($H = 13.0$, $p < 0.01$), P3 ($H = 8.0$, $p < 0.05$) and O1 ($H = 11.0$, $p < 0.05$). Therefore, spectral power during the first reading reflects the fact of interest, while during the repeated reading it shows a change of content assessment to a subject of interest. A change in the theta-band spectral power during the first reading in percent compared to control is given in Fig. 2.

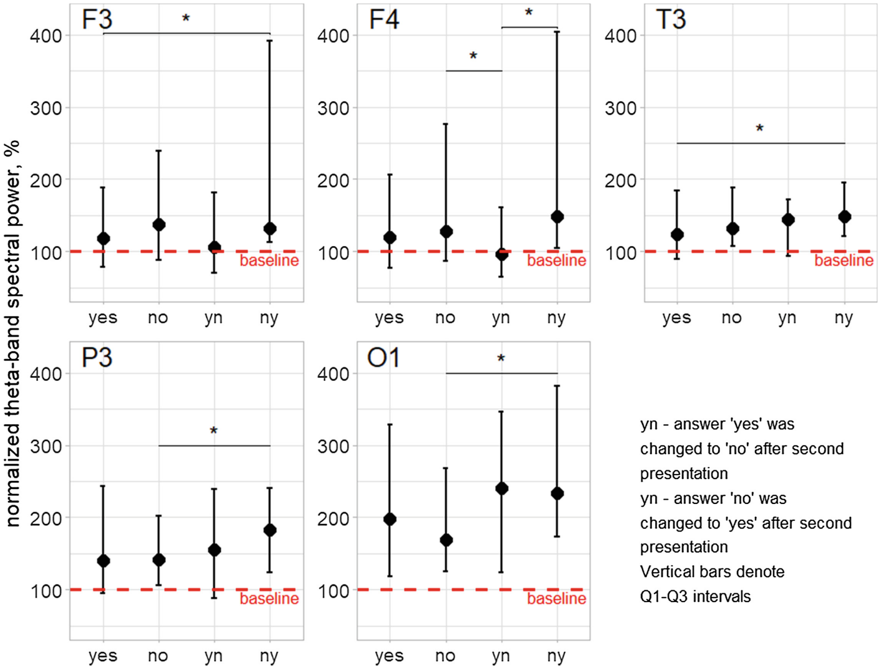

Fig. 2. Intragroup indicators of the theta-band spectral power during the first reading, standardized with resting state with open eyes. *- $p < 0,05$, unpaired Wilcoxon rank-sum test.

Results of analyzing fixation duration within the range of 80–800 ms are given in Fig. 3. The eye movement parameters during reading also reflect a subjective level of interest. The fixation duration was lower in the case of positive assessment. The median fixation duration in the case of a positive answer during the first presentation was 215 ms as compared to 219 ms in the case of a negative answer ($W = 90637850$, $n = 26910$, $p < 0.01$). The fixation duration during the first text demonstration allows predicting a subsequent change in the answer to positive or negative ones ($H = 113.42$, $n = 26910$, $df = 3$, $p < 0.0001$).

During the second presentation, fixation duration was 204 and 208 ms respectively ($W = 29319536$, $n = 15239$, $p < 0.05$), and the difference taking into account a change in the answer which already happened was also significant ($H = 62.26$, $n = 15239$, $df = 3$, $p < 0.0001$). Only two groups of doubt have not significant differences (Fig. 3, on the left). Density (on the right) in a given fixation duration range shows that the density for the answer “interesting” and the answer “uninteresting” with its future change is slightly higher in the median area compared to opposite answers. This describes a quicker scanning type of reading in case of the already existing or potential interest.

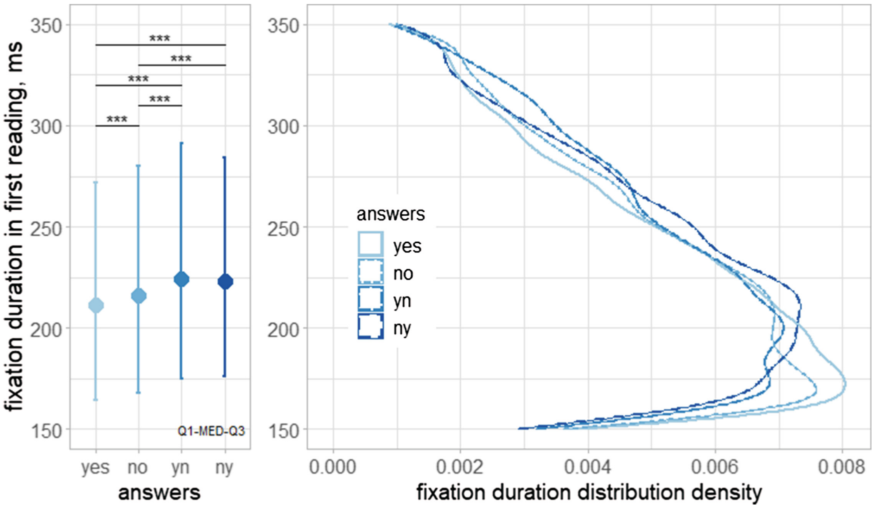

Fig. 3. Intragroup change of fixation duration in case of reading during the first presentation and answering questions about the level of interest. ***- $p < 0.001$, unpaired Wilcoxon rank-sum test. The right figure shows fixation duration distribution density in the range 80–800.

A decrease in saccade amplitudes in case of reading during the first ($W = 70552925$, $n = 24164$, $p < 0.05$) and second ($W = 21684005$, $n = 13412$, $p < 0.05$) presentations compared to the control is not solely related to the answer to the question about interest. It also allows predicting a future change in the answer after the first presentation ($H = 16.73$, $n = 24164$, $df = 3$, $p < 0.0001$), and occurred change after the second one ($H = 13.73$, $n = 13412$, $df = 3$, $p < 0.01$). The values of all four answer options have differences. However, the indicator value and interest have a non-linear relationship, like in the case of fixation duration but with opposite tendency.

4 Discussion

The activity in the EEG theta-band indicated the brain mechanisms that ensure a top-down control and activate large areas in the brain [14]. Theta activity changes are commonly identified when cognitive tasks are performed; it shows integrative information processing [14]. The increasing activity in the theta-band in frontal leads is related to positive emotions, including interest [12], as well as to the fact that the stimulus is new [14]. Theta activity changes in frontal and temporal channels may be related to the working memory involving and connected with the capability of predicting words in a context [15], in occipital leads shows the connection between visual attention and preference [16]. When the text complexity increases, fixation duration and the number of regressive saccades grow as well, whereas the saccade amplitude decreases, which was shown in early works related to reading [10]. Theta activity reflects associative and integrative processes that could characterize the influence of interest as factor. Therefore, interest is characterized by a quicker and a smother reading process, revealed by in the fixation durations distribution density figure (Fig. 3). At the same time, some doubt in answering triggers a considerable increase in fixation duration, which could be related to difficulties in analyzing and assessing the content.

5 Conclusion

Eye movement parameters and EEG in the theta-band reflect a subjective assessment of interest during reading the information. Moreover, some indicators may act as predictors of changes in answers after the second presentation. Therefore, eye movement parameters and EEG can be used for determining a person's emotional and cognitive state as well as for assessing various types of content. The obtained data could be useful in devising high-quality teaching materials or creating efficient advertisements.

References

1. Reeve, J., Lee, W., Won, S.: Interest as emotion, as affect, and as schema. In: Interest in Mathematics and Science Learning, pp. 79–92. American Educational Research Association (2015). https://doi.org/10.3102/978-0-935302-42-4_5
2. Izard, C.E.: Basic emotions, natural kinds, emotion schemas, and a new paradigm. Perspect. Psychol. Sci. **2**, 260–280 (2007). https://doi.org/10.1111/j.1745-6916.2007.00044.x
3. Silvia, P.J.: Interest - the curious emotion. Curr. Dir. Psychol. Sci. **17**, 57–60 (2008). https://doi.org/10.1111/j.1467-8721.2008.00548.x
4. Hidi, S.E., Renninger, K.A.: Interest development and its relation to curiosity: needed neuroscientific research. Educ. Psychol. Rev. **31**, 833–852 (2019). https://doi.org/10.1007/s10648-019-09491-3
5. Graf, L.K.M., Landwehr, J.R.: Aesthetic pleasure versus aesthetic interest: the two routes to aesthetic liking. Front. Psychol. **8**, 1–5 (2017). https://doi.org/10.3389/fpsyg.2017.00015
6. Sung, B., Vanman, E., Hartley, N.: Interest, but not liking, drives consumer preference toward novelty. AMJ **27**, 242–248 (2019). https://doi.org/10.1016/j.ausmj.2019.06.003
7. Rayner, K.: Eye movements in reading and information processing: 20 years of research. Psychol. Bull. **124**, 372–422 (1998). https://doi.org/10.1037/0033-2909.124.3.372
8. Rayner, K., Reichle, E.D., Stroud, M.J., Williams, C.C., Pol-latsek, A.: The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. Psychol. Aging **21**, 448–465 (2006). https://doi.org/10.1037/0882-7974.21.3.448
9. Anisimov, V.N., Fedorova, O.V., Latanov, A.V.: Eye movement parameters in reading sentences with syntactic ambiguities. Hum. Physiol. **40**, 521–531 (2014). https://doi.org/10.7868/s0131164614040031(inRussian)
10. Raney, G.E., Rayner, K.: Word frequency effects and eye movements during two readings of a text. Can. J. Exp. Psychol. **49**, 151–173 (2007). https://doi.org/10.1037/1196-1961.49.2.151
11. Lindner, M.A., Eitel, A., Strobel, B., Köller, O.: Identifying processes underlying the multimedia effect in testing: an eye-movement analysis. Learn. Instr. **47**, 91–102 (2017). https://doi.org/10.1016/j.learninstruc.2016.10.007

12. Hu, X., Yu, J., Song, M., Yu, C., Wang, F., Sun, P., Wang, D., Zhang, D.: EEG correlates of ten positive emotions. Front. Hum. Neurosci. **26**, 11–26 (2017). https://doi.org/10.3389/fnhum.2017.00026
13. Anisimov, V.N., Latanov, A.V.: Method and system for recording eye movement. RU № 2 696 042 C2 (2017). (in Russian)
14. Cavanagh, J.F., Frank, M.J.: Frontal theta as a mechanism for cognitive control. Trends Cogn. Sci. **18**, 414–421 (2014). https://doi.org/10.1016/j.tics.2014.04.012
15. Kawasaki, M., Yamaguchi, Y.: Effects of subjective preference of colors on attention-related occipital theta oscillations. Neuroimage **59**, 808–814 (2012). https://doi.org/10.1016/j.neuroimage.2011.07.042
16. Rommers, J., Dickson, D.S., Norton, J.J.S., Wlotko, E.W., Federmeier, K.D.: Alpha and theta band dynamics related to sentential constraint and word expectancy. Lang. Cogn. Neurosci. **32**, 576–589 (2017). https://doi.org/10.1080/23273798.2016.1183799

Age Features of Eye Movements in Adolescents When Reading from Various Electronic Devices

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Abstract. This paper presents the study of age-related changes in oculomotor activity of 11–15-year-old adolescents when they are reading texts from various electronic devices. The study involved 74 teenagers; 38 of them were reading from a display made using liquid crystal technology, 36 participants were reading from a display made using e-ink technology. In adolescence, the formation of skills that support the reading process does not stop. Heterochrony in the development of mental operations and brain structures that support them is reflected in age-related changes in the speed of information perception and information processing. The study of the perception of texts from various electronic devices that have different page-turning mechanisms, which influences the total reading time, did not reveal clear differences between reading from a liquid crystal display and an e-ink display within the short-term use.

Keywords: Adolescent · Reading · Eye movements · Displays

1 Introduction

The study of changes in oculomotor activity at different stages of the development of reading skills is one of the priorities of Developmental psychophysiology [1]. Reading is a complex cognitive process, the most important components of which are the visual perception of the text and the extraction of information with the help of oculomotor function. Eye movements during reading are seen as a reflection of complex multi-stage cognitive processes associated, firstly, with the perception of the text, its lexical and semantic analysis, embedding information in the general context and its processing, and, secondly, with the development of a general reading strategy and specific patterns. Studies have shown that the parametric characteristics of eye movements are determined by both the muscular activity of the oculomotor apparatus and cognitive processes. They are associated with the influence of various morphological and visual properties of the text and visual information processing [2, 3].

The relevance of the study of oculomotor activity comes from the current widespread tendency to introduce various electronic devices for displaying textual information into everyday and educational activities at rather early stages of cognitive development. Currently, during puberty, which is characterized by desynchronization between the links of the regulatory system and a decrease in cortical control, emotional instability,

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reduced adaptive capabilities and work capacity [4], adolescents actively use different electronic devices for reading and leisure, preferring them to books. Over the past decade, there has been a constant increase in the time that teenagers spend on various interactions with digital texts (text messaging, Internet search, emailing, chatting and reading posts on social networks and websites). However, there are differences between reading from paper and reading from an electronic device [5]. Experience in using devices and the visual characteristics of the text (font size, line length, etc.) have the biggest influence [6].

In the literature, it is noted that changes in the functional state of adolescents when working on a computer is characterized, primarily by visual fatigue, which is noted by 40 to 92% of users [7] and a decrease in mental performance [8]. There was determined a direct correlation between the frequency of ophthalmic problems and age and work experience of a computer user. Objective (blinks per second) and subjective (visual fatigue scale) studies have shown that reading from an LCD display causes higher visual fatigue in comparison with an e-ink reader and a paper book [9]. There was also revealed heterochronous growth of negative changes in the functional state after using a computer, which is associated with an increase in the general adaptive capabilities of the organism with age [7]. The identification of mechanisms and strategies of oculomotor activity during reading from various devices may serve as a predictor of possible difficulties in perceiving educational texts.

2 Methods

2.1 Ethics Statement

The research methods were approved by the ethical committee of the Institute of Developmental Physiology of the Russian Academy of Education.

2.2 Participants

The study involved 74 teenagers. 38 participants read from the LCD display, 36 - from e-ink display. The primary analysis of the data showed that it is necessary to take into account not only the age of the adolescent, but also the school grade. The subjects were divided into the following groups:

Age groups: 11–12 years - 13 people (average age 12.1); 12–13 years - 19 people (average age 13.2); 13–14 years - 21 people (average age 14.0); 14–15 years - 21 people (average age 15.3);

School grade groups: 6th grade - 18 people (average age 12.3); 7th grade – 22 people (average age 13.4); 8th grade - 14 people (average age 14.3); 9th grade - 20 people (average age 15.3).

2.3 Design and Apparatus

The main research paradigm is based on the registration of oculomotor activity in adolescents (11–15 y.o.) reading a deliberately complex text from electronic devices equipped with displays of one of two types: liquid crystal display and electronic ink display.

The study is based on binocular registration of eye movements using video registration with the elements of the photoelectric method using Eyegaze Analyzing System by «Interactive Minds». The shooting speed with variable polling is 120 Hz (~1 shot in 8 ms). Accuracy is 0.45° (3.8 mm on the screen). The preset minimum duration fixation is 50 ms. The apparatus was equipped with a specially made additional holder for "devices". The layout of the text was always the same when reading from different devices. Two "devices" were used. The display of the first was made using liquid crystal technology (TFT) - Digma; the second display used electronic ink technology (e-ink) - PocketBook. Specifications: contrast PocketBook - 7.4:1, Digma - 300:1, brightness (cd/m^2) PocketBook - 37.9, Digma - 250–300.

2.4 Stimuli

The stimulus material was a complex philosophical text. The average number of words in a sentence was 15; the average number of letters in a word was 6; the Flash-Kincaid coefficient was 27.94; the percentage of abstract words was 7.5. The text was split into 6 slides, 10 lines each. Monospaced font of a comfortable size (4 mm) was used for reading from a distance of 50 cm. All visual characteristics of texts were similar for different devices.

3 Results and Discussion

The analysis of oculomotor activity showed that the formation of skills that ensure reading processes does not stop in adolescence. There was found a significant correlation between the age of participants and such temporal and integrative indicators of eye movements recorded during reading as duration of all types of fixations ($r = -0.229$ - -0.260, $p < 0.05$), percentage of regressions ($r = -0.340$, $p < 0.05$), reading speed ($r = 0.275$, $p < 0.05$), and reading time ($r = -0.275$, $p < 0.05$). For example, the average duration of progressive saccades was 244 ms in the 6th grade, and it decreased to 228 ms in 9th grade. The decrease in the duration of other types of fixation also ranged from 10 to 30 ms. The number of regressive fixations decreased with age from 9.5% to 7%. The average time taken to read also decreased from 106.4–110.0 to 86.7–87.1 s - within 20–23 s. The reading speed increased on average by 3 characters per second from 11.2 to 13.8 from 6th grade to 9th grade. At the same time, the average amplitude of saccades practically did not change with age. The amplitude of progressive saccades was 2.7 angular degrees (in our experiment 2.7° makes 6 symbols), regressive saccades - 1.8–2.3 angular degrees. These data partially confirm the studies of age-related variability of oculomotor activity and such changes as a decrease in the total reading time, fixation duration, a decrease in the number of fixations, re-fixations and regressions, an increase in the amplitude of saccades and the chance of missing short and function words in the text [10, 11].

The graph of changes in the durations of various types of fixations has a parabolic shape. The mean of fixation duration at the age of 13–14 is higher than at the age of 11–12 and 14–15. It was shown [3] that the graph of changes in the reactivity of the motivational system also has its peak, which reaches its maximum by the age of

12–13. At the beginning of puberty, the reactivity of motivation exceeds the gradually increasing reactivity of regulatory structures (areas of the frontal cortex), which reduces their influence on the organization of activity. Thus, it is the motivational and emotional factor at this that has the greatest influence on the reading process. Motivation had a significant impact [12] on the differences in reading skills: the ability to generalize, the speed of reading the whole text and individual words.

There was noted a rather sharp increase in the degree of text internal representation in the 9th grade (14–15 y.o.). In comparison with the early adolescence, the score of text comprehension and reproduction rises two times from 6–7% to 12–13%. It should be noted that grouping older adolescents by school grade gives bigger increase (by 1.5%) in the level of text comprehension than grouping by age. In our opinion, this is due to the fact that natural science subjects (chemistry, biology) are being introduced from the 8th–9th grades. Knowledge in the exact sciences becomes more complicated, which develops and consolidates new abstract concepts in the adolescent and makes it possible to better perceive the stimulus material presented in the experimental study. With age, the speed and efficiency of lexical access, the integration of pragmatic knowledge and the level of discourse representation increase, and therefore directly affect the change in the duration of progressive fixations [13].

The efficiency of cognitive performance during adolescence is supported or mediated by emotionally attractive factors. Consequently, the parameters of oculomotor activity during reading, as a complex polymodulated cognitive activity, are influenced by emotional “coloring” of the text, emotional involvement of an adolescent in this type of educational work [14]. At this age, it is important to take into account the motivational involvement in the reading process, which becomes not only a way of gaining new knowledge, but also a way of teenager socialization. If this method is not very important for the group of adolescents they belong to, there is an increase in the tension of this cognitive skill.

The analysis of the parameters of oculomotor activity using various electronic devices showed that the main differences in the mechanics of reading are mainly in the different time spent on turning the text “pages”. When using a PocketBook, the total time is 11–15 s (2.2–3.0 s per page), while when using swiping (sliding the finger across the screen) when reading from Digma is 4–6 s (around 1.0 s per page). The influence of the factor “Electronic device” on the time of page turning in different age groups was the following: 11–12 y.o. - $F(1, 11) = 17.83$, $p = 0.001429$; 12–13 y.o. - $F(1, 17) = 49.65$, $p = 0.000002$; 13–14 y.o. - $F(1, 19) = 17.30$, $p = 0.000532$; 14–15 y.o. - $F(1, 19) = 28.82$, $p = 0.000035$. Similar effect was noted in different school grades. Analysis of variance revealed that the factors “Age group” and “School grade group” have a different degree of influence on the temporal indicators of eye movements. So, the influence of the factor “Age group” on the duration of progressive fixations when reading from Digma (TFT) was $F(3, 34) = 3.55$, $p = 0.0245$, when reading from Pocket (e-ink) the influence was tendentious - $F(3, 32) = 2.83$, $p = 0.0542$; on the average duration of all fixations when reading with Digma - $F(3, 34) = 3.81$, $p = 0.0186$, when reading from Pocket - $F(3, 32) = 3.16$, $p = 0.0381$; on the duration of setting fixations when reading with Digma - $F(3, 34) = 3.27$, $p = 0.033$, when reading from Pocket - $F(3, 32) = 2.97$, $p = 0.0464$. The influence of the factor “School grade” on the duration of progressive fixations was noted only when using factor analysis without dividing students into groups according to the devices they used; the effect on the average duration of all fixations when reading with Digma was F(3, 34) = 3.31, p = 0.0317, when reading from Pocket - F(3, 32) = 3.15, p = 0.0382; on the duration of setting fixations when reading from Digma - F(3, 34) = 3.29, p = 0.0322, when reading from Pocket - F(3, 32) = 4.02, p = 0.0155. The research data and correlation analysis indicate that when reading from Pocket (e-ink), the significance of influence of age factors on oculomotor activity decreases, i.e. reading from a low-contrast display had a negative effect on the skill. It should be noted that assessing the influence of the school grade on the degree of text understanding made it possible to reveal significant differences ($p < 0.05$) in this indicator between the adolescents of the 6th and the 9th grades.

The reading time when using a display with e-ink technology is on average 17–18% longer than when using a LCD display. It should be noted that the greatest difference in reading time when using various devices was registered in older adolescence (26%) and in younger adolescence (18–24%). This partially agrees with the data of Nielsen [15], who found that reading from an e-ink reader was 10.7% slower, and from an electronic tablet - 6.2% slower than when reading a classic paper book. Contrast has a marked effect on visual perception. Low-contrast leads to decreased efficiency of perception and oculomotor activity within 10–20% [16].

Some studies did not find difference in the increase of visual fatigue during prolonged reading from various devices [17]. However, the study [6] of eye movements in reading from three different devices at adolescents revealed difficulties in reading from devices with e-ink display: it is shown a relative increase of reversible and progressive saccades. Reading from an e-ink display causes a number of physiological changes in adolescents, indicating a higher physiological cost of its use in comparison with the paper. The analysis of the dynamics of the number of errors showed that the effect of eye fatigue and an increase in the number of saccadic movements began after reading more than 3–4 thousand characters from a LCD display. In our study, the number of characters with spaces was only 1300, so the opposite tendency was noted, when the number of saccades was higher when reading texts from the e-ink display. Apparently, the number of saccades grows as the total reading time increases.

The analysis of the ratio of different fixation types to their total number showed that average percentage of progressive fixations is ranges from 63% to 65%, average percentage of regressive fixations is ranges from 7% to 10%. There was established direct relationship between the proportion of regressions and the duration of progressive and regressive fixations, as well as with the total number of fixations. A high amount of correlations was showed between the durations of regressive and setting fixations when reading from a low-contrast display (e-ink), but when reading from a LCD display a high amount of correlations was showed between the durations of progressive and line fixations. This observation suggests that reading from a low-contrast display causes not only a greater number of clearly traced regressions as a result of both oculomotor reading errors and lexical word recognition errors, but also makes the participants look at each word longer, which is reflected in a slight increase of the duration of fixations.

4 Conclusion

In adolescence, the development of skills supporting the reading process does not stop. However, at the same time, the graph of changes in the speed of perception and processing of textual information on the age scale has a parabolic shape, i.e. from 6th to 7th–8th grades the indicators of oculomotor activity deteriorate, and then there is a sharp improvement. Apparently, this could be explained by the heterochrony of the development of cognitive processes and the brain structures supporting them. Along with the different time of the formation of cognitive functions, their manifestation in educational activity is largely influenced by the emotional and motivational processes, characteristic of puberty. It is possible that the decreased interest in reading is associated with changes in the motivational aspect and explains the decrease in reading skills. Differences in temporal indicators of oculomotor activity in different groups of adolescents (by school grade and age) indicate a greater influence of the learning experience on the reading process. The use of various electronic devices when reading complex texts made it possible to determine the influence of display type and the type of text presentation (the way pages are turned). Reading from a display with electronic ink technology (e-ink), which has a low image contrast, showed that the parameters of eye movements have inferior characteristics compared to reading from a liquid crystal display. However, it is important to take into account the short study period, during which the negative consequences of reading from a display with its own luminosity might not have occurred.

References

1. Bezrukikh, M.M., Ivanov, V.V.: Eye movement activity during reading of students in lower grades with different degrees of reading skills. Foreign Lang. Teach. **46**(1), 9–18 (2019)
2. Calvo, M.G., Meseguer, E.: Eye movements and processing stages in reading: relative contribution of visual, lexical, and contextual factors. Span. J. Psychol. **5**(1), 66–77 (2002). https://doi.org/10.1017/S1138741600005849
3. White, S.J., Liversedge, S.P.: Linguistic and nonlinguistic influences on the eyes' landing positions during reading. Q. J. Exp. Psychol. **59**(4), 760–782 (2006). https://doi.org/10.1080/02724980543000024
4. Gorev, A.S., Machinskaya, R.I., Farber, D.A.: Influence of arbitrary relaxation on the brain functional state and effectiveness of cognitive activity in boys at different stages of adolescence. New Res. **2**(55), 5–20 (2018)
5. Siegenthaler, E., Wurtz, P., Groner, R.: Improving the usability of E-Book readers. J. Usabil. Stud. **6**(1), 25–38 (2010)
6. Kuchma, V.R., Teksheva, L.M., Vyatleva, O.A., Kurganskiy, A.M.: Features of the perception of information from an electronic device for reading (reader). Probl. Sch. Univ. Med. Health **1**, 39–46 (2012)
7. Baranov, A.A., Kuchma, V.R., Teksheva, L.M.: Reading, computer and health. Curr. Pediatrics. **7**(1), 21–25 (2008)
8. Hasanova, N.N., Trokhimchuk, L.F., Filimonova, T.A.: Students organism functional state assessment in conditions of work on a computer. Adyghe State Univ. Bull. Ser. 4 Nat.-Math. Tech. Sci. **1**, 69–75 (2012)
9. Benedetto, S., Drai-Zerbib, V., Pedrotti, M., Tissier, G., Baccino, T.: E-readers and visual fatigue (2019). https://doi.org/10.1371/journal.pone.0083676

10. Blythe, H.I., Liversedge, S.P., Joseph, H.S.S.L., White, S.J., Rayner, K.: The uptake of visual information during fixations in reading in children and adults. Vis. Res. **49**, 1583–1591 (2009). https://doi.org/10.1016/j.visres.2009.03.015
11. Häikiö, T., Bertram, R., Hyönä, J., Niemi, P.: Development of the letter identity span in reading: evidence from the eye movement moving window paradigm. J. Exp. Child Psychol. **102**, 167–181 (2009). https://doi.org/10.1016/j.jecp.2008.04.002
12. McGeown, P.S., Duncan, L.G., Griffiths, Y., Stothard, S.E.: Exploring the relationship between adolescents' reading skills, reading motivation and reading habits. Read. Writ. **28**, 545–569 (2015). https://doi.org/10.1007/s11145-014-9537-9
13. Huestegge, L., Radach, R., Corbic, D., Huestegge, S.M.: Oculomotor and linguistic determinants of reading development: a longitudinal study. Vis. Res. **49**, 2948–2959 (2009). https://doi.org/10.1016/j.visres.2009.09.012
14. Somerville, L., Hare, T., Casey, B.: Fronto-striatal maturation predicts cognitive control failure to appetitive cues in adolescents. J. Cogn. Neurosci. **23**(9), 2123–2134 (2011). https://doi.org/10.1162/jocn.2010.21572
15. Nielsen, J.: iPad and Kindle reading speeds (Jakob Nielsen's Alertbox) (2010). https://www.nngroup.com/articles/ipad-and-kindle-reading-speeds
16. Sears, A., Jacko, J.A.: Human-Computer Interaction Fundamentals. CRC Press, Boca Raton (2009). https://doi.org/10.1201/9781410615862
17. Siegenthaler, E., Bochud, Y., Bergamin, P., Wurtz, P.: Reading on LCD versus e-Ink displays: effects on fatigue and visual strain. Ophthalmic Physiol. Opt. **32**(5), 367–374 (2012). https://doi.org/10.1111/j.1475-1313.2012.00928.x

Dependence of Eye Movement Parameters During Sight-Reading on Pianist's Skill and Complexity of Musical Notation

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Abstract. We investigated dependence of eye movement parameters on musical notation complexity and performance quality. 29 students of piano classes of Tchaikovsky Moscow State Conservatory and The Gnesins Russian Academy of Music were enrolled in the study. The participants were asked to sight-read three two-staves fragments of classical music works of different levels of complexity. Pianists were divided into two groups based on total score for all three fragments – medium score (MS) group and high score (HS) group. We assessed the the eye-hand span (EHS), the duration of gaze fixations (FD), number of fixations (NF), percentage of refixations after regressive saccades (RFP) and fixations on hands percentage (FHP). The value of EHS parameter significantly decreased as the background of increasing complexity of the musical fragment for FD the opposite pattern was observed. For other parameters, these dynamics were not revealed. Simple and complex musical fragments in the MS group lead to significantly more fixations than HS group. In this case, the NF parameter turned out to be a predictor of a well-developed sight-reading skill. The PRF values were significantly larger in a simple musical fragment. For a MS group the proportion of refixes is significantly higher in a simple piece of music. Thus, the PRF parameter turned out to be sensitive to the level of a sight-reading skill when the task is relatively simple. The FHP parameter in general was significantly higher for the HS group than for MS group.

Keyword: Eye movements · Sight-reading · Music

1 Introduction

Musical performance is the result of one of the most complex functional integrations that people can perform. Studying sight-reading is a particularly promising experimental approach to examine cognitive processes. During sight-reading it is necessary to process a huge amount of incoming visual information combined with producing a complex sequence of actions as the output. This requires a highly structured coding, as well as execution processes characterized by anticipation and going beyond the low-level processes of controlling eye movements when reading a text. The skill of sight-reading

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is formed over the years, but even among the highly qualified musicians not everyone can reach mastery in it.

It is well-established, that both when reading a verbal text aloud [1] and when sight-reading with simultaneous performance [2–5], the eye moves ahead of the reproduced place. Therefore, eye-hand span (EHS) was introduced to estimate the span between reading the notation characters and playing them. EHS was previously shown to be influenced by the complexity and structure of the music itself [6, 7]. The effect of skill on EHS was also demonstrated: experienced musicians have a higher EHS value compared to less experienced ones [3, 4, 8]. Thus, EHS depends on both the experimental conditions (the nature of the stimulus material) and the skill of the musician.

In this paper the process of sight-reading is considered as a viable model of a complex visual-motor task. The processes of perceiving visual information are reflected in the parameters of eye movements and depend on a number of factors, for example, on the complexity of the text [9]; and the result of sight-reading is the quality of musical reproduction of the text. Notably, the skill of sight-reading includes not only the visual-motor task of reproducing written notes, but also an important musical component of performance – phrasing and intonation of the text or, as musicians also say, “meaningful” performance. Therefore, this paper examines the correlation between the eye movement parameters and both the complexity of the musical text as well as the quality of the performance.

2 Methods

2.1 Ethics Statement

The research methods were approved by the ethical committees of the Biological facility of Lomonosov Moscow State University.

2.2 Participants

The participant group consisted of 29 students (19 men and 10 women) of Tchaikovsky Moscow State Conservatory and Gnesins Russian Academy of Music at the age of 18–25 specializing in piano (22.3 ± 1.8, M ± SD) with an experience of playing the piano varying from 12 to 20 years (15.6 ± 2.1) participated in the study.

2.3 Equipment

A Yamaha P-45 digital piano was used for the performance. The performance was recorded in the MIDI data format synchronously with the recording of eye movements using the Arringtone eye tracker (Arringtone Research Inc., USA, Scene Camera Eye Tracking System option, frequency 30 Hz) without rigid head fixation. Using the original method of recording and subsequent processing of the recorded signals, the coordinates of the gaze were determined taking into account the movement of the head relative to the notes.

2.4 Data Processing and Analysis

The musical quality of reading was evaluated by a professional teacher-musician according to a traditional 5-point scale (5 – excellent, 4 – good, 3 – satisfactory, 2 – bad). Based on the sum of points for the performance of three musical fragments, the pianists were divided into groups with low scores (8–11 points, MS – medium score) and high scores (12–15 points, HS -high score). We analyzed the fixation durations (FD), which were filtered out in the range of 90–600 MS, since the FD of this range is associated with physiologically significant visual processes during reading [9]. The number of fixations (NF) in each bar of a musical fragment was normalized by the number of notation characters. The proportion of refixes after regressive saccades (PRF) was calculated as the ratio of their number to the total number of fixations when reading each music piece. Percentage of hand fixations (FHP) was calculated as the ratio of their number to the total number of fixations when reading each musical piece. The last parameter was introduced in the analysis as when sight-reading, a musician performs a visual-motor task and periodically performs saccades on the hands to correct the position of the hands relative to the keyboard. Presumably, this parameter may also be sensitive to the level of skill development and the complexity of the musical text. In the scientific literature, no studies assessing hand fixation while sight-reading have been found, although this parameter is of particular interest for analysis. We also analyzed the EHS, which was estimated as the number of musical symbols between the current position of the eye on the text and the position of the notes currently being played on the keyboard. The EHS was calculated based on MIDI data and the eye position recorded by the eye tracker.

Data sets were tested for compliance with the normal distribution (Shapiro-Wilk test). For paired comparisons Student's t-tests and Mann-Whitney (MW) U-test were used depending on the data distribution. The effect of various factors on the parameters under scrutiny was evaluated by the ANOVA analysis of variance and Kruskal-Wallis (KW) test depending on the distribution of values. For paired multiple comparisons, the Bonferroni correction and Dunn's test were used.

3 Results

EHS significantly depended on the "musical fragment" factor ($F(2,3139) = 33.22$, $p < 0.0001$), as well as on the "group" factor ($F(1,3489) = 25.22$, $p < 0.0001$) (Fig. 1). FD significantly depended on the "musical fragment" factor ($F(2.3462) = 72.82$, $p < 0.0001$) (Fig. 1), but there was no significant effect of the "group" factor ($F(1.3463) = 0.01$, $p = 0.92$). NF significantly depended on the "musical fragment" factor ($F(2,3149) = 15.01$, $p < 0.0001$) and the "group" factor ($F(1,3519) = 40.28$, $p < 0.0001$) (Fig. 2). PRF significantly depended on the factors "musical fragment" (KW, $H(2.83) = 7.96$, $p = 0.019$) and "group" (MW, $Z(83) = -2.39$, $p = 0.017$) (Fig. 3). For FHP no significant effect of the "musical fragment" factor was found (KW, $H(2.83) = 0.42$, $p = 0.81$), but statistically significant differences were revealed between the groups (MW, $Z(85) = 2.78$, $p = 0.005$) (Fig. 3).

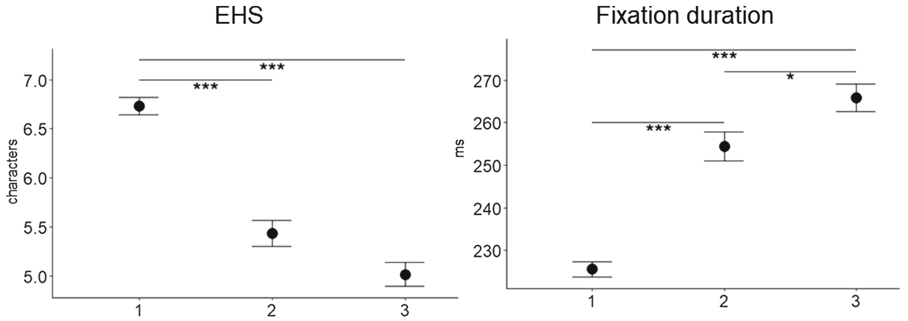

Fig. 1. On the left, EHS (eye-hand span, characters), on the right, FD (duration of fixations, ms) during the sight-reading musical fragments with an increasing complexity. Mean ± SEM. *** – p < 0.001; * – p < 0.05

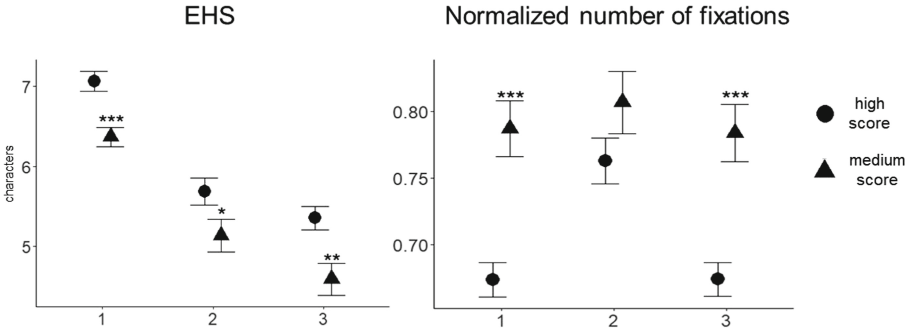

Fig. 2. On the left, EHS (eye-hand span, characters), on the right, NF (normalized number of fixations) during the sight-reading musical fragments with increasing complexity for a group with high and average performance ratings. Mean ± SEM. *** – p < 0.001; * – p < 0.05

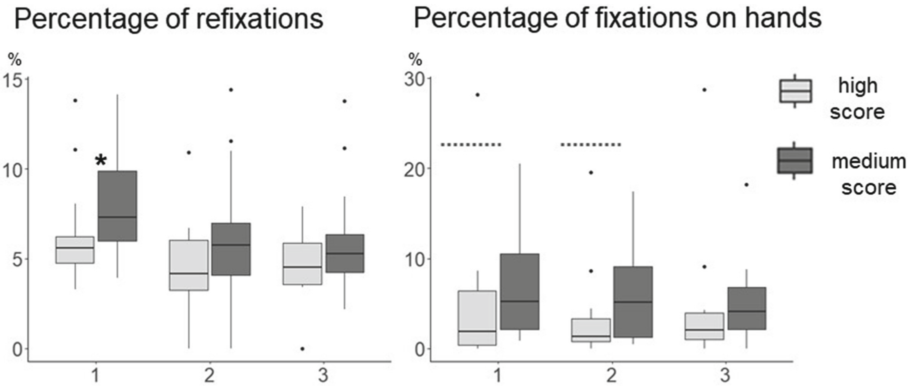

Fig. 3. On the left, PRF (percentage of refixes,%), on the right, FHP (percentage of hand fixations,%) while reading from a sheet of music fragments with increasing complexity for a group with high and average performance ratings. Median (25%-75%). *** – p < 0.001; * – p < 0.05; dotted line – 0.05 < p < 0.10.

4 Discussion

The value of EHS parameter significantly decreased as the background of increasing complexity of the musical fragment which corresponds to the results of previous studies [3, 4, 8, 10–12]. For FD the opposite pattern was observed, which is also consistent with the literature data that the fixation duration increases with increasing the text complexity, since the complexity of the text increases the requirements for visual information processing resources both when reading verbal text [9, 13] and musical text [12, 14]. For other parameters, these dynamics were not revealed, which is presumably due to the different texture of musical fragments and, accordingly, the specifics of reading them. In particular, the same NF values were observed for simple and complex fragments, but these values were significantly higher for a fragment of an average complexity. The musical texture of this fragment required simultaneously reading and playing chords of at least 4 notation characters (4-voice chorale), which, apparently, lead to a greater number of fixations. Interestingly, the NF in a musical fragment of average difficulty did not significantly differ between the groups of pianists with different scores. Therefore, in this case we can conclude that the choral structure of a musical text affected the number of fixations more strongly than the skill of sight-reading (at a certain level of development). At the same time simple and complex musical fragment in the MS group leads to significantly more fixations than in the HS group. In this case, the NF parameter turned out to be a predictor of a well-developed sight-reading skill.

The PRF values were significantly larger in a simple musical fragment. On the one hand, these results seem to contradict those obtained when reading a verbal text of varying complexity [15], where refixes are considered a correlate of difficulties encountered when reading. On the other hand, for a MS group pianists the proportion of refixes is significantly higher in a simple piece of music (Fig. 3). Thus, the PRF parameter turned out to be sensitive to the level of a sight-reading skill when the task is relatively simple.

The FHP parameter in general was significantly higher for the HS group than for the MS group. However, for a simple musical piece and that of medium complexity the differences were found only at the trend level. Sight-reading is not just a visual-motor task, but also a spatial one, since the spatial position of the note must be transferred to the topographical space of the instrument [16]. In other words, a musician performs the task of transferring an object from one coordinate system to another. The better the pianist performs this task, the less fixations on his hands he needs to make and, accordingly, the more time he has to read the notes.

Rosemann with colleagues [10] showed a positive correlation between the EHS value and the cognitive abilities of musicians (visual image recognition, speed of cognitive and psychomotor processes). Thus, EHS is a complex parameter that evaluates the ability to effectively recognize visual information, transfer an object from one coordinate system (musical stanza) to another (topography of the instrument), and form a complex coordinated motor response pattern at a high speed of mental processes. Taken together, the relatively lower values of EHS and NF indicators in the group with high scores can be associated with greater efficiency of working memory functioning, thus recognizing standard patterns of musical notation, and, as a result, successfully integrating eye and hand movements during performance in the HS group [17].

Considering the value of EHS at the performing tasks of varying complexity in the "resource theory" of D. Kahneman [18], it can be assumed that the pianist reads simpler musical fragments at the skill level, which requires a minimum of resources. More complex pieces of music require more conscious control and involve RP processes. This, in turn, raises the requirements for available resources, which is reflected decreasing of EHS parameters. This fact can explain the decrease in the EHS value with an increase in the complexity of the musical text in both groups of pianists. The increase in the complexity of the text increases the requirement for the cognitive processes of recognizing the musical pattern both in the visual-spatial system of notation and in the harmonic-semantic system. This means that a smaller number of characters per unit of time can be recognized.

Since EHS is considered as an integral indicator of cognitive activity it should be paid attention to the processes of working memory as a central mechanism in the system of cognitive process. It is known the capacity of working memory according to Cowan is estimated within 3–4 elements and the value of EHS exceeds this value. Therefore, it can be assumed that pianists recognize notation characters patterns rather than by single characters.

5 Conclusions

In conclusion, an increase in the complexity of a musical text significantly causes an increase in the duration of fixations in both groups of pianists, while the differences between the groups are not significant. And the EHS value decreases with an increase in the complexity of the musical text in both groups, while pianists with high scores have significantly higher EHS in each task. The parameter normalized number of fixations was significantly influenced by both the level of skill development (significant differences between groups of pianists in a simple and complex task) and the texture of the musical text itself (the absence of significant differences between groups in a text of average complexity which has texture features).

To summarize, sight-reading of a complex musical text is characterized by longer fixations and a smaller volume of the read musical text ahead of a playback. Pianists with higher scores are characterized by more advanced text coverage, fewer fixations, refixes, and hand fixations.

References

1. Levin, H., Kaplan, E.A.: Grammatical structure and reading. In: Levin, H., Williams, J.P. (eds.) Basic Studies on Reading, pp. 143–161. Basic Books, New York (1970)
2. Goolsby, T.W.: Eye movement in music reading: effects of reading ability, notational complexity, and encounters. Music Percept. **12**(1), 77–96 (1994). https://doi.org/10.2307/40285756
3. Sloboda, J.A.: The eye-hand span: an approach to the study of sight-reading. Psychol. Music **2**, 4 (1974). https://doi.org/10.1177/030573567422001
4. Truitt, F.E., Clifton, C., Pollatsek, A., Rayner, K.: The perceptual span and the eye-hand span in sight reading music. Vis. Cogn. **4**(2), 143–161 (1997). https://doi.org/10.1080/713756756

5. Weaver, H.E.: Studies of ocular behavior in music reading. I. A survey of visual processes in reading differently constructed musical selections. Psychol. Monograhpy **55**, 1–30 (1943). https://doi.org/10.1037/h0093537
6. Rayner, K., Pollatsek, A.: Eye movements, the eye-hand span, and the perceptual span during sight-reading of music. Curr. Dir. Psychol. Sci. **6**(2), 49–53 (1997). https://doi.org/10.1111/1467-8721.ep11512647
7. Wurtz, P., Mueri, R.M., Wiesendanger, M.: Sight-reading of violinists: eye movements anticipate the musical flow. Exp. Brain Res. **194**(3), 445–450 (2009). https://doi.org/10.1007/s00221-009-1719-3
8. Furneaux, S., Land, M.F.: The effects of skill on the eye–hand span during musical sight–reading. Proc. R. Soc. Lon. Ser. B Biol. Sci. **266**(1436), 2435–2440 (1999). https://doi.org/10.1098/rspb.1999.0943
9. Rayner, K.: Eye movements in reading and information processing: 20 years of research. Psychol. Bull. **124**(3), 372 (1998). https://doi.org/10.1037/0033-2909.124.3.372
10. Rosemann, S., Altenmüller, E., Fahle, M.: The art of sight-reading: influence of practice, playing tempo, complexity and cognitive skills on the eye–hand span in pianists. Psychol. Music **44**(4), 658–673 (2016). https://doi.org/10.1177/0305735615585398
11. Sloboda, J.A.: Experimental studies of music reading: a review. Music Percept. **2**(2), 222–236 (1984). https://doi.org/10.2307/40285292
12. Souter, T.: Eye movement and memory in the sight reading of keyboard music. Doctoral dissertation, University of Sydney, Australia (2001)
13. Rayner, K., Duffy, S.A.: Lexical complexity and fixation times in reading: effects of word frequency, verb complexity, and lexical ambiguity. Mem. Cognit. **14**(3), 191–201 (1986). https://doi.org/10.3758/BF03197692
14. Halverson, D.A.: Biometric analysis of eye movement patterns of sight-singers. Doctoral dissertation, Ohio State University, USA (1974)
15. Anisimov, V.A., Fedorova, O.V., Latanov, A.V.: Eye movement parameters in reading sentences with syntactic ambiguity in Russian. Hum. Physiol. **40**(5), 521–531 (2014). https://doi.org/10.1134/S0362119714040033
16. Stewart, L., Walsh, V.: Music perception: sounds lost in space. Curr. Biol. **17**(20), 892–893 (2007). https://doi.org/10.1016/j.cub.2007.08.012
17. Tereshchenko, L.V., Boyko, L.A., Ivanchenko, D.Y., Zadneprovskaya, G.V., Latanov, A.V.: Characteristics of music playback and visio-motor interaction at sight-reading by pianists depending on the specifics of a musical piece. Commun. Comput. Inf. Sci. **943**, 169–182 (2019). https://doi.org/10.1007/978-3-030-05594-3_14
18. Kahneman, D.: Attention and Effort, vol. 1063. Prentice-Hall, Englewood Cliffs (1973)

Linear and Non-linear Patterns of Eye Movements in Lexical Search: Expert Versus Novice Language Learners

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Abstract. In the current study linear and non-linear eye movement patterns of lexical search were distinguished, based on the combination of intersaccadic angle and saccade direction measures, which proved to differ in subjects with different vocabulary knowledge. Participants, who were classified as experts and novices by their vocabulary test score, were asked to find 10 foreign language words in letter matrices. Eye movement data – peak saccade velocity and blink rate – indicated higher level of cognitive load in subjects with lower vocabulary test results. Subjects with minor vocabulary knowledge tended to adopt a non-linear eye movement pattern, characterized by frequent change of saccade direction and lack of prevalent direction, whereas proficient language learners were more inclined to demonstrate a more structured search pattern with prevailing either horizontal or vertical directions. The results confirmed our hypotheses: subjects with lower, intermediate and higher vocabulary expertise demonstrated different performance, different rates of cognitive load markers and different eye movement patterns. The acquired data, combined with the results of our previous study, support the argument that experts' advantage in professional tasks is mediated by cognitive control.

Keywords: Experts and novices · L2 learners · Visual search · Eye movement patterns · Intersaccadic angle · Saccade direction

1 Introduction

Features of experts' and novices' information processing is a challenging area of eye movement research. Experts have extensive and in-depth knowledge and skills in domain-specific areas as compared to novices. When solving cognitive tasks, they demonstrate faster and more accurate execution. The key concept of the experts-novices studies is that solving visual tasks differs in people with different level of expertise: in general, the feature of experts' eye movements is their "fluency" of viewing and focus on relevant details, which is based on their extensive knowledge of the subject [1] and the attention distribution in favor of the target areas of interest, while ignoring irrelevant areas [2]. This common idea notwithstanding, evidence of experts' and novices' basic eye movement parameters seem to be domain-specific. In some cases, experts were

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reported to make more short fixations, as compared to novices, e.g. in reading mathematical proofs [3], while other research report a more efficient gaze behavior indexed by lower fixation rates, e.g. as in laparoscopic surgery training environment [4, 5].

Integrative eye movement measures are often used to solve this discrepancy, such as the ratio of fixation duration and saccadic amplitudes, that characterizes the preference of either ambient or focal visual systems [6]. This metric has been used in a number of comparative studies of expert and novice cognitive performance. [7, 8]. Other possible measures of visual search task performance, which can be used to study the nature of scanning process, are the saccadic direction and intersaccadic angles [9]. This particular measuring technique was applied in this research.

Visual search in a complex environment is a common task for experts and novices in any domain. In the current research we modelled a lexical search task, where subjects were supposed to find familiar, but undefined words among randomly assigned letter charts. As visual search involves both looking (moving the gaze to new locations) and seeing (distinguishing between targets and non-targets), the identification of eye movement patterns involves defining to which degree each process was involved. As demonstrated in previous research, structured and unstructured search patterns can reflect the use of different cognitive strategies, such as the choice between looking versus seeing strategy. The latter are connected with the active managed search [10] and high cognitive control rates [11].

In our previous study [12] we defined three scanning patterns, based on the interrelation of saccade direction and intersaccadic angle. These patterns proved to be connected to the levels of impulsivity and executive or cognitive control involvement. Subjects who tended to demonstrate a steady linear eye-movement pattern (“Horizontal sequential”) also showed low Impulsivity indices. In this case, subjects’ search was organized in left-right, bottom-top manner. In contrast, the subjects with high impulsivity indices demonstrated a less structured search. Therefore, executive and cognitive control manifested itself in linear characteristics of eye movement patterns.

The question of which scanning method leads to higher performance remains open. Some studies show that unstructured search movements lead to faster responses with less error rates, while others show the opposite trends. It is also not completely clear how the scanning methods are related to the level of expertise [13]. Some authors insist that experts use less structured and more intuitive strategies, while others hold the opposite opinion.

The current study is aimed at identifying visual lexical search patterns in subjects with different expertise in foreign languages. We hypothesized that subjects will demonstrate different performance scores, different rates of cognitive load markers (peak saccade velocity, blink rate) and cognitive control in a lexical search task depending on their foreign language vocabulary knowledge. These parameters should be reflected in their eye movement patterns: linear or non-linear.

2 Method

32 Russian-speaking subjects took part in the research. Before the main task the subjects did a WAT test [14] to estimate their English vocabulary level. The subjects had to find

10 English 4-letter words in 15*15 matrices containing English letters (randomized by frequency) in 40 s (a relatively easy task for skilled English learners and a reasonably hard, but solvable one for novice learners).

All procedures performed in the study were in accordance with the ethical standards of the ethics committee of Lomonosov Moscow State University and with the Helsinki declaration.

Recorded Data. We recorded the search success rate and eye movement data. Eye movements were sampled monocularly at 250 Hz using the SMI iView X RED 4 (FireWire) tracking system with on-line detection of saccades and fixations and a spatial accuracy $< 0.5°$.

Visual search patterns of eye movements were defined on the basis of saccade directions and intersaccadic angles. SMI BeGaze data about the starting (Saccade Start Location X, Y) and ending (Saccade End Location X, Y) coordinates of the saccades (identified by SMI BeGaze by velocity and acceleration thresholds) were used.

We used the procedure of saccadic direction angles computation similar to the one described by Amor et al. [9], where the horizontal angle for the *i*-th saccade (α_i) is computed as:

$$\arctan(a_i) = \arctan\left(r_i, y / r_i, x\right),$$

where r_i,y = |Location End Y - Location Start Y|, and r_i,x = |Location End X - Location Start X|.

The obtained angles (0°–90°) we attributed to 8 directions according to substraction values of y_i and x_i, where y_i = Location End Y - Location Start Y, and x_i = Location End X - Location Start X. Similarly to the previous research [13], we distinguished 8 possible directions. The percent of saccades in every direction was counted up for every trial.

The angle between the *i*-th saccade and the successive saccade (β_i) was computed as: in case both saccades were directed upwards or both directed downwards

$$\beta_i = 180 - (|a_i - a_i + 1|),$$

in case one saccade was directed upwards and the other downwards:

$$\beta_i = 180 - a_i - a_i + 1$$

The percent of 0–45°, 45–90°, 90–135°, 135–180° angles was counted up for every trial.

Data Processing. The total of 288 trials was recorded. The data were calculated and subjected to factorial ANOVA using IBM SPSS Statistics 20.

3 Results

Cluster analysis was used to categorize the subjects on the basis of their WAT performance. We opted a 3-cluster solution: lower score (cluster center = 55,75, 8 subjects), intermediate score (cluster center = 97,46, 13 subjects), higher score (cluster center = 132,06, 11 subjects). The groups varied in their verbal search performance: the average of 0.86 words was identified in the low WAT score group; intermediate WAT score group found 1.35 word per trial; 1.95 words were found on average in the high WAT score group. The differences proved to be significant (F (2; 286) = 28. 33; p < 0,01).

Thus, it was found that subjects with a lower level of language competence demonstrate poor performance and find fewer lexical units in random letters. In addition, it was found that for this group of respondents solving the task is associated with higher cognitive load, manifested in an increase in the number of blinks and the peak saccade velocity. Subjects with lower WAT scores demonstrated higher blink rate and higher peak saccade velocity as compared to subjects with intermediate and high WAT score (see Table 1).

Table 1. Eye movement data of subjects with different vocabulary knowledge

	Blink rate (total count per trial – 40s)	Peak saccade velocity ($^{o}/_{s}$)
Low WAT score	7.4 (4.5)	212 (72)
Intermediate WAT score	4.2 (3.1)	206 (56)
High WAT score	4.1 (2.9)	169 (55)
The results are significant at	F(2;288) = 6,6, p < 0,01	F(2;288) = 12,9, p < 0,01

As it was expected, the obtained results indicated that the subjects with lower linguistic competence achieve less success and spend more effort while solving lexical problems. It was much more interesting to find out what strategies of search activity are used by people with different linguistic experience and different levels of performance, and to what extent these strategies are subject to conscious cognitive control.

In order to identify the scanning patterns, we analyzed saccadic directions and intersaccadic angles for each trial. If a saccade is represented as a vector, the horizontal angle to the x-axis is its direction, and the angle between two consecutive saccadic events is the intersaccadic angle, which is a marker of the change in eye movement direction. Further, cluster analysis was used to define search patterns based on saccade direction and intersaccadic angle measures. We opted for a 3-cluster solution, which corresponded to the 3 patterns of visual search in our previous study (see Table 2).

Therefore, three search patterns were identified: “Horizontal” - mostly horizontally oriented directions, intersaccadic angle values with little change in direction (0°–45°), a few “backtrack” 135°–180° angles (49 trials); “Vertical” – more vertical (mostly downward) directions, intersaccadic angle values, indicating little change of direction and occasional “backtrack” 135°–180° angles (44 trials); “Non-linear” - a relatively even distribution of saccade directions and intersaccadic angles, with slight prevalence of horizontally oriented saccades (136 trials). The use of Non-linear pattern was associated with higher saccadic amplitude and peak saccade velocity (see Table 3).

Table 2. Cluster analysis results

	Horizontal pattern (49 trials)	Vertical pattern (44 trials)	Non-linear pattern (136 trials)
Angles 0–45° (%)	45.76	41.62	31.97
Angles 45–90° (%)	13.98	17.45	20.13
Angles 90–135° (%)	11.74	14.97	18.93
Angles 135–180° (%)	28.51	25.96	28.97
Direction right-upward (%)	24.74	15.02	17.07
Direction upward-right (%)	5.15	9.32	9.51
Direction upward-left (%)	5.04	10.47	9.59
Direction left-upward (%)	13.06	10.86	12.94
Direction left-downward (%)	17.40	12.91	14.04
Direction downward-left (%)	5.37	13.61	9.89
Direction downward-right (%)	5.65	12.94	10.20
Direction right-downward (%)	23.59	14.86	16.76

Table 3. Saccade velocity and amplitude measures in search patterns

	Peak saccade velocity ($^{o}/_{s}$)	Saccadic amplitude (°)
Horizontal	161 (37)	2.1 (1.1)
Vertical	179 (46)	2.9 (2.9)
Non-linear	202 (71)	5.5 (6.0)
The results are significant at	F(2;288) = 9,9, p < 0,01	F(2;288) = 12,9, p < 0,01

Next, using the coefficient of contingency, we attempted to find out if there was a relationship between the level of language competence and the patterns of eye movements. The coefficient of contingency between WAT score cluster and eye-movement cluster equals 0.21, p < 0,01 (see Table 4). The result maintains that subjects with different levels of linguistic competence use different strategies for scanning the search space. The data in Table 4 show that subjects with lower WAT score tended to use the non-linear pattern more frequently, while higher WAT results were associated with increasing use of linear horizontal and vertical patterns. At the same time, the strategies themselves obviously differed in order and control during implementation. The implementation of a horizontal or vertical scanning pattern implied the use of a higher level of cognitive control. In contrast, the non-linear pattern reflected a chaotic, poorly controlled search.

Table 4. Crosstabulation results (n trials) for use of the patterns in subjects with different WAT score

	Low WAT score	Intermediate WAT score	High WAT score
Horizontal pattern	5.8%	19.5%	29.9%
Vertical pattern	14.7%	18.5%	21.8%
Non-linear pattern	79.5%	62%	48.3%

4 Discussion

The results of the study indicate that language expertise can be traced in eye movement patterns in visual search task. Notably, blink rate and peak saccade velocity, acknowledged markers of cognitive load [15] increase in subjects with lesser language competence, which can be attributed to the laborious vocabulary task. The obtained results correspond to the vast amount of research on the eye movement strategies of experts and novices in terms of providing eye movement evidence for higher cognitive load of novices [16], which is especially manifested in saccade metrics [17].

Although oculomotor measures have long been used in relation to search efficiency [18], expert-novice research in different domains demands introduction of novel complex eye movement patterns, such as the way of identifying structured and unstructured search patterns. In the present study subjects with lower lexical test score demonstrated more frequent use of a non-linear scanning pattern, while the use of linear patterns increased in more efficient language learners.

As shown in previous research, structures and unstructured search patterns can reflect the use of different cognitive strategies, such as choosing “looking” versus “seeing” strategy [10]. Therefore, the question, raised by the current research, is whether the revealed eye movement patterns are determined by cognitive strategies, which, in turn, are induced by experience, or whether they can be accounted for by the increased cognitive load.

The results of our previous research, where non-linear eye movement pattern was associated with higher impulsivity index [12], support the latter hypothesis to a certain extent. As higher peak saccade velocity is supposed to be related to higher cognitive load and as it has also been registered in impulsive subjects, the use of Non-linear pattern can reflect reduction of cognitive control.

The acquired data can contribute to a challenging discussion in cognitive psychology on the features of experts’ cognitive activity [19]. Although experts retrieve relevant information quicker, their execution is not entirely effortless and intuitive. However, the distinct feature of experts is the higher cognitive control, which is reflected in more structured eye movement patterns.

5 Conclusions

The present study documented eye movement features of expert and novice language learners in vocabulary search task, which a) indicate higher level of cognitive load in subjects with lower vocabulary test results (higher peak saccade velocity and blink rate in less proficient subjects) and b) different visual lexical search patterns on the basis of eye movement data on intersaccadic angles and saccade direction (which were named Horizontal, Vertical and Non-linear).

The described patterns correspond to the patterns obtained in preceding research [12], which had also been shown to correspond to cognitive control factor. The current study displayed the relation of cognitive load and the preference of using the linear and non-linear pattern. According to the empirical data, these patterns are more or less manifested in subjects according to their expertise in foreign languages.

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References

1. Gegenfurtner, A., Lehtinen, E., Säljö, R.: Expertise differences in the comprehension of visualizations: a meta-analysis of eye-tracking research in professional domains. Educ. Psychol. Rev. **23**(4), 523–552 (2011). https://doi.org/10.1007/s10648-011-9174-7
2. Jarodzka, H., Scheiter, K., Gerjets, P., Van Gog, T.: In the eyes of the beholder: how experts and novices interpret dynamic stimuli. Learn Instr. **20**(2), 146–154 (2010). https://doi.org/10.1016/j.learninstruc.2009.02.019
3. Inglis, M., Alcock, L.: Expert and novice approaches to reading mathematical proofs. J. Res. Math. Educ. **43**(4), 358–390 (2012). https://doi.org/10.5951/jresematheduc.43.4.0358
4. Wilson, M., McGrath, J., Vine, S., Brewer, J., Defriend, D., Masters, R.: Psychomotor control in a virtual laparoscopic surgery training environment: gaze control parameters differentiate novices from experts. Surg. Endosc. **24**(10), 2458–2464 (2010). https://doi.org/10.1007/s00464-010-0986-1
5. Vogt, S., Magnussen, S.: Expertise in pictorial perception: eye-movement patterns and visual memory in artists and laymen. Perception **36**(1), 91–100 (2007). https://doi.org/10.1068/p5262
6. Velichkovsky, B.M., Joos, M., Helmert, J.R., Pannasch, S.: Two visual systems and their eye movements: Evidence from static and dynamic scene perception. In: Bara, B.G., Barsalou, L., Bucciarelli, M. (eds.) Proceedings of the XXVII Annual Conference of the Cognitive Science Society, pp. 2283–2288. Lawrence Erlbaum, Mahwah (2005). https://doi.org/10.17691/stm2019.11.4.01
7. Blinnikova, I.V., Rabeson, M.D., Izmalkova, A.I.: Eye movements and word recognition during visual semantic search: differences between expert and novice language learners. Psychol. Russia State Art **12**(1), 129–146 (2019). https://doi.org/10.11621/pir.2019.0110
8. Kasprowski, P., Harezlak, K., Kasprowska, S.: Development of diagnostic performance & visual processing in different types of radiological expertise. In: Proceedings of the 2018 ACM Symposium on Eye Tracking Research & Applications, pp. 1–6. ACM, Warsaw (2018). https://doi.org/10.1145/3204493.3204562

9. Amor, T.A., Reis, S.D., Campos, D., Herrmann, H.J., Andrade, J.S.: Persistence in eye movement during visual search. Sci. Rep. **6**(1), 20815 (2016). https://doi.org/10.1038/srep20815
10. Watson, M.R., Brennan, A.A., Kingstone, A., Enns, J.T.: Looking versus seeing: strategies alter eye movements during visual search. Psychon. Bull. Rev. **17**(4), 543–549 (2010). https://doi.org/10.3758/PBR.17.4.543
11. Toner, J., Montero, B.G., Moran, A.: Considering the role of cognitive control in expert performance. Phenomenol. Cogn. Sci. **14**(4), 1127–1144 (2015). https://doi.org/10.1007/s11097-014-9407-6
12. Blinnikova, I., Izmalkova, A.: Modeling search in web environment: the analysis of eye movement measures and patterns. In: International Conference on Intelligent Decision Technologies, pp. 297–307. Springer, Cham. (2017). https://doi.org/10.1007/978-3-319-59424-8_28
13. Emhardt, S.N., Kok, E.M., Jarodzka, H., Brand-Gruwel, S., Drumm, C., van Gog, T.: How experts adapt their gaze behavior when modeling a task to novices. Cogn. Sci. **44**(9), 1–26 (2020). https://doi.org/10.1111/cogs.12893
14. O'Dell, F., Read, J., McCarthy, M.: Assessing Vocabulary. CUP, Cambridge (2000)
15. Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., Van de Weijer, J.: Eye Tracking: A Comprehensive Guide to Methods and Measures. OUP, Oxford (2011)
16. Amadieu, F., Van Gog, T., Paas, F., Tricot, A., Mariné, C.: Effects of prior knowledge and concept-map structure on disorientation, cognitive load, and learning. Learn. Instr. **19**(5), 376–386 (2009). https://doi.org/10.1016/j.learninstruc.2009.02.005
17. Keskin, M., Ooms, K., Dogru, A.O., De Maeyer, P.: Exploring the cognitive load of expert and novice map users using EEG and eye tracking. ISPRS Int. J. Geo-Inf. **9**(7), 429–446 (2020). https://doi.org/10.3390/ijgi9070429
18. Boot, W.R., Becic, E., Kramer, A.F.: Stable individual differences in search strategy? the effect of task demands and motivational factors on scanning strategy in visual search. J. Vis. **9**(3), 1–6 (2009). https://doi.org/10.1167/9.3.7
19. Gobet, F.: Three views on expertise: philosophical implications for rationality, knowledge, intuition and education. J. Philos. Educ. **51**(3), 605–619 (2017). https://doi.org/10.1111/1467-9752.12253

Eye Movements in Visual Semantic Search: Scanning Patterns and Cognitive Processing Across Three Cultures

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Abstract. The study compares performance and eye-movement indicators in students from Russia, Japan, and China when searching for English words among randomly organized letters. The assumption was that social and linguistic experience affects visual scanning strategies and cognitive processing of verbal material. The study involved 64 respondents, demonstrating similar levels of English proficiency. Eye movements were recorded with SMI Gaze & Eye-tracking System (SMIRED 250 Hz). Russian respondents were the most successful at performing the task. Presumably, their success is determined by the experience in analyzing letter strings during sequential cognitive processing. Significant differences between the groups were established for both fixation duration and saccadic amplitude that describe the characteristics of cognitive processing (Velichkovsky et al., 2005). The Russian sample was characterized by high fixation durations ($m = 239.5$ ms) and low saccade amplitudes ($m = 4.1°$), demonstrating the focal pattern of attention distribution. The opposite trend toward ambient and gliding type of processing was recorded in the Japanese sample. In addition, the parameters of intersaccadic angles and saccade directions were analyzed. Return saccades were most characteristic of the Japanese group with direction changes in the range of 90–135°. Russian students demonstrated saccades of a sequential pattern in the range of 0–45°. Chinese students considered letter sets only once showing the smallest number of return saccades (the range of 135–180°). Based on the results of this study, the basic characteristics of visual semantic search can be associated with the first language experience that defines the patterns and the architecture of cognitive processing.

Keywords: Cross-cultural differences · Cognitive processing · Eye movements · Visual semantic search · Linguistic experience · Writing system

1 Introduction

The assumption that people of different cultures use different cognitive processing styles or strategies is repeatedly supported by academic research [1, 2]. Most studies compare respondents who belong to Western or European culture to those who come from Eastern or Asian cultures. The idea that Western culture instills an analytical style of

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information processing, while Eastern culture implies a holistic style has become topical. The style preferences result in different patterns of attention distribution (either to the salient object or to the background characteristics) and judgment (either based on an object's attributes and their categorization, or on the basis of contextual information and similarity) [3]. Characteristics of language systems, particularly, features of scripts are considered among the factors of culture that may be important along with social relations.

The development of European culture is associated with alphabetic writing systems, while Asian civilizations have relied on hieroglyphic scripts for many centuries. The alphabetic script involves a subtle distinction between individual morphemes and word composition that can be broken down into elements. Hieroglyphic writing is based on the perception of more holistic configurations. Although hieroglyphs generally take up less space than words, they have a greater semantic capacity. Reading one character provides more information than reading one letter [4]. Thus, it can be assumed that the characteristics of a script determine certain strategies for information processing. People who practice hieroglyphic writing should use a more holistic type of cognitive processing when analyzing visual information with shorter fixations and longer gaze movements.

Differences in the characteristics of cognitive processing between the representatives of Eastern and Western cultures have been found in a number of studies using eye movements. In particular, in the work of H. Chua, J. Boland and R. Nisbett [5], where the subjects attempted to memorize complex foregrounded figures, it was shown that the oculomotor pattern of Chinese participants was characterized by a greater number of shorter fixations and transitions between figure and ground. A review by Y.-K. Tsang and H.-Ch. Chen [6] found that, while some aspects of eye movement control in reading seem to be universal (e.g., the availability of orthographic information in the parafoveal preview), others are more script-specific (e.g., the size of the perceptual span).

This study is aimed to determine the extent to which information processing is governed by the properties of a language and its writing system. The research compares the performance and eye-movement patterns during lexical search across three groups of respondents: Russian, Japanese, and Chinese students. The experimental task was to search and identify meaningful words in a foreign language in a field of chaotically arranged Latin letters. We assumed that the number of successfully identified words, fixation and saccade duration, as well as the scanning pattern can differ among respondents who have mastered different scripts since their early years.

2 Method

2.1 Sample

The study involved 64 respondents: 43 women and 21 men. 22 participants were included in the Russian-speaking sample, 20 respondents composed the Japanese sample, 22 people represented the Chinese sample. The average age of the subjects was 19, 20 and 23 years, respectively. The Russian-speaking group included 22 participants with the average age of 19. The Japanese-speaking group was represented by 20 respondents with the average age of 20. Finally, the Chinese-speaking group included 22 participants of 23 years of age on average. The ratio of men to women was equal in all three groups. The students demonstrated similar levels of English proficiency supported by the results of the Word Associates Test [7] offered to each participant prior to the experimental series.

2.2 Stimuli and Task

The subjects were presented with letter matrices for analysis (See Fig. 1a). The stimulus material included eighteen matrices with randomized letters of the Latin alphabet. Randomization procedure was thoroughly described in our previous work [8]. It was performed in accordance with the frequency of letter use in the English language. Each matrix incorporated 10 different words. The length of the target words varied from 4 to 9 letters. The task of the subjects was to find a word and mark it by pressing a computer mouse button.

L	B	A	W	T	P	U	L	N	S	M	Y	H	I	N
O	M	U	S	I	C	F	E	S	F	D	R	O	E	D
R	A	H	N	I	L	E	Y	R	T	F	I	U	A	T
I	H	S	T	D	A	K	I	N	D	A	W	S	E	N
Q	Y	E	N	V	T	E	K	M	T	C	N	E	P	E
A	O	P	N	E	H	O	E	N	T	S	I	O	F	H
M	U	R	S	M	H	L	O	V	E	F	E	G	V	K
I	N	O	H	N	O	E	H	N	D	S	O	T	O	I
S	G	C	T	M	D	A	R	J	A	N	H	B	D	S
G	E	U	O	G	W	T	I	R	A	E	S	R	D	S
Y	A	G	S	X	G	E	V	W	W	Z	A	A	I	H
A	P	I	R	S	I	I	E	U	O	N	F	O	U	K
N	C	H	I	L	D	E	R	T	I	T	E	E	C	S
R	T	T	L	I	H	R	N	D	O	S	M	I	E	S
T	S	H	E	I	D	E	A	A	C	O	E	O	E	U

Fig. 1. (a) Sample stimulus matrix and (b) a matrix with a scan path and mouse clicks

2.3 Procedure

First, having been pretested on English verbal competence with the WAT test, the respondents completed a questionnaire that collected information on biographic data, linguistic background, and current physical state. Next, they participated in two experimental series with nine stimulus matrices presented in each series. Each of the eighteen stimuli appeared on the monitor for 40 s. A calibration point was displayed between stimuli. All procedures were conducted in accordance with the Declaration of Helsinki and were approved by the local ethics committee of Lomonosov Moscow State University.

2.4 Recorded Data

The indicators of eye movement (fixation duration and saccade amplitude) were recorded by the SMI Gaze and Eye-tracking System (SMI RED 250 Hz).

The data of 475 samples were additionally analyzed for the parameters of saccadic angles and changes in gaze direction. The procedure, used to describe the search patterns, analyzed two angles, i.e., the angle between a saccadic event and the horizontal direction ("Direction") and the angle between two consecutive saccadic events ("Intersaccadic angle"). The data about the coordinates in the starting point and the ending point of the saccades were provided by SMI BeGaze. Saccades are identified by SMI BeGaze by their velocity and acceleration thresholds. This procedure of analyzing saccadic direction angles is similar to the one described by T.A. Amor and colleagues [9] and was applied in our previous research [10].

2.5 Data Processing

Statistical processing was conducted with IBM SPSS Statistics 19 package.

3 Results and Discussion

3.1 Word Recognition Results

The total numbers of words and, specifically, the numbers of horizontally-oriented words detected by the respondents significantly differed in the three language groups ($F(2,124) = 15.4, p < 0.01$; $F(2,124) = 14.9, p < 0.01$)[1]. Russian students had more success (total $m = 11.5$, horizontal orientation $m = 10.07$, vertical orientation $m = 1.32$) than Japanese (total $m = 8.41$, horizontal orientation $m = 6.72$, vertical orientation $m = 1.72$) and Chinese students (total $m = 5.3$, horizontal orientation $m = 4.57$, vertical orientation $m = 0.75$). Since the level of language proficiency in all groups was approximately the same, these results can only be explained by the fact that the task itself was less demanding for native Russian language speakers. Mastering literal writing involves the skill of element-wise reconstruction of lexical units, which was the key scope in solving the experimental problem. However, mastering hieroglyphic scripts does not imply the development of these cognitive skills. Perhaps this explains why the Chinese- and Japanese-speaking students find it more challenging to construct letter chains and assess their lexical relevance.

The number of identified vertically-oriented words differs at the level ($F(2, 124) = 4.6, p < 0.05$). In this respect, Japanese students demonstrated better results in comparison to Russian and Chinese subjects. Taking into account the fact that their total scores were considerably lower than those in the other groups, this trend seems to point to a relevant feature of visual scanning in Japanese respondents. Successful strikes on the vertically-oriented words can be explained by the fact that Japanese hieroglyphic system is characterized by vertical reading.

3.2 Scanning Patterns

Examining the scan paths of individual respondents (see Fig. 1b), we noticed completely different patterns of visual search activity. In order to describe these patterns, we calculated the directions of saccades and intersaccadic angles for each trial. Considering

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[1] The results of each participant in two series were analyzed. Two records were dismissed as a result of undue calibration of the apparatus.

the saccade directions, we found that significant differences in data mark two general trends (see Fig. 2). First, Russian respondents demonstrate considerably more saccades in horizontal direction to the right, which suggests the preference for sequential patterns in the Russian language (literal) writing system. Second, Japanese respondents demonstrate more saccades in the vertical directions, i.e. the upward-left direction (M = 10.33, compared to 8.9 in the Russian group and 9.1 in the Chinese group (F (2,473) = 5.008, p = 0.007)) and the downward-right direction (M = 11.21, compared to 9.87 in the Russian group and 9.43 in the Chinese group (F(2, 473) = 4.788, p = 0.009)). No evident significant trends were established in the Chinese respondents' results.

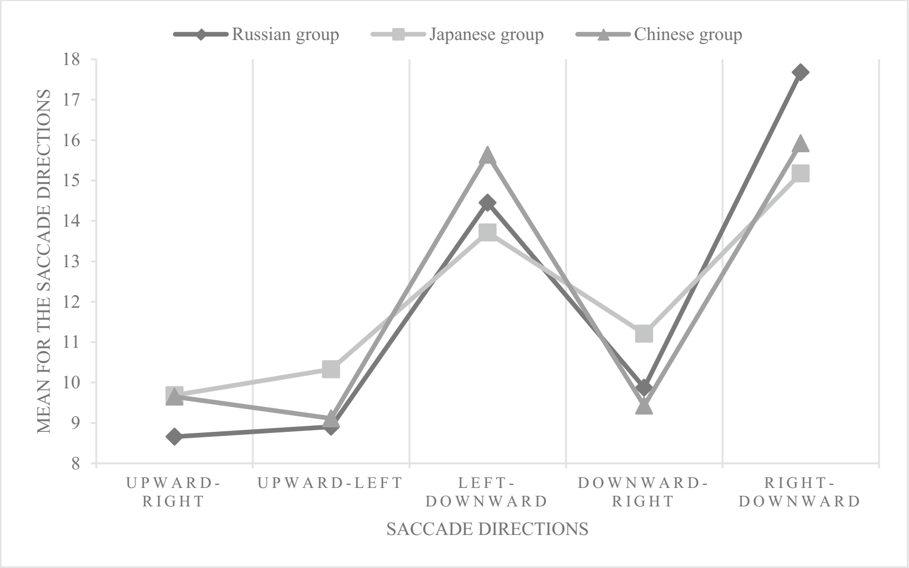

Fig. 2. Statistically significant differences between groups in the saccade directions

The analysis of the saccade directions showed that the Japanese students resorted to vertical transitions significantly more often when searching for words. This may be due to the distinct characteristics of the Japanese scripts, where the vertically-oriented positioning of words is typical.

The analysis of variance for the change in saccade directions during the search demonstrated that students of the Japanese group more often than others showed intersaccadic angle values within the range of 90–135° (F (2,473) = 17.02, $p < 0.001$). This means that the switches between horizontal and vertical guides were rather common in their trials. This trend may indicate a higher lability of eye-movements and easier switch between horizontal and vertical directions. These data are consistent with the higher performance in identifying vertically-oriented words.

Participants in the group of Russian students demonstrated progressive saccades with intersaccadic angles of 0–45° (F (2,473) = 12.58, $p < 0.001$) significantly more often, which corresponds to a sequential eye-movement pattern with the priority for horizontal guide-lines in reading.

The group of Chinese students show the smallest number of recurrent saccades with intersaccadic angles in the range of 135–180° ($F(2,473) = 3.899$, $p = 0.021$). That means they rarely return to the previously scanned material as compared to the representatives of the other groups. Perhaps this is due to the logographic writing of the Chinese language, where each unit is interpreted unambiguously, reducing the need for returns in visual scanning. This feature of scanning seems to impede the total performance in the lexical search task, since the cognitive processing in lexical decision presumes recurrent letter-strings analysis. Namely, if the relevant letter combination does not fall into the focus of a fixation at once, the subject tends to skip the target and never returns to the same area of the matrix.

3.3 Cognitive Processing Features

One of the significant characteristics of cognitive processing is the ratio of fixation duration and saccade amplitude in eye movement patterns [11, 12]. For both of these parameters, significant differences were found between groups ($F(2,1114) = 85.66$, $p < 0.01$; $F(2,1114) = 42$, $p < 0.01$, respectively)[2]. The values presented in Fig. 3 indicate that Japanese respondents used a strategy differing from the one of the other groups. The Russian sample was characterized by high indices of the average fixation duration ($m = 239.5$ ms) and low indices of the saccade amplitude ($m = 4.1°$). Similar trends, though

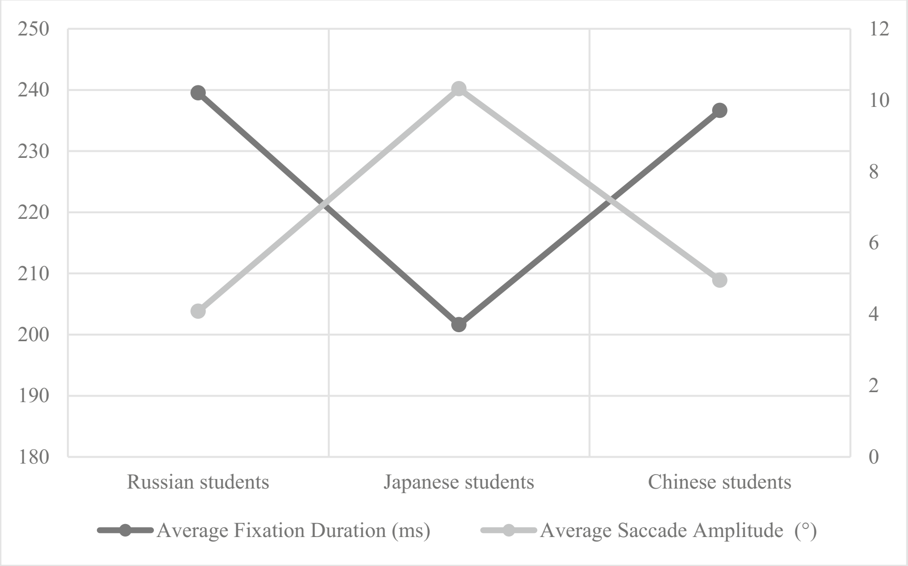

Fig. 3. The ratio of fixation duration and saccade amplitude in eye movement patterns

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[2] The total of 1152 trials were recorded, though 36 of them were dismissed as a result of undue calibration of the apparatus.

with less dramatic values, were observed in the Chinese respondents (m = 236.63 ms for fixation durations and m = 4.95° for saccadic amplitudes). For the Japanese sample, the opposite tendency was recorded: lower indices of the average fixation durations (m = 201.6 ms) and higher indices of saccade amplitudes (m = 10.3°).

This finding suggests that Russian respondents used a method of cognitive processing based on focal attention, while native Japanese speakers demonstrate an ambient and sliding type of processing. The cognitive processing strategy applied by the Chinese respondents seems similar to the one, used by Russian-speakers. However, if this strategy is to be considered comprehensively in connection with the scanning pattern, a specific method to solve the lexical search task is observed in the trials of Chinese respondents. This pattern agrees with the general trends of modern Chinese language development towards simplification of hieroglyphic writing and introduction of sound-letter writing. The results can also be attributed to the peculiarities of reading directions in the respondents' native language.

4 Conclusion

The analysis of the task performance, saccade directions and the ratio of fixation durations and saccade amplitudes in the identification of visual verbal stimuli shows that the writing system of the native language affects the parameters of visual semantic search. It appears that linguistic experience, being connected to mastering a particular writing system, plays a role in determining the cognitive architecture of the two core components of search: the patterns of visual scanning and the style of cognitive processing.

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References

1. Nisbett, R., Masuda, T.: Culture and point of view. Proc. Natl. Acad. Sci. USA **100**, 11163–11170 (2003). https://doi.org/10.1073/pnas.1934527100
2. Yu, L., Reichle, E.D.: Chinese versus English: Insights on cognition during reading. Trends Cogn. Sci. **21**(10), 721–724 (2017). https://doi.org/10.1016/j.tics.2017.06.004
3. Nisbett, R.E., Peng, K., Choi, I., Norenzayan, A.: Culture and systems of thought: holistic versus analytic cognition. Psychol. Rev. **108**(2), 291–310 (2001). https://doi.org/10.1037/0033-295x.108.2.291
4. Li, X., Liu, P., Rayner, K.: Eye movement guidance in Chinese reading: is there a preferred viewing location? Vision Res. **51**(10), 1146–1156 (2011). https://doi.org/10.1016/j.visres.2011.03.004
5. Chua, H.F., Boland, J.E., Nisbett, R.E.: Cultural variation in eye movements during scene perception. Proc. Natl. Acad. Sci. USA **102**(35), 12629–12633 (2005). https://doi.org/10.1073/pnas.0506162102
6. Tsang, Y-K., Chen, H.-Ch.: Eye movement control in reading: logographic Chinese versus alphabetic scripts. PsyCh J. **1**(2), 128–142 (2012). https://doi.org/10.1002/pchj.10
7. Read, J.: Research in teaching vocabulary. Annu. Rev. Appl. Ling. **24**, 146–161 (2004). https://doi.org/10.1017/S0267190504000078

8. Blinnikova, I.V., Rabeson, M.D., Izmalkova, A.I.: Eye movements and word recognition during visual semantic search: differences between expert and novice language learners. Psychol. Russ., State art. **12**(1), 129–146 (2019). doi: https://doi.org/10.11621/pir.2019.0110
9. Amor, T.A., Reis, S.D., Campos, D., Herrmann, H.J., Andrade, J.S.: Persistence in eye movement during visual search. Sci. Rep. **6**(1), 20815 (2016). https://doi.org/10.1038/srep20815
10. Blinnikova, I., Izmalkova, A.: Modeling search in web environment: the analysis of eye movement measures and patterns. In: Czarnowski, I., et al. (eds.) International Conference on Intelligent Decision Technologies, pp. 297–307. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-59424-8_28
11. Goldberg, J.H.: Measuring software screen complexity: Relating eye tracking, emotional valence, and subjective ratings. Int. J. Hum. Comput. Interact. **30**(7), 518–532 (2014). https://doi.org/10.1080/10447318.2014.906156
12. Velichkovsky, B.M., Joos, M., Helmert, J.R., Pannasch, S.: Two visual systems and their eye movements: Evidence from static and dynamic scene perception. In: Bara, B.G., Barsalou, L., Bucciarelli, M. (eds.) Proceedings of the XXVII annual conference of the Cognitive Science Society, pp. 2283–2288. Lawrence Erlbaum, Mahwah (2005). https://doi.org/10.17691/stm2019.11.4.01

Saccade Trajectories in the Presence of Emotional and Non-emotional Distractors

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Abstract. A considerable body of research on saccade trajectory has been carried out to gain a better understanding of cognitive processes. Deviations in a saccade trajectory could be caused by the distractor stimuli appearing during the saccade initiation. Several recent studies explored specific distractor features that make saccades curve away from distractor stimuli. They have shown that this deviation is affected not only by visual, but also by semantic saliency. However, many previous studies have focused only on the visual images with presumably evolutionary significance, such as violent scenes or frightened faces. The general purpose of this study was to understand whether more abstract semantic information, such as word meaning, could affect the saccade trajectory. In particular, the focus of our interest was saccade deviation after the presentation of emotional distractors compared to non-emotional ones. For a more detailed study, various measures of saccade trajectories were used, such as saccade deviation, overall direction and initial direction. Contrary to the previous research, our results did not match our initial hypothesis about significant changes in the saccade trajectory owing to the word meaning. The results suggest that competitive interaction of word meaning and saccade timing could be more complex than has been previously thought.

Keywords: Attention · Saccade trajectory · Distractor · Emotion

1 Introduction

An increasing number of publications on visual perception show the growing role of eye movements in cognitive psychology. With the worldwide spread of new equipment for measuring eye fixations and eye movements, the features of these micro-movements became popular external measures reflecting internal brain processes. Among the brain processes which can be studied through eye movements, emotional information processing is a field of great interest.

Many authors argue that the stimuli based on fear tend to capture more visual attention as compared to the non-emotional ones [1–3]. However, most of these studies are limited in interpretation, because emotional stimuli were relevant for the task, and participants were paying attention to them in order to complete the task. Therefore, the question as to whether emotional stimuli automatically attract attention remains insufficiently tested. To address this issue, distractor stimuli which are completely irrelevant to the task are usually used, and appear on the screen during the saccade initiation.

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Subsequent analysis of saccade trajectories confirmed the assumption that covert attention can be biased, not only by physical characteristics of a distractor stimulus [4–6], but also by its emotional load (for example, saccades tend to "deviate" from frightened faces or violent scenes). Anatomically, this phenomenon is explained by the commonality of subcortical information processing between the Amygdala, which is involved in the processing of emotional information, the Pulvinar nuclei and the Superior colliculus, which are involved in saccades programming. However, there is a lack of empirical research focusing specifically on a single saccade trajectory in the presence of an emotional distractor stimulus.

In 2009, Nummenmaa et al. have found that the scene emotional load can affect saccade trajectories, even if the emotional scene is not associated with the task. The authors used a saccade trajectory as a dependent variable. Participants in their experiment were instructed to perform vertical saccades, the trajectory of which was orthogonal to the emotional and neutral images presented at a saccade onset. Therefore, all images were completely irrelevant to the task. The results showed a significant influence of the emotional image on the saccade curvature, which makes it possible to say that the oculomotor system is affected by the emotional contents of the scene, even if the emotional distractor is completely irrelevant to the task [7]. In 2012, Schmidt and colleagues replicated the study of Nummenmaa et al., but used emotional and neutral faces instead of emotional and neutral scenes [8]. Their results showed that the main effect of facial expressions was significant, however, only angry faces significantly changed the saccade trajectory.

Taking into account the results from Nummenmaa et al.'s and Schmidt et al.'s studies, it can be argued that the emotional load of a distractor image affects eye movement. Nevertheless, the stimuli used in these works (faces or scenes of violence) are quite simple in terms of visual information processing. Brain areas involved in visual perception and in the eye movements programming have a high speed of image processing, but are unable to analyse a stimulus in detail. This effect follows both from theoretical assumptions and experiments [9]: the more complex the object, the longer it takes for the attentional system to analyse the visual stimulus and the more delayed and the weaker the effect of saccade deviation from the distractor. In the experiment by Laidlaw et al., participants produced saccades from the fixation point to the target position, while task-unrelated (normally oriented or inverted), emotionally neutral faces or scrambled non-faces appeared on the screen. The results showed that face distractors affected saccade deviations, but only when the time latency between the distractor appearance and the saccade start were long enough. Weaver and colleagues decided to use more complex stimuli [10]. They investigated whether linguistic content could influence saccade trajectories. The results of Weaver et al.'s experiment showed that the main effect of emotional (taboo) and non-emotional words was similar at the interval from 100 to 400 ms, but then it acquired a statistically significant difference (800 ms).

Saccade trajectory deviations at short time intervals between a saccade start and the distractor appearance (100–400 ms) can be explained by the topographic and retinotopic maps changes, when, due to the appearance of black letters on a white background, the saccade deviates from a word as from a simple distractor without any semantic meaning. Neurolinguistic data also demonstrate that it is impossible to extract the word meaning at such early stages of visual information processing (Kutas & Hillyard, 1980). An evoked potential for a word, not corresponding to the context of a sentence, appears only 400 ms after reading this word (N400). Thus, in Weaver et al.'s experiment, time course plays a dual role: on the one hand, time is required for the semantic analysis of the word; while on the other hand, attention decrease occurs over time, and as a result, the saccade curvatures decrease as well. If in the interval from 100 to 400 ms it is quite possible to observe a linear decrease in the deviation of the saccade with time, in the interval from 400 to 800 ms the influence of the semantics of the word is also added to the trajectory of the saccade. This conclusion suggests that the saccade will not "straighten out" linearly in the interval from 400 to 800 ms, and that it is the interval in which the complex dynamics of competitive interactions between time and word meaning can be traced.

The main goal of our study was to find out how time intervals and emotional load of a word can affect exogenous (involuntary) attention. We addressed two questions: first, whether there is a difference in the saccade trajectories for emotional and neutral words, and second, how much time between word onset and the saccade initiation is necessary for this difference to emerge.

Accordingly, we hypothesized that (1) word meaning could affect saccades trajectories; (2) due to time latency necessary for semantic processing and for the transfer of semantic information to the attentional system, the difference in saccade trajectory deviations caused by emotional and non-emotional words will appear between 400 and 800 ms.

To address the first question, the intervals of 400 and 800 ms were used to replicate the effect found in Weaver et al.'s study. To address the second question, (1) the intervals of 500, 600 and 700 ms were additionally used for a more detailed study of the temporal processing dynamics, and (2) in addition to the saccade deviation analysed by Weaver and colleagues, the saccadic trajectory was also calculated through the initial and overall direction for a more detailed analysis of saccade trajectories dynamics.

2 Methods

2.1 Participants

Thirteen participants (8 females) aged from 18 to 22 studying at the National Research University "Higher School of Economics" were recruited for the experiment as volunteers. All participants had normal or corrected to normal vision, spoke Russian as a native language and were naive to our experimental hypotheses.

2.2 Apparatus, Stimuli and Procedure

Eye movements were registered using the EyeLink1000 + TowerMount eye-tracker. The automatic detection algorithm detected a saccade using speed and acceleration parameters 30°/s и 8000°/s2, respectively. For the calibration and validation procedure, nine points were used. The participants were allowed to proceed with the experiment, if the mean calibration error was less than 0.45° for all 9 points and less than 1° for each one point. The experiment was programmed using OpenSesame (a program to create experiments for psychology, neuroscience, and experimental economics) for an SMI display with 1920 × 1080 screen resolution. The distance between a participant's eyes and the experimental display was 62.5 cm. Thus, there were 39.5 pixels on the screen for one visual angle. To fix the participant's head position, a chin rest was used.

The stimulus set included ten neutral and ten obscene Russian words. Both sets of words were normalized for word length and word frequency as far as possible. By analogy with the study by Weaver et al., obscene words were used, because obscene vocabulary is more expressive than words denoting emotions. For example, the word "accident" in the ENRuN database of Russian emotional database [11] has a score of 3.47/5 on the fear scale, however, when a participant hears the word "accident", s/he does not feel the fear, although s/he knows that the word "accident" itself implies fear.

The experimental display consisted of a black fixation cross and three empty black rectangles (right, center, and left) in the upper half of the screen (Fig. 1). In order to obtain results with minimal difference from Weaver and colleagues' results, the distances between the fixation cross and the rectangles, the position of the rectangles relative to each other, as well as the sizes of the rectangles and arrows, were recalculated and programmed according to the parameters described by Weaver and colleagues in their study.

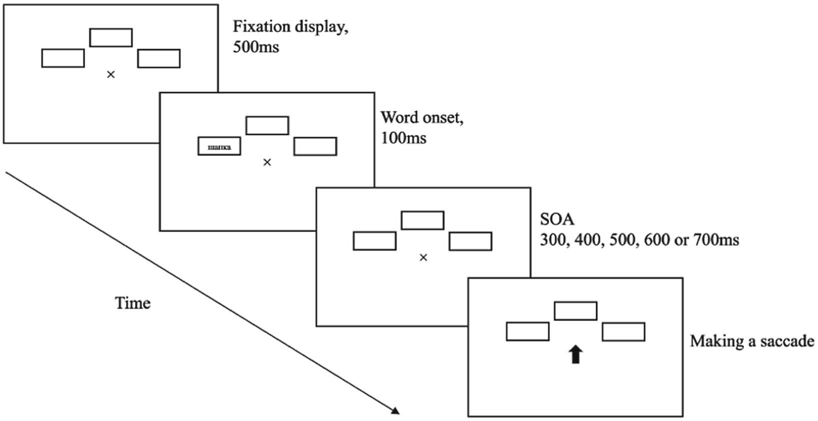

Fig. 1. Experimental procedure

2.3 Experimental Design

The saccade trajectory was used as a dependent variable. The time latency (time intervals between the word onset and the saccade start: 400, 500, 600, 700 and 800 ms) and word meaning (emotional or non-emotional) were used as independent variables.

3 Results

The Means and Standard errors for Saccade deviation, Overall direction and Initial direction for emotional and non-emotional words and different time intervals are presented in Table 1.

Table 1. Descriptive statistics for Saccade deviation, Overall direction and Initial direction

SOA	Word	Saccade deviation		Overall direction		Initial direction	
		M	SE	M	SE	M	SE
300	Emotional	0.134	0.111	0.073	0.131	0.094	0.095
300	Non-emotional	0.026	0.272	0.040	0.103	0.004	0.223
400	Emotional	0.0009	0.190	−0.019	0.121	0.004	0.164
400	Non-emotional	−0.196	0.331	−0.113	0.244	−0.198	0.258
500	Emotional	−0.102	0.519	0.006	0.095	−0.093	0.519
500	Non-emotional	−0.082	0.201	−0.055	0.111	−0.074	0.154
600	Emotional	0.021	0.155	−0.009	0.061	0.014	0.129
600	Non-emotional	0.072	0.156	0.157	0.466	−0.003	0.153
700	Emotional	0.084	0.288	−0.007	0.102	0.103	0.234
700	Non-emotional	0.093	0.119	0.084	0.101	0.066	0.113

To calculate the effects of time and word meaning on saccade trajectories, the repeated measures ANOVA (rmANOVA) was used. The main effect of word meaning (M = 0.03°, SD = 0.22 for emotional words and M = 0.06°, SD = 0.19 for non-emotional ones) on Saccade deviation wasn't found (F(1.9) = 0.51, MSE = 0.1, p = 0.5, η2 = 0.05), in contrast to the main effect of time (F (4.36) = 2.94, MSE = 0.05, p = 0.03, η2 = 0.25). The mean values of deviations for intervals of 400, 500, 600, 700 and 800 ms were M = 0.04°, SD = 0.14; M = 0.08°, SD = 0.21; M = 0.01°, SD = 0.27; M = 0.009°, SD = 0.21; M = 0.05°, SD = 0.17, respectively. However, the interaction of word meaning and time neutralized its effect (F (4.36) = 0.84, MSE = 0.07, p = 0.5, η2 = 0.08). An additional comparison of two extreme intervals of 400 ms and 800 ms by Student's test (t(37.97) = − 0.128, p = 0.89) also showed no significant differences (Fig. 2).

For Initial direction, the main effect of word meaning wasn't found either (F (1.9) = 1.2, MSE = 0.08, p = 0.3, η2 = 0.11), but the main effect of time was significant (F (4.36) = 1.2, MSE = 0.04, p = 0.035, η2 = 0.24). For the Overall direction, there were no significant effects of time (F (4.36) = 1.44, MSE = 0.05, p = 0.23, η2 = 0.13) and word meaning (F (1.9) = 0.15, MSE = 0.031, p = 0.7, η2 = 0.02).

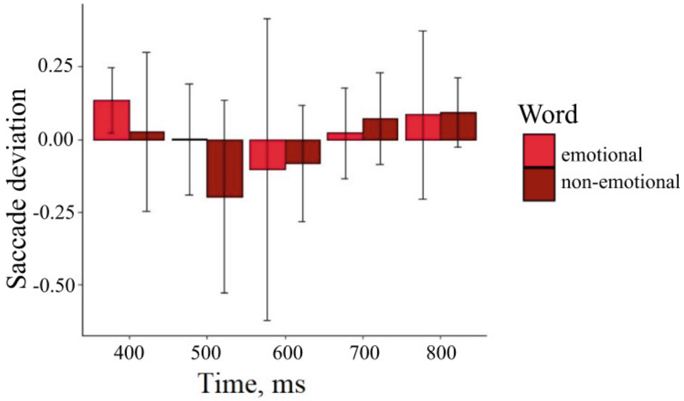

Fig. 2. Saccade trajectory deviation differences and standard errors for emotional and non-emotional trials.

4 Discussion

Despite many similarities in the experimental design, our results appear to be quite different from Weaver and colleagues'. First, we found no effect of word meaning. Second, the main effect of time for Saccade deviation ($F(4,36) = 2.94$, $MSE = 0.05$, $p = 0.03$, $\eta 2 = 0.25$) and Initial direction ($F(4,36) = 1.2$, $MSE = 0.04$, $p = 0.035$, $\eta 2 = 0.24$) was found. However, in Weaver et al.'s study, the effect of the emotional word for 400 ms interval was 5°, while in this experiment it was less than 0.1°; in Weaver and colleagues study, the average effect of a non-emotional word for an interval of 800 ms showed a deviation from the word; in this experiment, under the same conditions, saccades deviated to the word. There are a few possible explanations below as to why such discrepancies could emerge.

Differences in the Experimental Design. In Weaver et al.'s study, the participants performed saccades to the middle, right and left rectangles. In our experiment, participants were instructed to perform saccades from the fixation cross to the middle rectangle only (in order to save the participants' time and prevent fatigue). This procedure simplification reduced all the subject's actions to a single saccade, from fixation point to the middle rectangle.

Difference in the Stimulus Material. The words used in Weaver and colleagues' study might be different from the words which were used in this experiment, and we are not able to compare them directly because of the differences between cultures and languages.

Obscene Words. It is impossible to assess whether obscene words seem visually unacceptable to young people between the ages of 18 and 22 or not (in contrast to older generations).

Exclusions. During pre-processing, Weaver and colleagues excluded 16.7% of trials in which participants were making a saccade to an inappropriate location. In our experiment, according to a similar criterion, a much greater number of trials were excluded (from 35 to 60% for individual participants). A more detailed analysis of the saccade recording at low speed in the EyeLink DataViewer showed an interesting effect: the saccades with a big deviation from distractor, tend to slow their speeds halfway to the endpoint. The automatic algorithm interpreted this speed reduction as the end of the saccade and recorded its further movement as a second saccade, which ended on the target. This suggests that, in contrast to our experiment, Weaver and colleagues regarded such a saccade as one, which allowed them to obtain large values of saccadic deviations.

However, the automatic saccade detection algorithms reported by Weaver and colleagues contradicts that assumption: the algorithm used by Weaver and colleagues recognized the saccade using the velocity and acceleration parameters 30°/s and 8000°/s2 respectively, similar to the algorithm used in our study.

5 Conclusion

In this study, the competing interaction of time and word meaning in their influence on saccade deviations was studied. We attempted to determine the minimum time interval necessary for the word meaning to bias the saccade trajectory. However, we were able to only partially replicate the effects found in previous studies (in particular, we replicated the effect of time, but not the effect of word meaning). This suggests either there is no difference between emotional and non-emotional words, or the competitive interaction of word meaning and time is more complex than has been previously thought. Further investigations into the distractor word meaning effect on eye movements are necessary to find plausible explanations for the inconsistencies in experimental data.

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References

1. Junghofer, M., Bradley, M., Elbert, T., Lang, P.: Fleeting images: A new look at early emotion discrimination. Psychophysiology **38**, 175–178 (2001). https://doi.org/10.1111/1469-8986.3820175
2. Nummenmaa, L., Hyönä, J., Calvo, M.: Eye movement assessment of selective attentional capture by emotional pictures. Emotion **6**, 257–268 (2006). https://doi.org/10.1037/1528-3542.6.2.257
3. Eastwood, J.D., Smilek, D., Merikle, P.M.: Negative facial expression captures attention and disrupts performance. Percept. Psychophys. **65**, 352–358 (2003). https://doi.org/10.3758/BF03194566
4. Cardoso-Leite, P., Gorea, A.: Comparison of perceptual and motor decisions via confidence judgments and saccade curvature. J. Neurophysiol. **101**, 2822–2836 (2009). https://doi.org/10.1152/jn.91269.2008
5. McSorley, E., Haggard, P., Walker, R.: Time course of oculomotor inhibition revealed by saccade trajectory modulation. J. Neurophysiol. **96**, 1420–1424 (2006). https://doi.org/10.1152/jn.00315.2006

6. McSorley, E., Haggard, P., Walker, R.: The spatial and temporal shape of oculomotor inhibition. Vis. Res. **49**, 608–614 (2009). https://psycnet.apa.org/doi/10.10-16/j.visres.2009.01.015
7. Nummenmaa, L., Hyo’na, J., Calvo, M.: Emotional Scene Content Drives the Saccade Generation System Reflexively. J. Exp. Psychol. Hum. Percept. Perform. **35**, 305–323 (2009). https://psycnet.apa.org/doi/https://doi.org/10.1037/a0013626
8. Schmidt, J., Belopolsky, A., Theeuwes, J.: The presence of threat affects saccade trajectories. Vis. Cogn. **20**, 284–299 (2012). https://doi.org/10.1080/13506285.2012.658885
9. Laidlaw, K., Badiudeen, T., Zhu, M.J., Kingstone, A.: A fresh look at saccadic trajectories and task irrelevant stimuli: Social relevance matters. Vis. Res. **111**, 82–90 (2015). https://doi.org/10.1016/j.visres.2015.03.024
10. Weaver, M., Lauwereyns, J., Theeuwes, J.: The effect of semantic information on saccade trajectory deviations. Vis. Res. **51**, 1124–1128 (2011). https://doi.org/10.1016/j.visres.20-11.03.005
11. Lyusin, D., Sysoeva, T.: Emotional norms for nouns: the database ENRuN. Psikhologicheskii Zhurnal **38**, 122–131 (2017). (in Russian)

The Variety of Cognitive Decisions

Cognitive Mechanisms of Ambiguity Resolution

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Abstract. Here, we offer a reflection on ambiguity, its typology, production and effects as well as cognitive mechanisms of disambiguation. We approach ambiguity from the cognitivist viewpoint combined with elements of enactivism understood as embodied knowledge, interactivity and distributiveness. Without refuting the cognitivist paradigm or incurring into contradiction, we use these features as additional engines of our reflexing. Ambiguity is enacted by a network of heterogeneous participants (agents, subjects, objects) in various roles and with varying degrees of reflexive awareness and intentionality. Based on this we built a typology of ambiguity according to several criteria: the degree of awareness or intentionality, pragmatic effects achieved, language mechanisms, the volume of encoded conceptual information, the type of modality, and the number of events referred to. We hold that the process of disambiguation is triggered by cognitive context and conceptual primes over time, both in pre- and post-position.

Keywords: Ambiguity · Disambiguation · Manipulation · Cognitive context · Decision-making

1 Introduction

Ambiguity is an indispensable element of everyday communication. It is the embodiment of the flexibility of mind and the epitome of our interpretative cognitive functions. Despite numerous attempts to study the nature of ambiguity and its conceptual and pragmatic mechanisms [1–5], ambiguity, polysemy and vagueness [6–8] a further and more detailed study is required to explore its conceptual foundations, production mechanisms, typology and disambiguation decision-making.

One of the most renowned typologies of ambiguity was the one offered by Empson, who analyzed numerous examples of poetry. He saw ambiguity as “a verbal nuance giving room for alternative reactions to the same piece of language” [9]. Empson’s typology largely reflected the main sources of lexical ambiguity – metaphor, polysemy, and simile among others. Since the publication of his work, there have been several attempts to structure ambiguity [6, 10, 11]. However, most authors focused on the typology of lexical ambiguity only.

Whatever its type, there is always more than one interpretation, more than one understanding of a sentence, an utterance, an image, a gesture or even a situation. In the

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neurological sense, the processes, which enable the brain to select a one-way path to produce the mind-experienced awareness, are perception and interpretation. Ambiguity is not about undecidability in interpretation, it is about a choice or choices, which are based on the mental ability to perceive and interpret a complex environment without experiencing the subjective difficulty of having to solve problems and find solutions [12]. In Berthoz's domain, embodied experiences play a key role in the perception and interpretation of reality: it is the aggregate of the visual system, the brain and the entire body, which generate a visual impression. This impression is not felt as complex and problematic because all the available solutions are embedded in it. The same is true about language: language is a complex apparatus enabling the user (speaker, listener) to engage in complex interactions in a complex world without experiencing any difficulty. Berthoz names this property of complex living systems (like the visual system in the human brain) *simplexity.* It enables the experiencer to engage in interactions in a complex environment without experiencing its complexity, that is, without having to solve detected problems. Simplexity bridges the phenomenological mismatch between the complexity of systems and interactions modelled by specialists in a third-person perspective (as meta-cognitive observers) and the user-friendliness of structures and interactivity in a first-person perspective (as epi-cognitive agents and experiencers). Recent research extends this problematic to social science (ergonomy, management), including language [13]. In this perspective, ambiguity can be envisaged as a case of failure in simplexity: cognitive events in which ordinary simplexity, for some reason, appears to break down.

In our research, we attempted to reflect on ambiguity within an integrative approach, offering a trans-paradigm perspective on ambiguity by merging language and cognition. Specifically, we looked at ambiguity from the point of view of embodied and linguistic experiences.

2 Towards a Typology of Ambiguity

Building a typology of ambiguity is a tantalizing task. Ambiguity is conceptually elusive and, consequently, difficult to analyze given a variety of its types. A typology of ambiguity cannot be based on a single criterion or analyzed within one paradigm. Ambiguity requires a multifaceted approach developed on the cognitive, psychological, philosophical and linguistic basis. There are several questions to be considered before attempting a typology of ambiguity.

Temporality. When the enactive process of interpreting one semiotic situation (object, saying, a road sign, etc.) concludes on two possibilities or more, ambiguity occurs. Ambiguity is a result of several possible interpretations of one situation. Each situation can be interpreted as a mental representation of an event. By contrast, ambiguousness is the ongoing feeling experienced by a subject who cannot arrive at a conclusion, not even ambiguity as a result and conflict between two representations; and operational ambiguousness does not necessarily lead to conclusive representational ambiguity. Todorov defines fantastic literature in terms of experienced ambiguousness: a fantastic novel leaves the reader unable to decide whether mysterious events are to be ascribed to natural or supernatural causes from the beginning to the end of the narration [14]. Although dictionaries tend to consider those terms as synonyms, *ambiguousness* and *ambiguity* are sufficiently distinctive to occasionally occur together in literary criticism. First-order empirical, unreflexive ambiguousness is construed in a first-person perspective by an internal, engaged agent, while second-order reflexive, epistemic ambiguity is construed in a third-person spectatorial perspective by a disengaged observer. On this basis, ambiguousness and ambiguity are to be distinguished as epi-cognitive and meta-cognitive construals.

Nature of Ambiguous Items. The question is what kind of 'items' are good candidates for 'accidents', semiotic divergence and resulting ambiguity. In theory, natural objects and qualia are not prone to ambiguity. Natural objects are shaped by converging motor patterns, both intra-subjective (multimodality) and inter-subjective (standard routines, norms, civilized culture). In practice, some natural objects are intrinsically ambivalent in that they possess traits, which are normally typical of completely incompatible categories, for instance, animals looking like plants (biomimetism), mirages, etc. Fortunately, they are exceptions rather than the rule. It would be impossible to survive in the world when a table can be perceived as a table and something different. The same holds true about qualia.

Artefacts can be designed to be deliberately ambiguous, like the famous duck-rabbit. Such artificial ambiguity rests on the principle of closure in Gestalt psychology. The perception of the duck-rabbit depends on how the observer conduces the construal of the image, which is designed to present alternative paths, a kind of gestaltian labyrinth.

Language. A variety of linguistic features are prone to suggest diverging conceptual paths: lexical homonymy, homophony, homography, syntactic arborescence, the impossibility to manage some anaphoric chains (*John dropped Peter's hat, picked it up and put it on his head*). In this domain, lexical and grammatical ambiguity is language-specific. The English *language* does not distinguish between the general human faculty (the French *langage*) and the specific language spoken by a community (the French *langue*, which is also the living organ; see the English *tongue* with the same polysemy). Concerning anaphoric chains in syntax, in Basque, the translation of *his* is disambiguated by two possessives, the reflexive possessive *bere* (his = John's) and the obviative possessive *hare* (his = Peter's). English and French *we* and *nous* first-person plural pronouns do not explicit whether the addressee is to be included or not; many languages like guarani (Paraguay) distinguish two pronouns, the inclusive vs exclusive first-person plural pronouns. In English, *will* can be ambiguous in some contexts (prediction vs necessity), which cannot happen in German (*werden* unequivocally means either the future or *to become* depending on a syntactic position; and *wollen* means volition). In discourse, at the scale of entire sentences or cues, linguistic ambiguity tends to occur in written texts, whose reading is disconnected from the material environment of conversation. In situated speech, interpretation is distributed between verbal cues and non-verbal clues, so ambiguity is more uncommon. It does happen though, incidentally or intentionally, as in this remarkable instance (from a genuine conversation in French between two linguists): "Pourquoi me regardes-tu comme une bête curieuse?" "Why are you staring at me like/as if I were a curious animal?" In this context, *curieuse* can mean either *showing curiosity* or *bizarre*, and the construction relates this equivocal property either to the observing addressee *tu*, or to the observed speaker *me*. The question stalled the conversation, leaving all participants perplexed.

Phenomenological Networking of Ambiguities. Ambiguity is a cognitive event and as a cognitive event, it is distributed between a coalition of participants. It emerges from a network of agents and objects (being enacted by those agents) and cannot always be traced back to an unequivocal source. In France, some road signs by double carriageways say “Fin de limite de vitesse à 90 km/h” without telling the driver if he/she should accelerate to 110 or slow down to 70 km/h, which is a real nuisance when there is no obvious reason for slowing down. In this case, ambiguity is on the side of the driver, not on that of the designer of the sign. Obviously, ambiguity is accidental and unintended. The duck-rabbit, ambiguity is planned (intended) by the designer and performed by the observer.

Ambiguity is a distributed performance grounded in embodied cognition and carried out by a network of heterogeneous actors (agents, subjects, objects) having various roles, varying degrees of reflexive awareness and intentionality. With such criteria, it becomes possible to shift from a representational – computational approach to ambiguity to an enactive and distributed one. These two approaches are not incompatible as it may seem: embodied cognition reflects mental representations. The constituting processes differ in those two paradigms but the results very often converge, especially in the domain, of ambiguity.

With these in mind, we posit that ambiguity can be classified according to: the degree of awareness or intentionality (intended vs unintended ambiguity); pragmatic effect achieved (constructive vs destructive ambiguity); language mechanisms (lexical, morphological and syntactic ambiguity); volume of conceptual information encoded (fixed vs varying scope ambiguity); number of events referred to (event-referential ambiguity, several interpretations of one event vs a single reference to several events); type of modality (verbal and non-verbal ambiguity (visual ambiguity, gesture ambiguity and ambiguity of the situation)). The proposed typology of ambiguity is presented in Table 1.

Table 1. Proposed criteria and the typology of ambiguity.

Criteria	Types of ambiguity
Degree of awareness or intentionality	Intended ambiguity Unintended ambiguity
Pragmatic effect achieved	Constructive ambiguity Destructive ambiguity
Language mechanisms involved	Lexical ambiguity, morphological ambiguity syntactic ambiguity
Volume of conceptual information encoded	Fixed scope Varying scope
Number of events referred to	Event-referential ambiguity: reference to one event possible reference to several events
Types of modality	Verbal ambiguity Non-verbal ambiguity (visual, gesture, situational, etc.)

It should be noted that all types of ambiguity can be intended or unintended depending on the speaker's goal of using an ambiguous word or creating an ambiguous situation. Unlike vagueness, which does not lead to a polemic or controversy, ambiguity results from occasionally intentional cognitive sabotage. The speaker resorts to intended ambiguity to achieve a complex communicative effect. Pragmatic motives and communicative goals tend to blend in intended ambiguity since pragmatic factors and social variables are an inseparable part of any communicative act.

In most cases, intended ambiguity is used for manipulation – gaining control or forcing the recipient to make a decision that he or she probably would not have made. By opting for an ambiguous word or an ambiguous structure, the speaker distracts the recipient's attention. We argue that intended ambiguity leads to manipulation since when the speaker intends to alter the recipient's opinion or deliberately distort it. Manipulation and numerous techniques of achieving it have become a popular topic of linguistic narrative. Our analysis of extensive linguistic data shows that averaging, the use of ambiguous and vague lexis, euphemisms as well as different forms of modality expressing probability or likelihood are amongst the most popular techniques of achieving ambiguity.

Consider the following example:

A decade has not made the concept of Thatcherism attractive to the British people. According to Gallup (April 1989) the term Thatcherism has negative connotations ***for most people****. MORI (April 1989) found* ***widespread support*** *for the idea of a society which placed collective over individual values.* ***Surveys of attitudes*** *to so-called Thatcherite ideas (for example, a government sticking to its principles, however unpopular; not consulting with the major economic interests; and the government's inability to do much about unemployment) found that,* ***on average****, Thatcherite supporters (40%) were outnumbered by opponents (47%)* (https://www.english-corpora.org/bnc1/).

In this example, the lexis in bold – *for most people* (it is not clear for how many), *widespread support* (it is not evident how many people supported the idea), *surveys of attitudes* (it is not clear what attitudes were surveyed and how many respondents participated in the survey), create an opportunity to draw numerous inferences, which are made individually depending on a combination of pragmatic characteristics of the recipient, including his/her age, education, gender, social status, etc. These techniques of achieving manipulation result in several interpretations of the same event.

Unintended ambiguity occurs if the speaker, for some reason, perceives polysemy as monosemy. Our analysis of intended and unintended ambiguity has proved that intended ambiguity tends to be used for manipulation.

Constructive ambiguity can be defined as an intentional choice of words permitting the freedom to choose between several interpretations. Constructive ambiguity as a communicative strategy is often used in politics, diplomacy and international law. Moreover, the theory of diplomacy puts emphasis on the art of ambiguity and disambiguation in peace agreements. Pehar [15] notes that "while ambiguities have led to a continuation or re-starting of hostilities in some cases, in many other cases they have provided the only bridge between conflicting parties and allowed for a cessation of violence".

(https://www.diplomacy.edu/resources/general/use-ambiguities-peace-agreements).

We differentiate constructive ambiguity as a strategy and as a term denoting the phenomenon. The examples above illustrate the mastery of using ambiguous language for achieving a certain goal whereas the example below illustrates the use of the term 'constructive ambiguity' as such:

Last night's vote was a triumph for what diplomats call constructive ambiguity. To allow everyone in Serbia and Kosovo to be able to get on with the rest of their lives, we could do with a lot more of it. (https://www.economist.com/eastern-approaches/2010/09/10/brussels-trumps-inat).

Although most would like the IRA to disband completely rather than lurk in the wings, the judicious application of constructive ambiguity has helped to keep the peace process afloat. (https://www.economist.com/britain/2015/08/29/the-consequences-of-a-killing).

Initially, the term 'constructive ambiguity' was negative rather than positive. Consider the example below dating back to 2007:

Now was the time for the Eurocrat to deploy his most potent weapon: constructive ambiguity. "Why don't we make a reference to nuclear in paragraph 7, cross-ref it to another mention in paragraph 11, then cross-ref that to a report that nobody can remember reading?" he said, trying to stifle his excitement. Across the table, there were baffled looks: "What exactly does that mean?" asked one diplomat. "Precisely," shot back the Eurocrat. Diplomats call it "constructive ambiguity": wording an agreement — or a disagreement — so as to disguise the fact that there wasn't one (https://www.economist.com/middle-east-and-africa/2005/04/14/a-spat-of-sorts).

As we just said, constructive ambiguity was initially perceived as a destructive communicative strategy aimed at evasive and duplicitous responses. However later, it acquired a more positive if not completely positive meaning while retaining the initial negative one. This is an interesting example of enantiosemy – the term having two meanings, one of which is the opposite of the other.

This interpretation of constructive ambiguity is rather close to another subtype – strategic ambiguity. The two terms are often used interchangeably. In our earlier works, we interpreted the terms 'strategic' and 'constructive' as synonyms referring them to the same subtype [16]. However, further research has shown that strategic ambiguity may not necessarily be constructive since there are strategies aimed at achieving purely negative objectives. Similarly to constructive ambiguity, the term 'strategic ambiguity' has started to acquire a more positive meaning. This could probably be explained by both extralinguistic and linguistic factors – the primary meaning of 'strategic' as opposed to 'unplanned and chaotic' and numerous examples of strategic ambiguity for reaching a positive goal.

According to the criterion of language mechanisms, ambiguity can be classified as lexical, morphological and syntactic. These types of ambiguity result from polysemy, homonymy or syntax. Among these three types of ambiguity, lexical ambiguity is more frequent since lexis is more flexible and more easily responds to both extralinguistic and linguistic changes.

According to the volume of conceptual information encoded, we distinguish scope ambiguity, which can be of two subtypes – fixed or varying. Our research has shown that scope ambiguity is mainly achieved through the use of pronouns (it, they, we), quantifiers (every, all), negations, and adverbial modifiers. We deliberately chose an excerpt from the minutes of a regular business meeting to show the ubiquity of scope ambiguity:

> *I don't know if you're aware that using low sulphur coal, reduces only by 50% whereas if you use the other method it reduces by 90%, and what, in fact, Didcot are doing by that, is really not giving us a very good service. And, to top* **it**, *they are actually importing their coal which comes from Africa, which is another aspect (unclear). However, whatever, the reason why I mention* **it**, *I do notice that Greenpeace are thinking of, perhaps some members saw* **it** *in the press, did you, that Greenpeace are making a formal complaint to the European Commission about switching from de-sulphurisation to importing low sulphur coal, and it may be something that we should focus on it as well (*https://www.english-corpora.org/bnc/).

The pronoun *it* in the example above may refer to different things: in *to top it* it covers all the preceding conceptual information about methods, percentages, etc. In *why I mention it,* the pronoun may mean the whole problem of using coal, or the availability of different methods of reducing its negative impact on the environment or many other options. In *some members saw it in press* it may refer to an array of scenarios or situations related to carbon footprint, reducing emissions, using sulphur coal, etc. This example vividly shows a wide scope of conceptual information that can be encoded by a pronoun thus resulting in ambiguity.

The number of events a sentence may accidentally or intentionally refer to is another criterion of the proposed typology. Event-referential ambiguity is all about references rather than purely semantic meaning. We hold that this type of ambiguity has several subtypes: a possible reference to two or more events in one context, numerous interpretations of the same event and a reference to different events occurring in different contexts. We analyzed the first subtype in more detail in our earlier work [16].

In this paper, we will reflect on another subtype of event-referential ambiguity, in which a sentence activates three different contexts as shown in the following example: (Rus.) *Он гуляет* (*on guliaiet*, informal), which may mean a) he has gone out for a walk and is walking; b) he is having an affair and is cheating on his wife; and c) he is having a rowdy party. One sentence refers to three completely different events – a walk, an affair and a party.

There are examples of several possible interpretations of the one event in the same context. For instance, the interpretations of *The paper is ready to be delivered* may vary from *The paper is ready so I can deliver it now* or *The paper is ready so it can be delivered by somebody else* or even *The paper is ready so it can be delivered to somebody else.*

According to the type of modality, ambiguity can be categorized into verbal and non-verbal, the latter is represented by such types as visual ambiguity, ambiguity of gestures and ambiguity of a situation. Visual ambiguity is known to be caused by multistable perception. The earliest known, the famous duck-rabbit, dates back to 1892. Research has shown that the viewer sees only one image at a time. However, there is an instant of ambiguity or fuzziness in which neither object is clearly perceived [17]. This can be explained by object consistency – the ability to recognize objects from different viewing positions, differently colored or seen from abnormal angles [18]. Holistic perception as a form of perceptual analysis also plays an important role in the recognition and, consequently, in the disambiguation of reversible image.

Non-verbal ambiguity also includes ambiguous gestures and situations, which are mainly studied in cognitive psychology and social science. Gestures are known to facilitate disambiguation. However, recent research shows that gestures may both perform the function of a context to an ambiguous sentence or verbal descriptions can operate as a context to resolve the ambiguity of a gesture [17]. Similarly to gestures, ambiguous situations invite more than one interpretation. Having found themselves in an ambiguous situation, participants tend to seek resolution sometimes unconsciously [19]. Non-verbal ambiguity (there is more to it than just the types described above, for instance, the ambiguity of facial expressions, body language, etc.) needs further trans-disciplinary research.

3 Ambiguity Perception and Resolution

Ambiguity is experienced as an unanswered question, which is reconstructed *a posteriori*: "what is that thing", or "what does the sentence mean". It happens when automatic construal fails at the moment of encountering diverging conceptual paths, which creates a dilemma. Facing ambiguity, interlocutors have to extract meaning from what they hear. From the point of view of perception, ambiguity: 1) can be perceived in the intended way with the intended meaning and the message extracted. This occurs when interlocutors have common conceptual ground, knowledge, attitudes and strive for 'interactive alignment' [6]; 2) may remain unnoticed by the recipient due to several reasons: pragmatic factors, different level of the development of the conceptual system and, finally, linguistic factors (as is the case with non-native speakers). From the point of view of its pragmatic effect, ambiguity may be enjoyed by the recipient (for instance, in humorous discourse) or it may complicate the understanding of a message and result in a communicative failure. The recipient may not have sufficient background knowledge to resolve ambiguity or may make wrong inferences due to differences in the combination of cognitive, social, professional, value and gender attributes.

It has long been known that ambiguities require much more time and effort to understand that unambiguous sentences or structures [18–20]. Psychological consequences of ambiguity result in its slower perception. Experiments demonstrate that it takes longer to process sentences with three meanings than those having two or one [1]. Disambiguation is a complex cognitive process involving a whole array of conceptual structures ranging from separate concepts to conceptual scenarios or scripts. Generally speaking, the 'right' meaning is inferred from context, which is understood broadly as any type of information, which can be used for resolving the ambiguity dilemma (conceptual, linguistic, visual, etc.). Each meaning is activated by a different clue – a prime. Consider the following example of the polysemous word *brain.* The Word Net 3.1 entry of the noun *brain* describes the following senses:

1. brain, encephalon (that part of the central nervous system that includes all the higher nervous centers; enclosed within the skull; continuous with the spinal cord).
2. brain, brainpower, learning ability, mental capacity, mentality, wit (mental ability).

3. brain, psyche, nous (that which is responsible for one's thoughts, feelings, and conscious brain functions; the seat of the faculty of reason).
4. brain, genius, mastermind, brainiac, Einstein (someone who has exceptional intellectual ability and originality).
5. brain as food (WordNet3.1).

Search hits from several corpora – iWEB, BNC Corpora and the linguistic application (https://ludwig.guru) provide numerous examples of different senses, each having a different prime, mostly in pre-position. Primes are given in bold:

(1) *So these* ***channels****show significant although not extensive sequence homology with the* ***nicotinic acetylcholine receptor,****which enables you to place them in the same class of being a* ***ligand binding channel****. Had* ***similar evolutionary origins****. It* ***binds barbiturates****. Similarly, the* ***glycine receptor****is also an* ***inhibitory chloride channel****, also found in* ***brain****and closely related to the G A B A, A receptor.*

(2) *I'm resisting temptation to get involved in this* ***debate****. Let's stick to this concept. I welcome it, I think* ***it shows good thinking****on the part of our* ***officers****and I would like to suggest that er, I* ***take er, a back seat****on this one, and I, I, I'd feel probably,* ***set up a sub-committee****, I would think* ***four or five is ample****, and I would like to propose that Malcolm* ***chairs this meeting****, so that we* ***have a fresh brain****and* ***a younger brain****,* ***looking at****the future's problems. How do you feel about it?*

(3) *It is not so much that* ***machine learning****will be* ***superior to our brain****, but that* ***our brain****extended with machine learning will be superior to* ***our brain****without it.* (https://www.english-corpora.org/bnc/).

In each example, the noun *brain* is used in one of its meanings being primed by a set of conceptual (semantic) clues, which gradually shape a conceptual scenario with the adequate sense of the word *brain* filling in one of its conceptual lacunas. For instance, consider example (1), in which the noun *brain* means 'part of the central nervous system that includes all the higher nervous centres; enclosed within the skull'. The sequence of conceptual clues looks as follows: *channels – sequence homology – nicotinic acetylcholine receptor – enables – class – ligand – binding channel – evolutionary origins – binds – barbiturates – glycine – receptor – inhibitory chloride – channel.* These primes help activate the intended sense of the word since they gradually create a mental picture of the brain as a human organ in its purely anatomical or biochemical sense. One may argue that even the immediate environment, *found in brain*, is enough for disambiguation since it brings about the idea of brain as an organ. However, this narrow context would not disambiguate the two senses – brain as an organ and brain as food. In example (2) the noun *brain* is used metaphorically meaning 'people'. The identified conceptual clues create a scenario of a meeting, debate, election or appointment: *debate – good thinking – officers – suggest – take a back seat – set up a sub-committee – I would like to propose – chairs a meeting.* Example (3) demonstrates the use of the noun *brain* in the sense 'brain power, mental ability'. This sense is activated by the primes *machine learning – superior* to and is an indispensable part of a scenario of the battle between artificial and human intelligence.

The question about the number and character of primes required for the disambiguation remains open and needs further research. For instance, consider the primes in example (1) *channels – sequence homology – nicotinic acetylcholine receptor – enables – class – ligand – binding channel – evolutionary origins – binds – barbiturates – glycine – receptor – inhibitory chloride – channel.* Undoubtedly, they help activate a whole scenario for disambiguation. However, the question is how many primes are needed for disambiguation. Would just two be enough – *receptor* and *channel*? None of the meanings of the noun *brain* fits the context delineated by these two nouns.

Another interesting observation comes from the fact that ‘wrong’ interpretations of meaning, or ‘wrong’ inferences are kept in the working memory for several seconds [18, 20]. It means that primes in post-position may also facilitate disambiguation. It happens in humorous discourse, when in comedic timing the punch line comes long after the clause boundary thus allowing the listener time to pursue wrong interpretations, but quickly enough to ensure that the original word or phrase that activated the multiple meanings is still available in working memory after the punch line (ibid). In our example (2), *so that we have a fresh brain and a younger brain, looking at the future’s problems*, ‘looking at the future problems’ may act as a prime in post-position. Let us abridge example (2):

I would like to propose that Malcolm chairs this meeting, so that we have a fresh brain and a younger brain, looking at the future’s problems. How do you feel about it?

Or even shorter:

We have a fresh brain and a younger brain, looking at the future’s problems. How do you feel about it?

Therefore, we conjecture that both types of primes, preceding the ambiguous word and primes in post-position, are crucial for resolving ambiguity.

4 Conclusion

Ambiguity is a complex conceptual phenomenon, which requires transdisciplinary research. In essence, it is a distributed biosemiotic performance grounded in embodied cognition and carried out by a network of heterogeneous actors in various roles and with varying degrees of awareness and intentionality. It is enacted by a coordination of participants (agents, subjects, the objects they produce, the environment; all of this depending on individual and collective autopoiesis. As a complex perceptual and conceptual phenomenon, ambiguity becomes even more challenging when combined with generality, vagueness or sensitivity to context. The proposed typology of ambiguity is based on several criteria – pragmatic factors and the pragmatic effect achieved, language mechanisms, the volume of conceptual information encoded by an ambiguous word or phrase, the number of events referred and the type of modality used. These types are further divided into subtypes offering a more detailed understanding of the mechanisms of the phenomenon.

Ambiguity is processed through the complex cognitive process of disambiguation. It involves a whole array of conceptual structures ranging from separate concepts to larger conceptual representations. The intended meaning is inferred from cognitive contexts with the help of primes. Traditionally, primes have been studied in preceding positions. However, we argue that primes in post-position are also crucial for disambiguation since they remain activated long enough to draw relevant inferences. Each sense of a word is primed differently by primes in pre- and post-position. Further research into ambiguity should combine a variety of traditional linguistic and novel cognitive and psycholinguistic approaches for a deeper understanding of its sources, types, functions and mechanisms of disambiguation.

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References

1. Barsalou, L.: Context-independent and context-dependent information in concepts. Mem. Cognit. **10**, 82–93 (1982). https://doi.org/10.3758/BF03197629
2. Croft, W.: Quantifier scope ambiguity and definiteness. In: Dahlstrom, A., et al. (eds.) Proceedings of the Ninth Annual Meeting of the Berkeley Linguistics Society, pp. 25–36. Linguistic Society of America (1983). https://doi.org/10.3765/bls.v9i0.2018
3. Garrod, S., Pickering, M.: Why is conversation so easy? J. Trend Cogn. Sci. **8**(1), 8–11 (2004)
4. Sennet, A.: Ambiguity. In: Zalta E.N. (ed.) The Stanford Encyclopedia of Philosophy (2016). https://plato.stanford.edu/archives/spr2016/entries/ambiguity/
5. Wasow, T., Perfors, A., Beaver, D.: The Puzzle of Ambiguity. Stanford University, Stanford (2003). https://www.stanford.edu/~wasow/Lapointe.pdf
6. Lakoff, G.: A note on vagueness and ambiguity. J. Linguistic Inquiry. **1**(3), 357–359 (1970). https://www.jstor.org/stable/4177575
7. Schick, F.: Ambiguity and Logic. Cambridge University Press, Cambridge (2003)
8. Tuggy, D.: Ambiguity, polysemy and vagueness. J. Cognitive. Linguist. **4**(3), 273–290 (1993)
9. Empson, W.: Seven Types of Ambiguity: A Study of Its Effects on English Verse. New Directions Publishing Corporation, New York (1966)
10. Yuzhannikova, M.: A typology of linguistic ambiguity. J. Siberian Fed. Univ. Humanit. Soc. Sci. **3** (8), 533–541 (2015)
11. Zalizniak, A.: The phenomenon of polysemy and ways to describe It. In: Rakova, M., Pethő, G., Rákos, C. (eds.): The Cognitive Basis of Polysemy. New Sources of Evidence for Theories of Word Meaning. Metalinguistica, vol. 19, pp. 93–121. Frankfurt am Main (2007)
12. Berthoz, A., Petit, J.L.: Complexity-Simplexity. Collège de France, Paris (2014). https://doi.org/10.4000/books.cdf.3339
13. Bottineau, D.: Les langues naturelles, objets complexes, systèmes simplexes: le cas du basque. In: Louis Begioni et Paola Placella (eds), Problématiques de langues romanes, linguistique, politique des langues, didactique, culture. Linguistica. **69**, 55–85 (2015)
14. Todorov, T.: Introduction à la Littérature Fantastique. Seuil, Paris (1970)
15. Pehar, D.: Diplomatic ambiguity: from the power-centric practice to a reasoned theory (2005). https://www.academia.edu/846829/Diplomatic_ambiguity_from_the_power_centric_practice_to_a_reasoned_theory_2005_Polemos_
16. Zabotkina, V.I., Boyarskaya, E.L.: Conceptual foundation of event-referential ambiguity. In: 5th International Multidisciplinary Scientific Conference on Social Sciences and Arts, vol. **5**(3.6), pp. 143–148. Albena, Bulgaria (2018)
17. Louwerse, M.M., Bangerter, A.: Effects of ambiguous gestures and language on the time course of reference resolution. Cogn. Sci. **34**(8), 1517–1529 (2010). https://doi.org/10.1111/j.1551-6709.2010.01135.x
18. Gazzaniga, M.S., et al.: The Cognitive Neurosciences, 4th edn. MIT Press, Cambridge (2009)

19. Wakeham, G.: Uncertainty: the history of the concept. In: Wright J.D. (ed.) International Encyclopedia of the Social & Behavioral Sciences (Second Edition), pp. 716–721 (2015)
20. Revlin, R.: Cognition: Theory and Practice. Worth Publishers, New York (2013)

Psychophysiological Interactions Underlying Meaning Selection in Ambiguity Resolution

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Abstract. In the present study, the interactions among brain areas involved in the processing of non-selected meaning while dealing with ambiguous word pairs were investigated. The study was aimed at clarifying the question of which brain structures and how exactly are involved in supporting the processes of unconscious selection of one of the meanings of a word and what can happen, at the same time, with its unselected meaning. Philips Achieva 3 T MRI scanner was used to obtain fMRI data on 17 healthy right-handed subjects performing the task of completion of adjective-noun pairs comprising words with missed letters: ambiguous pairs, as compared with unambiguous ones, had at least two variants of completion. Psychophysiological interaction analysis was conducted for the volume of interest located within the right and left hippocampus in which the effect of decreased BOLD signal was revealed in previous study. As a result the modulatory effect of the automatic disambiguation process on the functional coupling between the region of interest in the left hippocampus and the left and right inferior frontal gyrus, right caudate nucleus, the right inferior and superior parietal lobules (BA 39/7). The completion of ambiguous word pairs, as compared with unambiguous ones, was associated with a decrease in functional interactions within these integrated brain regions. The revealed data demonstrate the new evidence for involving the processes of suppressing unselected word meanings when choosing the meaning of an ambiguous word.

Keywords: Ambiguity · Inhibition · Functional MRI

1 Introduction

Humans store and process millions of bits of information during language acquisition, the majority of which is lexical semantics. On average we extract over 2000 bites of linguistic and more widely semantic data a day [1]. Most of it is ambiguous; so much more neuro-physiological activity is needed to choose a contextually relevant variant which is crucial for understanding the message. Language deals with many interconnected levels: lexicon, semantics, syntax, type and token frequencies, etc., therefore necessary cerebral

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computational capacities are enormous. Meaning (rather than syntactic structures, as previously accepted) must be the first generative component evoking the appearance and further development of language. The main concept is that of a parallel architecture in which phonology, syntax, the lexicon, and semantics are independent generative systems connected to each other via interfaces, and it is consistent both with neuroscience data and the mental theory of semantics [2]. General principles controlling both language and biological evolution are discussed, functional change and ambiguity before structural change and specialization is one of them [3–5].

Dealing with ambiguity is a challenging task. For instance, practically every word is ambiguous. Therefore, the cognitive system and the brain should have flexible and effective mechanisms to select one particular meaning among several possible. Considering one of the possible mechanisms of such ambiguity resolution, we focused on one of the proposed hypotheses that the unconscious process of automatic disambiguation while dealing with ambiguous stimuli heavily relies on the suppression of the non-selected meaning [6–8]. This hypothesis was supported by our recent fMRI study [9], which demonstrated that the process of completion of ambiguous word pairs, as compared with unambiguous pair, was associated with decreased hemodynamics in the posterior hippocampus bilaterally. This finding corresponds to the wide range of effects of willful or automatic forgetting exhibited as changes in interactions between the dorsolateral prefrontal cortex and hippocampus [10]. For instance, in a study [11] it was demonstrated that effective suppression of information for memorization led to a decrease in the coupling between the hippocampus and the left DLPFC. Although this suppression process was related to fulfilling instructions, we expected that similar functional coupling changes would be observed when such or similar but unconscious type of suppression will be involved in ambiguity resolution. This prediction was also based on the notion that suppression of hippocampal activity is associated with suppressing the memory traces in both human and rodent brain [12].

To test our prediction, we analyzed the interactions between brain areas involved in processing non-selected meanings with ambiguous word pairs. In a current study, the experimental model assumed that conditions required the completion of visually presented phrases with missing letters, which consisted of a pair of words “adjective-noun”. For example, the following phrases were presented: “mja-noj far-” ([mjasnoj farš], ground meat), “-ootballnui f_nat” ([“futbol’nyj fanat”], soccer fan), etc. Created research design provided an opportunity to assess the aftereffect of the selection (or rejection) of a word meaning. At the same time, this stimulus repeatedly encountered in different contexts, with semantic priming (requiring a different solution, for example, when presenting “mya_noi -arsh” (ground meat) after “vo_nnui -arsh” (military march)). The process of choosing the word meaning was controlled by the post-study survey of supposedly unconsciousness decision during the experiment. It was used to identify and reject samples in which both variants of completing phrases were recognized.

2 Method

2.1 Participants

The current fMRI study was conducted with the participation of 17 volunteers (7 males, 10 females) with the mean age 26.3 ± 4.5. Before the beginning of the experiment, participants gave written informed consent and completed the Edinburgh Handedness Inventory (Oldfield, 1971) All procedures were approved by the Ethics Committee of the N.P. Bechtereva Institute of the Human Brain, St. Petersburg, Russia. All volunteers were right-handed native Russian speakers without a history of psychological, neurological diseases or current medication intake.

2.2 Stimuli and Procedure

During the experiment, participants saw Russian adjective-noun pairs with missing letters on the screen (for example, “mja-noj far-” (“mjasnoj farš”,), “-utbol’nyj f-nat” (“futbol’nyj fanat”) etc.). They were instructed to complete these phrases explicitly. Depending on the position of a missing letter in the noun word, all stimuli were divided into two groups: 1) unambiguous phrases (could be correctly completed only in one way – “mja-noj far-”, “vo-nnyj ma-š”); 2) ambiguous phrases (had at least two variants of completion – “mja-noj -arš”, “vo-nnyj -arš”, where “-arš” can be completed both as “marš” and “farš”). In the ambiguous condition, the relevant variant of completion was unconsciously selected due to the context created by an adjective. In addition, the current experimental design allowed to estimate the priming effect of the selected/non-selected meaning during the second encounter with the same uncompleted noun with a different adjective, when a different meaning had to be selected (for example, the presentation of “mja-noj -arš” after “vo-nnyj -arš”).

The list of 96 stimuli (adjective-noun pairs) grouped into 12 lists was used in the fMRI study. The interval between repeatedly presenting phrases that were similarly looking but requiring different completion (depending on the context specified by an adjective) has consisted of the three trials.

Stimuli were presented on the screen for 5 s. Participants were instructed to press the button on the MR-compatible controller when they recognized the phrase and spell the completed variant (the voice was recorded throughout the experiment with the MR-compatible microphone with a noise reduction). The phrase remained on the screen for 5 s, regardless of the pressing of the button. Then the fixation cross was presented on the screen for 3 s or 8 s (the time was chosen with the 50:50 probability). Next, the new stimulus was presented on the screen. One fMRI study lasted for 16.8 min.

According to the pilot study, in some cases, participants realized multiple variants of completion for some phrases. To distinguish these phrases after completing the main experiment, participants filled a questionnaire. In this questionnaire, the phrases from the main task were presented in chronological order. The task was to indicate how many meanings a volunteer recognized for named phrases. Based on the answers, phrases for which a participant recognized both variants of completion were distinguished in an additional type of stimuli was distinguished. For example, if the phrase “s-hoe-ino” was presented on the screen and the participant indicated that, besides “suhoe vino”, he or she remembered/recognized the second variant of completion of the noun "-ino" – "kino", this phrase was classified as a double meaning condition. Phrases with explicitly recognized double meaning were excluded from further analysis.

Those trials in which participants did not recognize the second variant of completion of the noun were crucial for the study's central purpose to explore mechanisms of automatic processing of the non-selected meaning in ambiguity resolution settings. To our knowledge, this is the first study in the research field that controls for the number of recognized meanings. Another advantage of the current experimental design was that the same words were used in different conditions (types of stimuli) participants and, therefore, the effect of a particular word meaning was eliminated.

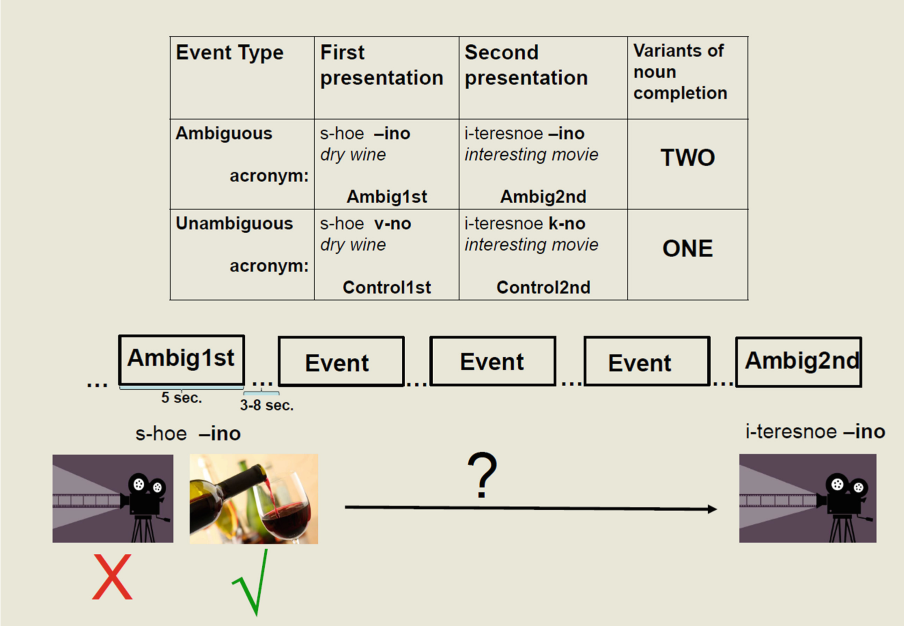
To sum up, experimental events of interest in the fMRI study was divided in the following way: 1) Ambig1st – the first presentation of an ambiguous noun (for example, "vo-nnyj -arš" – the variant of completion "marš"); 2) Ambig2nd – the second presentation of an ambiguous noun (for example, "mja-noj -arš" – the variant of completion "farš"); 3) Control1st – control condition for the condition Ambig1st – the presentation of an uncompleted noun that has to be finished the same way as the noun in the condition Ambig1st and is presented first in the pair like "marš-farš" ("vo-nnyj ma-š" – one variant of completion "marš"); 4) Control2nd – control condition for the condition Ambig2nd – the phrase "mja-noj far-" presented after "vo-nnyj ma-š". Figure 1 illustrates the scheme of the experimental design. Phrases in Ambig1st and Ambig2nd conditions and Control1st and Control2nd conditions were presented with the three stimuli interval.

2.3 fMRI Image Acquisition Procedure and Image Processing

The fMRI data (structural and functional) was recorded using a 3T Phillips Achieva scanner with the 8-channel receiving coil (Philips Medical Systems, Best, Netherlands). The specialized system for presenting visual stimuli NordicNeurolab was used to synchronize stimuli presentation (using E-prime) with participants' responses (by pressing the button) and BOLD signal registration in the scanner.

Structural images for each participant were recorded using T1-weighted pulse sequences of high resolution (T1W-3D-FFE; [TR] = 2.5 ms; [TE] = 3.1 ms; flip angle = 30°; 130 slices, [FOV] = 240 × 240 mm; matrix = 256 × 256, slice thickness = 0.94 mm). Functional images reflecting BOLD signal changes were obtained with echo-planar imaging (EPI) sequences (so-called dynamic scans): the registration time of 32 axial slices was 2 s (TE = 35 ms) with the FOV 208 × 208, flip angle = 90° and pixel size 3 × 3 mm. The thickness of the slices was equal to 3 mm. Individual structural images were further used for spatial normalization of individual data into a standard stereotactic space and for creating a mean grey matter image used as an "explicit mask" in the fMRI-data analysis (allowed to perform the statistical analysis only for those voxels, which were localized in the grey matter for all participants.

Individual dynamic scans have undergone several steps of preprocessing: 1) realignment of all images relative to the first dynamic scan with the calculation of head movement parameters; 2) slice-time correction; 3) normalization of functional images into a standard stereotactic space with the coregistration of structural T1-image with the first dynamic scan and its segmentation; 4) Gaussian smoothing (8 mm, FWHM). Preprocessing and statistical analysis were performed using the SPM12 software package



Event Type	First presentation	Second presentation	Variants of noun completion
Ambiguous acronym:	s-hoe **–ino** *dry wine* **Ambig1st**	i-teresnoe **–ino** *interesting movie* **Ambig2nd**	**TWO**
Unambiguous acronym:	s-hoe **v-no** *dry wine* **Control1st**	i-teresnoe **k-no** *interesting movie* **Control2nd**	**ONE**

Fig. 1. The scheme of the experimental design in the fMRI study. The table illustrates types of experimental conditions, the BOLD signal during which was analyzed to test experimental hypotheses. Pictures in the lower part illustrate variants of completion of the noun "*-ino*" ("*vino*" or "*kino*"). In the case, when the noun "*-ino*" is presented with the adjective "*s-hoe*", the context facilitates the unconscious choice of the variant "*vino*". The study tested if the alternative variant of completion ("*kino*") is inhibited during this choice. Another question was if this complicates the process of selection of supposedly inhibited variant during the second encounter (with the three stimuli interval) with the same noun "*-ino*", but in the context of the adjective "*i-teresnoe*").

(Statistical parametric mapping 12) running in Matlab (2012b, Mathworks Inc., Natick, MA, USA).

2.4 Psychophysiological Interactions Analysis

To analyze functional interactions characterizing the process of suppression of non-selected meaning during the unconscious meaning selection while dealing with ambiguity the generalized form of psychophysiological interactions analysis (gPPI-analysis) was performed. The gPPI-analysis allows to detect areas of the brain that change functional interactions with the predefined region of interest (ROI) in association with performed task. Importantly, the analysis is performed for all voxels in the brain. According to set goals the area in the posterior hippocampus was selected as the 4 mm-radius sphere ROI in the current study. This choice is supported by previous analysis and literature data.

Previously performed analysis of changes in local neuronal activity for the t-contrast "Ambig1st < Control1st" revealed significant changes in the BOLD signal in a number of areas including the posterior hippocampus bilaterally. Thus, compared to control condition with only one variant of completion of the word (Control1st), the unconscious choice of the right variant of completion of the same noun in ambiguous condition (Ambig1st) is characterized by significant decrease of the BOLD signal in bilateral posterior hippocampus. This is explained by the involvement of brain mechanisms of inhibition, which are activated to suppress the non-selected meaning in the settings of ambiguity. Besides, in neurophysiological literature the decreased activity in hippocampus is associated with the retrieval induced forgetting (RIF) (Anderson, Bjork, & Bjork, 1994).

Therefore, it is justifiable to assume that the ROIs in the hippocampi demonstrates the involvement in the process of suppression of non-selected meaning through changing its distant functional interactions.

On the first (individual) level of statistical analysis changes in functional interactions were assessed for each participant separately using the generalized linear model (GLM). GLMs included following regressors: 1) six PPI regressors for experimental conditions Ambig1st, Ambig2nd, Control1st, Control2nd, double meaning, and a separate regressor for trials, in which participants gave wrong variants of completion or did not give an answer; 2) six regressors used in the classical analysis for same events as PPI regressors (modelled with onset times of stimuli presentation); 3) regressor, representing time series of the mean BOLD signal in all voxels in the ROI; 4) 6 regressors representing head movement parameters obtained on the realignment step of preprocessing [13]. To calculate PPI regressors BOLD signal time series in the ROI were first deconvolved with the hemodynamic response function to reveal the underlying neuronal activity and then multiplied by stimuli onset times. All regressors were convolved with the standard hemodynamic response function and beta-coefficients of regression were estimated.

In the second (group) level of analysis participated beta-coefficients of linear contrasts “experimental condition” > “baseline” obtained on the individual level. The voxel-wise analysis was performed using the random effects model. The statistical inference was made based on the classical frequentist statistics with the voxel-wise threshold $p < 0.05$ corrected for multiple comparisons using the family-wise error corrections method (FWE).

3 Results

From two posterior hippocampal ROI analyzed in the current study significant changes in the psychophysiological interactions were revealed only for the left posterior hippocampus. In the Ambig1st > Control1st t-contrast between parameters of psychophysiological interactions, the modulatory effect of the automatic disambiguation process on the functional coupling between the region of interest in the left hippocampus and the left inferior frontal gyrus, right caudate nucleus, the right inferior and superior parietal lobules (BA 39/7) was revealed. The completion of ambiguous word pairs, as compared with unambiguous ones, was associated with a decrease in functional interactions within these brain regions (Fig. 2 and Table 1).

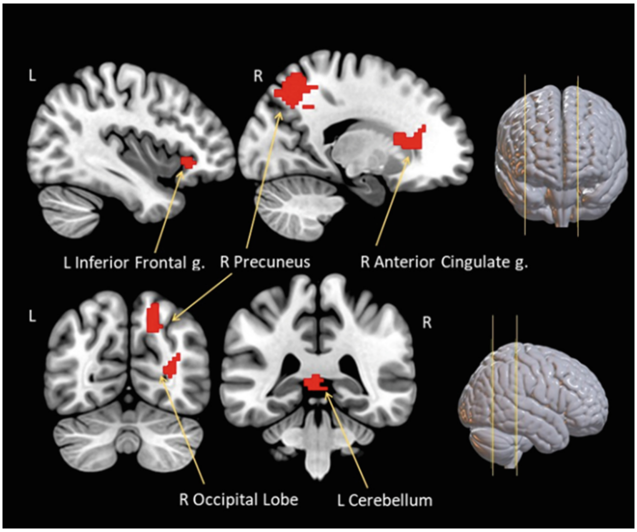


Fig. 2. Changes of functional interactions with the left hippocampus. Denotations: L/R – left/right hemisphere; g. – gyrus.

Table 1. Decreases of functional interactions with the left hippocampus associated with processing of non-selected meanings.

Brain region	Cluster level p-value (FWE-corrected)	k	T-value	Z- value	Peak MNI coordinates		
					x	y	z
R anterior cingulate gyrus/Caudate n./Middle frontal g	< 0.001	167	6.74	4.58	18	35	20
R occipital lobe/White matter	0.037	68	5.54	4.08	30	−67	14
L inferior frontal g	0.02	81	5.5	4.06	−39	26	−4
R precuneus	< 0.001	260	5.4	4.02	18	−58	47
L cerebellum	0.019	82	4.6	3.62	−3	−40	−4

Denotations: L/R – left/right hemisphere; k – cluster size in voxels; FWE – family-wise error; g. – gyrus; n. - nucleus.

4 Discussion

Considering that both the reduction of the BOLD signal in the left hippocampus and the reduction in its connectivity with prefrontal and parietal brain regions were associated with automatic disambiguation, the revealed data supports the hypothesis of suppression of the unselected meaning. Theoretically, this effect is close in its manifestation of the so-called *forgetting effect* associated with retrieving information from memory (retrieval-induced forgetting [14]), which at the neurophysiological level can manifest itself as a relative decrease in the activity of hippocampus. In line with this, a similar decrease in functional coupling between the hippocampus and the prefrontal cortex was observed in a number of situations where inhibition of competing memory is expected [12, 15, 16]. In such studies, the willful forgetting was associated with decreasing the hippocampus's local activity and decreased hippocampal-prefrontal coupling. Moreover, the greater the need to suppress the memory was imposed, the greater the connectivity decrease was observed [16].

In this respect, the present study, for the first time, demonstrated that similar connectivity changes could be revealed not only in forgetting-related conditions. Revealed results show the new evidence for involving the processes of suppressing unselected word meanings when choosing the meaning of an ambiguous word. This substantially impacts the previous neurobiological data and shows that inhibition-related activity can play a prominent role in comprehension based ion selection between two possible meanings. This also demonstrates that retrieval-induced memory suppression/forgetting, ambiguity resolution, and willful forgetting could be executed via similar neurobiological mechanisms of the fundamentally identical cognitive process of suppressing competing/alternative meaning. Our data show economical and therefore effective algorithm that the brain has developed to deal with dynamic and ambiguous surroundings. Biologically this cognitive achievement is critical for individual and species survival.

5 Conclusion

Revealed decrement of functional coupling between the hippocampus and prefrontal brain regions while subjects completed ambiguous, fragmented word pairs demonstrated new evidence towards how non-selected meanings of ambiguous information could be processed. Similar down-regulation of hippocampal activity was previously observed in the settings of willful instruction driven forgetting. Such purging awareness from unwanted memories is a voluntary process induced by study instruction. In the current study, subjects were not aware of the alternative context-inappropriate meaning, which was not selected and, probably, inhibited. Thus hippocampal down-regulation can be associated with both willful forgetting and unaware processing of non-selected meanings of the ambiguous word. Therefore the present research demonstrates the similarity in neurobiological basics for voluntary and automatic control of awareness content.

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References

1. Mollica, F., Piantadosi, S.T.: Humans store about 1.5 megabytes of information during language acquisition. R. Soc. Open Sci. **6**, 181393 (2019). https://doi.org/10.1098/rsos.181393
2. Jackendoff, R., Jackendoff, R.: Foundations of Language: Brain, Meaning, Grammar, Evolution. Oxford University Press, USA (2002)
3. Givón, T., Shibatani, M.: Syntactic complexity: Diachrony, acquisition, neuro-cognition, evolution (2009)
4. Natochin, Y., Chernigovskaya, T.: From archebiosis to evolution of organisms and informational systems. Biol. Commun. **65**, 215–227 (2020). https://doi.org/10.21638/SPBU03.2020.301
5. Chernigovskaya, T.V.: Biology, environment, and culture: From animal communication to human language and cognition. Vestn. Sankt-Peterburgskogo Univ. Filos. i Konfliktologiia. **36**, 157–170 (2020). https://doi.org/10.21638/SPBU17.2020.113
6. Allakhverdov, V.: The Experience of Theoretical Psychology. Publishing house St. Petersburg State University, Saint Petersburg (1993)
7. Gernsbacher, M.: Attenuating interference during comprehension: The role of suppression (1997)
8. Cleeremans, A., Allakhverdov, V., Kuvaldina, M.: Implicit Learning: 50 Years On (2019)
9. Kireev, M., Korotkov, A., Gershkovich, V., Moroshkina, N., Slioussar, N., Prokopenia, V., Allakhverdov, V., Chernigovskaya, T.: Brain mechanisms for meaning selection in the setting of ambiguity resolution: an fMRI study. In: The Night Whites Language Workshop: the Fifth Saint Petersburg Winter Workshop on Experimental Studies of Speech and Language (Night Whites 2019) (2020)
10. Anderson, M.C., Hanslmayr, S.: Neural mechanisms of motivated forgetting. Trends Cogn. Sci. **18**, 279–292 (2014). https://doi.org/10.1016/j.tics.2014.03.002
11. Benoit, R.G., Hulbert, J.C., Huddleston, E., Anderson, M.C.: Adaptive top–down suppression of hippocampal activity and the purging of intrusive memories from consciousness. J. Cogn. Neurosci. **27**, 96–111 (2015). https://doi.org/10.1162/jocn_a_00696
12. Bekinschtein, P., Weisstaub, N.V., Gallo, F., Renner, M., Anderson, M.C.: A retrieval-specific mechanism of adaptive forgetting in the mammalian brain. Nat. Commun. **9**, (2018). https://doi.org/10.1038/s41467-018-07128-7
13. Johnstone, T., Ores Walsh, K.S., Greischar, L.L., Alexander, A.L., Fox, A.S., Davidson, R.J., Oakes, T.R.: Motion correction and the use of motion covariates in multiple-subject fMRI analysis. Hum. Brain Mapp. **27**, 779–788 (2006). https://doi.org/10.1002/hbm.20219
14. Anderson, M.C., Bjork, E.L., Bjork, R.A.: Retrieval-induced forgetting: evidence for a recall-specific mechanism. Psychon. Bull. Rev. **7**, 522–530 (2000). https://doi.org/10.3758/BF03214366
15. Wimber, M., Alink, A., Charest, I., Kriegeskorte, N., Anderson, M.C.: Retrieval induces adaptive forgetting of competing memories via cortical pattern suppression. Nat. Publ. Gr. **18**, 582–589 (2015). https://doi.org/10.1038/nn.3973
16. Anderson, M.C., Bunce, J.G., Barbas, H.: Prefrontal–hippocampal pathways underlying inhibitory control over memory. Neurobiol. Learn. Mem. **134**, 145–161 (2016). https://doi.org/10.1016/j.nlm.2015.11.008

Phonetic Ambiguity Resolution: To Be or not to Be Aware

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Abstract. We present the results of the experiment investigating the mechanism of phonetic ambiguity resolution. A cross-modal priming paradigm was employed. This study takes into account factors potentially influencing the results but irrelevant to the issue itself: a word recognition task (not a lexical decision) was used; the measurements of the same word recognition in control and experimental conditions were compared; the semantic relatedness between the prime and the target word was provided by their common lexical root. The results are discussed from the perspective of activation/suppression approach to the meaning selection process in comparison with the positive/negative choice theory explanation. In contrast to activation-based models, the negative choice is not about the gradual suppression of the activated contextually irrelevant interpretation but aims at keeping it from becoming conscious within the current context. The obtained data is more consistent with the latter explanation and gives rise to some new research questions.

Keywords: Negative choice · Phonetic ambiguity resolution · Negative priming effect

1 Introduction

Any meaningful information implies its various interpretations and leads to the necessity to choose the one which is going to be realized as the only appropriate one for each instance of its recognition. It is the process of meaning selection that is usually referred to as a work of consciousness (even though the process itself is unconscious). Exploring the mechanisms involved in semantic ambiguity resolution can shed light on the understanding of meaning comprehension in general. Hence, this study can be regarded as a part of a theoretical research on the mechanisms of consciousness.

2 Background

Results of many studies on verbal ambiguity have shown that more than one of the possible interpretations are actualized at the moment of its perception: there is a positive priming effect for the words related to different meanings of an ambiguous word [1–7 but see also 8, 9]. Then, approximately 150 ms later, a positive priming effect is only observed

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for words related to the contextually appropriate interpretation. Most researchers paid their attention primarily to the question whether (and when) there was a positive priming effect for information related to the inappropriate meaning compared with contextually appropriate information. In much fewer studies it has been shown that contextually inappropriate interpretations tend to take even longer to recognize than others, unrelated to ambiguity: a negative priming effect is observed [10–13].

2.1 Activation-Based Model vs. Negative Choice Theory

As an illustration for the activation-based approach, we describe a model by M. A. Gernsbacher [10, 14], which focuses on the mechanism of suppression. Also, we present the positive/negative choice theory by V. M. Allakhverdov [15, 16] and compare the two.

The first general difference between these approaches is that the activation/suppression model assumes some degree of meaning activation which can differ for various meanings and can vary with time. According to the positive/negative choice approach, meaning selection is a one-time “yes and no” event: an appropriate meaning is chosen to be recognized while the inappropriate meaning(s) is (are) kept from becoming conscious. There are no levels or degrees to those choices.

Activation and suppression have different sources: activation happens as a function of word frequency (and in a lesser degree because of the context) and suppression – as a function of context. The more biases it provides, the more the inappropriate meaning gets suppressed. It is important to emphasize that it is widespread to consider frequency as a variable separate from the context and as a one influencing the initial degree of meaning activations. Another way would be to consider word frequency as a wider dimension of context which works in the same way as closer context does. Context (including frequency) influences the direction of meaning selection (which one will be chosen positively and which one – negatively). The minimal margin in favor of one meaning over others is enough to make the choice.

Another important distinction between the two models is that the activation-based approach explains and predicts priming effects but does not directly bind activation levels with conscious recognition. For example, a low-frequency contextually appropriate (and consciously recognized) meaning will only gain the same level of activation as a high-frequency inappropriate (and not recognized) meaning. Moreover, if there is not enough biasing information in the context (or due to a person’s poor comprehension skills), the inappropriate meaning is not supposed to be suppressed at all, despite the fact that it is not consciously recognized. Thus, if it has to be assumed that only the predominance in activation of one of the meanings is essential for the recognition, the idea of different activation levels seems redundant. Positive (and negative) choice of a meaning implies the recognition of that meaning (and non-recognition of others).

The final difference is crucial for explaining the results of our experiment. Both approaches connect context shifting to positive priming effect for previously inappropriate meaning but their causes and consequences are understood in opposite ways: The failure to suppress the meaning (which manifests in a positive priming effect) leads to the context shift; the prediction of the negative choice theory is that the context shift leads to the positive priming effect for the meaning rejected earlier.

The goal of the study was to test the hypothesis that for the conscious recognition of one meaning of an ambiguous word (positive choice), it is necessary to keep another possible interpretation from becoming conscious (negative choice). Negative priming effect for words semantically related to contextually inappropriate meanings (targets) was expected. A possible reason for this effect is that the meaning is not recognized within the current context and the only possibility for it to become conscious is to change the context. Thus, the time cost is due not to the longer processing of the word, but to its non-recognition at first. The important requirement for the experimental design was to ensure common context for each prime and its target word: It was supposed to be secured by their closeness in time and the natural intention of consciousness to reconcile incoming information.

3 Experiment

Phonetic ambiguity is a fruitful source for investigating the processes of meaning selection because it is: widespread and naturally occurring; intrinsically connected with the very process of speech comprehension; processed subjectively easily, quickly and accurately. In addition to the fact that meaning selection happens without any conscious experience of this process, more important is that the very possibility of various interpretations of a speech signal does not normally consciously realized – thus, the observed effects should be the least affected by other cognitive and metacognitive processes. The study was approved by the Ethical Committee of the Saint Petersburg Psychological Society (IRB00012426 Saint Petersburg Psychological Society IRB #1).

3.1 Method

Participants. Sixty-five right-handed native Russian speakers aged from 18 to 35 years old took part in the experiment. They reported no visual, hearing, neurological, or motor problems. They were not paid for participation.

Materials. We have chosen twelve phonetically ambiguous Russian words as primes. They were embedded in utterances biased toward each of their meanings. Twenty-four biasing contexts contained one of the homophones at the end and twenty-four equivalent contexts contained the homophones at the beginning of the utterances. We have also recorded twelve filler utterances (without the homophones).

Target words consisted of twenty-four words with the same root corresponding to each of the homophones meaning. The same root ensured their semantic relatedness and helped to avoid the contentious issue of how and what words associated with competing meanings are affected by meaning selection processes. To prevent the awareness of the ambiguity, the targets were chosen phonetically and graphically as different as possible from the primes. As a result, most of the targets were complex and quite different from each other in their formal characteristics, too. In addition, twelve rare, old-fashioned and pronounceable pseudo-words were chosen for the task.

The utterances and the targets were organized in four experimental sets. There were three conditions (see Table 1): the experimental condition included the utterances with the homophones and the words related with their inappropriate interpretations as targets; the control condition included the filler utterances with the same targets; the filler condition (the utterances with the homophones and the filler targets) was not analyzed.

Table 1. Examples of utterance-target pairs (conditions) in the experiment. The homophones (primes) are given in bold with their phonetic transcription in square brackets. The translation is given in italic.

Condition	Utterance	Target
Experimental	Лиц**а [l'its**ə**]** и прически у них похожие, поэтому их и перепутали друг с другом *They had similar faces and haircuts that's why they were mixed up with each other*	**В**ЫЛИ**Т**Ь *to pour out*
Control	Там всему могут научить: и по канату ходить, и жонглировать *They can teach you everything there: both to walk on a rope and juggle*	
Filler	Лить**с**я **[l'its**ə**]** дождь там может несколько дней, а потом месяцами сухо и жарко *It can rain for some days there and then it's dry and hot for months*	Д**О**ЛИ**МАН** *a dolman*

A total of thirty-six utterances were presented to each participant. The conditions were mixed in a pseudo-random order. The order of the targets was the same for all four sets. Contexts biased towards both interpretations of each homophone were presented within each set, but only one of them was either in the experimental or in the control condition; the context biased towards the other meaning was used for filler condition. If set 1(3) contained one of the targets in the experimental condition, this target was featured in the control condition in set 2(4) and vice versa. Set 1 and set 2 contained the utterances with the homophones at the beginning; sets 3 and 4 – with the homophones at the end.

Procedure. The experiment was conducted using the PsychoPy software and presented on a computer. The participants wore the headphones to assure audio quality control. They were instructed to listen to utterances on various topics. When words would appear on the screen (500 ms after each utterance), they were told to reply as fast as they can whether they were familiar with the word (by pressing the right arrow button) or not (the left arrow button). The task resembled lexical decision but it rather was a lexical recognition task. It aimed at ensuring that the resulting effects belong to the same kind of information processing as meaning selection. Before running one of the experimental sets, each participant listened to a training set and took a comprehension test after. The instruction to the test was to fill the gaps in the sentences they have just heard. This test intended to motivate participants to listen to the utterances attentively.

All of the participants were interviewed after the experiment to ensure they had not become aware of any case of ambiguity.

3.2 Results

Out of a possible total of 1560 response latencies, we discarded 3.8% due to incorrect answers. We z-standardized the reaction times (RTs) for each participant and excluded from the analysis the responses three SDs above and below the mean RT of each target word (<1%). Three targets (the same for both homophone positions) were not included in the analysis since their mean RTs in the control condition were approximately twice as long as the mean RT of all the other target words. We assume that these words formed a separate context due to their formal (or other) characteristics. Besides the fact that these targets stood out so significantly in the reaction times, we have also noticed a positive priming effect for them in the experimental condition (which is consistent with the theory).

Different methods of non-parametric statistical analysis were applied to examine the data in detail but averaging over items was deemed the most appropriate for this experimental design and material.

Data analysis showed significant increase in RT in the experimental condition compared with the control condition for the contexts where the homophones were situated at the end of the utterances: for data averaged over items W = 69.0, p = .056 (averaged over subjects W = 158.0, p = .024; without averaging U = 43567.5, p < .001). There was no evidence for significant difference between the conditions when the homophones were situated at the beginning of the utterances although in the experimental condition the RT was tending to slow down: W = 97.0, p = .27 (W = 225.0, p = .16; U = 53188.5, p = .23). The analysis of the combined data for both homophone positions showed a significant increase in RT in the experimental condition: W = 314.0, p = .043 (W = 751.0, p = .018; U = 194032.5, p = .005) (see Fig. 1).

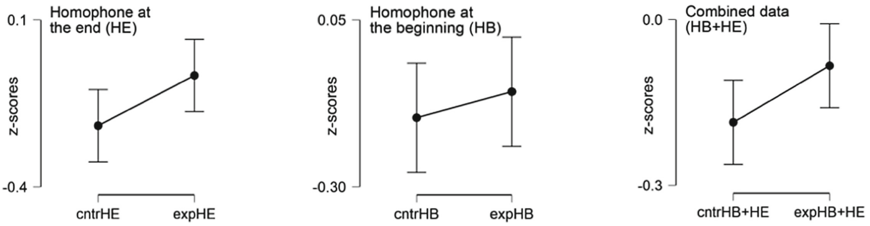

Fig. 1. The comparison of average z-scores of the target words recognition in the control (cntr) and the experimental (exp) conditions.

Furthermore, there was no statistically significant evidence that the negative priming effect was affected by the relative frequencies of the contextually appropriate and inappropriate meanings. To check it, all the targets were divided into two groups: those preceded by the utterances with more frequent inappropriate than appropriate meaning (in the experimental condition) and those preceded by more frequent appropriate than inappropriate meaning (frequencies of the word forms were derived from [17]). Then the proportion of cases of negative and positive priming effects between these groups was compared by chi-square test that did not reveal any statistically significant differences. In addition, RTs in different conditions within each group were compared using Dunn's post hoc test with multiple comparison correction. Similar to the results for the cases not divided by the relative frequencies of the homophones meanings, RTs in the experimental condition were longer than in the control when the homophones were positioned at the end ($z = -2.175$, $p_{dunn} = .015$ for cases where inappropriate meaning is more frequent than the appropriate one; $z = -2.238$, $p_{dunn} = .013$ – when the appropriate meaning is more frequent than the inappropriate one). We did not find any statistically significant differences of RTs when the homophones were at the beginning of the utterances ($z = -0.806$, $p_{dunn} = .21$; $z = -0.056$, $p_{dunn} = .47$).

4 Discussion and Conclusion

The results for the homophone final position condition could be explained, with some reservations, from the perspective of activation/suppression approach. A lot of preceding biasing context elements lead to strong suppression. A different frequency or degree of negative priming effect could probably be expected because of different initial levels of high- and low-frequency inappropriate meanings, but it is hardly possible to measure the impact of each contextual element on the overall resulting suppression to evaluate it. Such results also imply that all the participants in the random sample were generally skilled comprehenders (that is, were able to suppress inappropriate meanings).

The other explanation in accordance with the theory of positive and negative choice fits the obtained results as well: negative priming effect is due to keeping the inappropriate meaning from becoming conscious within the context where the choice has been made.

To understand the results for the cases where the homophone was placed at the beginning of the utterance, their differences from the homophone final position cases should be taken into consideration. First, there was less biasing information at the moment of meaning selection. From the perspective of activation/suppression view, nevertheless, the same strong suppression (as for the homophone final position cases) should have happened because there had been the same amount of biasing information by the end of an utterance which was supposed to suppress the inappropriate meaning but did not do so. Another possible explanation is that there was some amount of less skilled comprehenders (with insufficiently developed suppression mechanism) in the sample. However, if such comprehension impairment had been so usual, the significant negative priming effect would not have been observed for the cases where homophones were in the final position either. In line with the positive and negative choice explanation, the amount of biasing information does not matter – it should be just enough to make a choice. But why was a pronounced negative priming effect not obtained? Actually, it can be assumed that the negative choice did happen at the moment of meaning recognition, but – and here comes the second distinction: more time has passed from meaning selection until the target perception. Time itself cannot serve as an explanation because if some kind of weakening of the suppression is implied, we would have to return to the activation approach (in terms of positive/negative choice theory choice reduction seems illogical). The consistent explanation is that the more time passes (and the more information arrives), the more probable is that the context will shift. This shift leads to positive priming effect for information that was previously kept from recognition (it was actualized by the previous selection task and in a new context there is no necessity to keep it from becoming conscious anymore). Taking into account that each utterance indeed constitutes a single coherent context, such shifting was not ubiquitous – that is why the resulting data shows neither pronounced negative nor positive priming effect. Presumably, the context shift could sometimes happen due to the fact that most of the utterances contained two clauses, or the comprehension test after the training set provoked participants to try to memorize separate collocations.

This study provides evidence for treating the cause of the obtained effects as an important part of meaning selection process and not as an optional consequence of other circumstances of perception. The key variable underlying this process is the compatibility of various interpretations with the majority of context dimensions. Some challenging questions, as in what these context dimensions are and what factors cause context shifting, require future investigation.

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References

1. Onifer, W., Swinney, D.A.: Accessing lexical ambiguities during sentence comprehension: effects of frequency of meaning and contextual bias. Mem. Cognit. **9**(3), 225–236 (1981)
2. Seidenberg, M.S., Tanenhaus, M.K., Leiman, J.M., Bienkowski, M.: Automatic access of the meanings of ambiguous words in context: some limitations of knowledge-based processing. Cogn. Psychol. **14**, 489–537 (1982). https://doi.org/10.1016/0010-0285(82)90017-2
3. Rayner, K., Pacht, J.M., Duffy, S.A.: Effects of prior encounter and global discourse bias on the processing of lexically ambiguous words: evidence from eye fixations. J. Mem. Lang. **33**(4), 527–544 (1994). https://doi.org/10.1006/jmla.1994.1025
4. Lucas, M.: Context effects in lexical access: a meta-analysis. Mem. Cogn. **27**, 385–398 (1999). https://doi.org/10.3758/bf03211535
5. Gorfein, D.S., Brown, V.R., DeBiasi, C.: The activation-selection model of meaning: explaining why the son comes out after the sun. Mem. Cogn. **35**, 1986–2000 (2007). https://doi.org/10.3758/bf03192931
6. Tanenhaus, M.K., Leiman, J.M., Seidenberg, M.S.: Evidence for multiple stages in the processing of ambiguous words in syntactic contexts. J. Verbal Learn. Verbal Behav. **18**(4), 427–440 (1979)
7. Twilley, L.C., Dixon, P.: Meaning resolution processes for words: a parallel independent model. Psychon. Bull. Rev. **7**, 49–82 (2000). https://doi.org/10.3758/BF03210725
8. Simpson, G.B., Krueger, M.A.: Selective access of homograph meanings in sentence context. J. Mem. Lang. **30**, 627–643 (1991). https://doi.org/10.1016/0749-596X(91)90029-J
9. Tabossi, P., Zardon, F.: Processing ambiguous words in context. J. Mem. Lang. **32**(3), 359–372 (1993). https://doi.org/10.1006/jmla.1993.1019
10. Gernsbacher, M.A., St. John, M.F.: Modeling suppression in lexical access. In: Gorfein, D. (ed.) On the Consequences of Meaning Selection, pp. 47–64. APA Publications, Washington, D.C., (2000)
11. Simpson, G.B., Kang, H.: Inhibitory processes in the recognition of homograph meanings. In: Dagenbach, D., Carr, T.H. (eds.) Inhibitory Processes in Attention, Memory, and Language, pp. 359–381. Academic Press, New York (1994)
12. Simpson, G.B., Kellas, G.: Dynamic contextual processes and lexical access. In: Gorfein, D.S. (ed.) Resolving Semantic Ambiguity, pp. 40–56. Springer-Verlag, New York (1989)

13. Nievas, F., Mari-Beffa, P.: Negative priming from the non-selected meaning of the homograph. Br. J. Psychol. **93**, 47–66 (2002). https://doi.org/10.1348/000712602162445
14. Gernsbacher, M.A.: Mechanisms that improve referential access. Cognition **32**, 99–156 (1989). https://doi.org/10.1016/0010-0277(89)90001-2
15. Allakhverdov, V.M.: Opyt teoreticheskoy psikhologii [Experience of theoretical psychology]. Pechatny dvor Publ, Saint Petersburg (1993).(in Russian)
16. Allakhverdov, V.M.: Issledovaniya zakonomernostey vozniknoveniya oshibok pri operativnykh preobrazovaniyakh informatsii [Investigation of the errors patterns in the operational transformation of information]. Abstract of Cand. Sc. (Psychology) Dissertation. LGU Publ., Leningrad (1974). (in Russian).
17. Russian National Corpus. https://ruscorpora.ru

Stroop Effect: Conflict Detection and Control Strategy Factors

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Abstract. Three experiments (N = 190) were conducted to study the effect of control strategy on the strength of interference in a reverse Stroop task. The participants were asked to determine as quickly as possible the meanings of incongruent words (for example, the word "red" printed in blue) and to ignore the color of the text. Responses were registered using the "up", "down", "left" and "right" arrow keys on the keyboard. Colored squares were used to assign keys to responses in the current trial. For example, if the red square was in the top part of the picture, the participant had to press the "up" button in order to response "red". In the "conflict" stimuli, a square of the same color as the word was presented; in the control stimuli, there was no corresponding square. The color-meaning combinations were identical in both "conflict" and control stimuli. A significant difference in response times for conflict and non-conflict stimuli was only observed when 1) they were presented in separate blocks, or 2) the colored squares were presented before the word. This difference decreases significantly if the conflict stimuli are presented as a separate block after the block of control stimuli and if the block of control stimuli is presented after the conflict stimuli. The effect of cognitive control strategy and conflict detection on the efficiency of solution of interference tasks is discussed.

Keywords: Stroop effect · Cognitive control · Reverse Stroop effect · Response set effect · Response conflict · Block effect

1 The Stroop Effect

When performing any task, a person perceives irrelevant information. Yet, in most cases, the irrelevant information is not connected with any answers that can potentially be the solution to the task. In such cases, the irrelevant information is filtered out and does not have significant effect on how efficiently the main task is solved. However, if the irrelevant information is in some way similar to the correct answer, a cognitive conflict arises between relevant and irrelevant information. The Stroop effect (Stroop interference) is a classic example of a cognitive conflict situation. In the classic Stroop test, the subjects are asked to rapidly name the colors of the words, while ignoring their meanings. When there is a mismatch between the color and the meaning (e.g., the word "red" printed in blue), the subjects perform the task slower than they do when presented

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with a colored set of non-word characters (for example, “XXXXX”). There has also been observed a response set effect in the Stroop test: interference decreases if the word’s color does not correspond to any of the correct response in the current trial (for example, if all the words in the trial are printed in red or yellow and the word “pink” is presented).

2 The Mechanisms for Overcoming Cognitive Conflict

In spite of the cognitive conflict, the subjects give correct responses in most of the trials, although there is a time lag. The cognitive conflict is thought to be solved using cognitive control strategies. The cognitive control system consists of several mechanisms [1]. When discussing the overcoming of Stroop interference, the most often mentioned mechanism is response inhibition. This mechanism inhibits the wrong response (in this case, the meaning of the word). The earlier this mechanism is activated, the quicker the task is solved. However, there are other mechanisms of cognitive control. For example, V.M. Allakhverdov has hypothesized that the response is generated automatically, and then reevaluated [2]. The response is actualized after it has been confirmed to be different from the irrelevant stimulus (the successful performance of the “ignoring the irrelevant stimulus” task has been confirmed). Such “reevaluation” necessarily leads to slower response time. Therefore, the “reevaluation” mechanism should only be activated if signals of possible conflict have been discovered in the environment. If conflict and non-conflict stimuli are as similar as possible, it is hypothesized that a similar response time lag will be observed for both types of stimuli.

Response set effect can be explained by both the response inhibition mechanism and the mechanism for controlling the performance of the “ignoring the irrelevant stimulus” task. On the one hand, if the set of correct responses only contains the words “red” and “blue”, then the word “pink” does not activate the corresponding representation as strongly, therefore it is inhibited more easily. On the other hand, if the word “pink” is not part of the set of correct responses, there are few reasons to control the performance of the “ignoring the irrelevant stimulus” task (see [3] for a detailed analysis of the possible reasons for response set effect).

3 Experimental Stimuli

In our experiments, we used special stimuli, in which the conflict between possible responses was difficult to detect using heuristics such as “there is no responses conflict in the word “pink”. An incongruent Stroop stimulus was presented in the middle of the screen. The word was surrounded by four colored squares on the left, right, top and bottom (see Fig. 1a and 1b). The words “red”, “yellow”, “green”, “blue” and “purple”, the corresponding type colors and colored squares were presented an equal amount of times. The subjects’ task was to react as quickly as possible to the word’s meaning while ignoring its color. For example, if the word “white” had been presented, and the white square was at the top, the participant had to press “up” (as far as we know, the first variation of this method was used in Durgin [4]). The task was to react to the word’s meaning, not to its color, because, according to Sobel et al. [5], there has been observed a stronger color interference in visual search tasks.

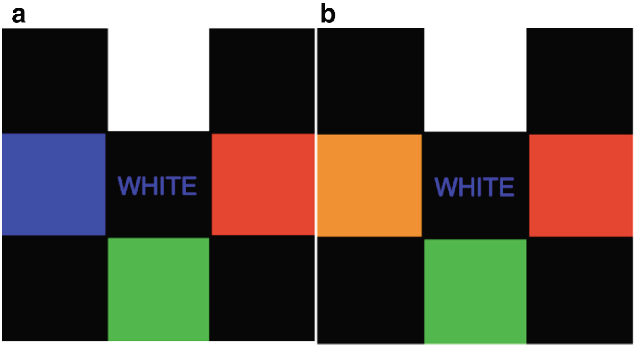

Fig. 1a. (On the left) – an example of a conflict stimulus, **Fig. 1b.** (on the right) – an example of a control stimulus. In the original experiment, the subjects were presented with Russian words and a different set of colors and words was used (the colors have been changed here for better illustration is the black-and-white version of the article).

The stimuli in Figs. 1a and 1b differ in the amount of conflict. In the Fig. 1a, there is a blue square (on the left) that is supposed to prompt the subjects to press the "left" button (conflict of responses). However, there is no such square in the Fig. 1b. Let us call the stimulus in 1a a "conflict stimulus", and the stimulus in 1b – a "control stimulus". Of course, there is some amount of conflict in the "control stimulus", too, because each of the directions (up, down, left, right) can correspond to a correct response in other trials. However, the Fig. 1a is the one where there is immediate conflict between two responses, while, for the Fig. 1b, it is impossible for the participant to response with the color of the target word.

4 Designs and Results of Experiments

If the stimuli 1a and 1b are presented in a randomized order, cognitive control cannot quickly distinguish the conflict stimulus from the control one using rules like "all pink stimuli are control stimuli". After the experiment, it usually takes some time to explain the difference between the conflict and control stimuli to the participants. In earlier experiments ($N = 30$) we have found that, when conflict and control stimuli are presented randomly in one block, mean reaction times for conflict stimuli and control stimuli did not differ significantly ($MD = 3$ ms; $F(1,28) = 0.4$; $p = .53$). However, if we compare two groups of subjects, where one group is presented with only conflict stimuli, and the other group – with control stimuli ($N = 60$), reaction times for conflict stimuli turn out to be significantly longer ($MD = 121$ ms; ($F(1,56) = 9.1$; $p < .01$) (see [6] for more details). This result shows that the magnitude of response set effect depends significantly on strategy used by the subjects. A similar result was shown in an experiment by Hassim and Parris [3], where standard Stroop stimuli were used. However, in their study, response set effect did not disappear when both types of stimuli were mixed – it was less pronounced, but stayed significant. More importantly, unlike the study by Hassim and Parris [3], our experimental design does not allow to interpret the results through activation of representations. Each color-word combination in our experiment was presented equal amount of times both when stimuli were mixed and when they were presented in separate blocks. Squares of each color were also presented equal amount of times in all experimental conditions.

We hypothesized that, if the proposition that there exists a “reevaluation” strategy is true, such strategy would also be used to process subsequent stimuli. An experiment was performed, in which a group of subjects (N = 20) was first presented with 120 conflict stimuli, and afterwards – with 120 control stimuli; while the second group (N = 20) was first presented with 120 control stimuli, and afterwards – with 120 conflict stimuli. We found that the difference in mean reaction times when responding to conflict and non-conflict stimuli was 159 ms when the first blocks of 120 stimuli were compared, and 14 ms when the second blocks of 120 stimuli were compared. The difference is statistically significant (T(1,29) = 86; p < .01; see [7] for details).

Therefore, we have verified the hypothesis that a block of conflict stimuli prompts the use of reevaluation strategy, while a block of non-conflict stimuli prompts responses without reevaluation. However, is it possible that these results are simply consequences of features of our stimuli? In the third experiment, we aimed to create within our experimental design a situation where the subjects would be able to distinguish conflict and non-conflict stimuli even if they were presented in the same block. To achieve this, we presented one group of subjects first with colored squares and then, after 1000 ms, a

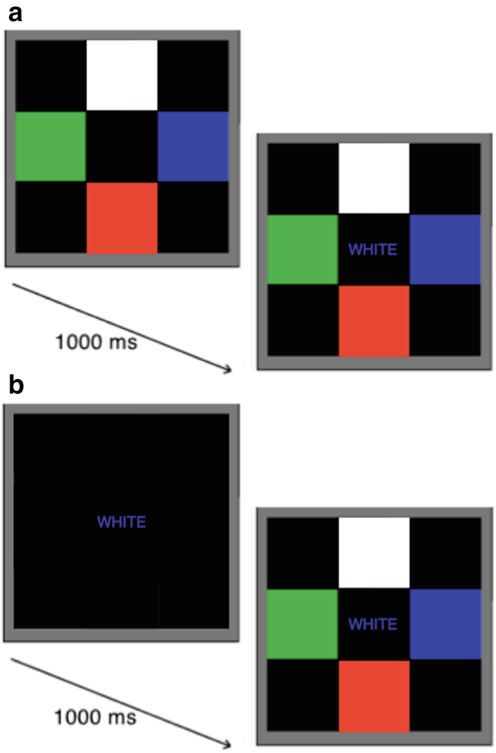

Fig. 2a and 2b. Examples of experimental conditions in Experiment 3.

Stroop word was shown (Fig. 2a). The second, control group, was first presented with a colored word and, after 1000 ms, colored squares were shown (Fig. 2b). As in previous experiments, all the words in the stimuli were typed in such a way that the meaning never coincided with the color. We used words "red", "blue", "green", "yellow" and "purple" and corresponding colors. Each colored square was presented in each position equal amount of times. In each trial, there was a square that corresponded to the target word's meaning. Such a square was presented in each position (top, bottom, left, right) 25% of the times. All conflict stimuli included a square of the same color as the target word (Fig. 1a), while control stimuli did not include such a square. The numbers of conflict and control stimuli were equal. It should be noted that, when colored squares were presented before the word (Fig. 2a), the subjects had an opportunity to detect the response conflict and to activate (or deactivate) the reevaluation strategy. However, if the subjects had less time to view the squares (2b), it was difficult to detect a response conflict or its absence.

As we have hypothesized, when colored squares were presented before the target word, response times for conflict stimuli were significantly longer than for neutral stimuli (MD = 24 ms; $t(1, 19) = 3.5$; $p < .01$). There was no such effect in the other group, where the order of presentation of the blocks was reversed (MD = −7 ms; $t(1,19) = 0.8$, $p = .43$).

5 Conclusions and Limitations

We were able to show in our experiments that response set effect is significantly modulated by how the stimuli are presented (mixed or in separate blocks), by the type of the previous block of stimuli and by the order of presentation of colored squares and target words. The effects that were discovered can be explained by the hypothesis of pre-activation of representations. At the same time, we obtained contradictory results regarding the effect of "reevaluation strategy" on the number of mistakes. Only in the third experiment we were able to find a significant decrease in the number of mistakes (by 2%) in the "reevaluation strategy" condition as compared to "no reevaluation strategy" condition. In the other two experiments, the increase in response times for conflict stimuli was not accompanied by any significant decrease in the number of mistakes. This result poses a following problem: how adaptive is distractor control in the Stroop test? It is possible that Stroop interference arises due to excessive control that is not necessary for performing such tasks. The idea that cognitive control may not be adaptive in simple tasks was proposed in the study by Bocanegra & Homme [8]. According to the authors, a simple task is a task that can be performed without integration of different features of stimuli. Solving a Stroop task does not require subjects to integrate several features of stimuli, therefore, it can be considered a simple task, where cognitive control is not adaptive.

It should be noted that we used a Stroop paradigm that is different from the classic Stroop test. Further experiments should be performed in order to verify if the current results will be reproduced in the "reacting to the color of the word" task. It also needs to be examined whether colors that are not included in the current trial color set and colors that never correspond to the correct response have different interferential effects.

Based on the current data, cognitive conflict arises and is solved at the level of cognitive control, not automatically. “Low-level” processes can only serve as a trigger for control mechanisms.

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References

1. Diamond, A.: Executive functions. Annu. Rev. Psychol. **64**, 135–168 (2013). https://doi.org/10.1146/annurev-psych-113011-143750
2. Allakhverdov, V.M., Allakhverdov, M.V.: Stroop effect: interference as a logic paradox [Феномен Струпа: интерференция как логический парадокс]. Vestnik of Saint Petersburg University. Psychology. Pedagogy [Вестник Санкт-Петербургского университета. Серия 16. Психология. Педагогика], **4**, 90–102 (2014). (in Russian)
3. Hasshim, N., Parris, B.A.: Trial type mixing substantially reduces the response set effect in the Stroop task. Acta Physiol. (Oxf) **189**, 43–53 (2018). https://doi.org/10.1016/j.actpsy.2017.03.002
4. Durgin, F.H.: The reverse Stroop effect. Psychon. Bull. Rev. **7**(1), 121–125 (2000)
5. Sobel, K.V., Puri, A.M., York, A.K.: Visual search inverts the classic Stroop asymmetry. Acta Physiol. (Oxf) **205**, 103054 (2020). https://doi.org/10.1016/j.actpsy.2020.103054
6. Starodubtsev, A.S., Allakhverdov, M.B.: Influence of expectation of conflict stimuli on stroop effect [Влияние установки о наличии конфликтных стимулов в тесте Струпа на величину интерференции]. Vestnik of Saint Petersburg University. Psychology. [Вестник Санкт-Петербургского университета. Психология] **7**(2), 137–153 (2017). (in Russian)
7. Starodubtsev: The influence of cognitive control on Stroop effect [Влияние когнитивного контроля на эффект Струпа] Petersburg Psychol. J. [Санкт-Петербуржский психологический журнал] **24**, 40–62 (2018). (in Russian)
8. Bocanegra, B.R., Hommel, B.: When cognitive control is not adaptive. Psychol. Sci. **25**(6), 1249–1255 (2014). https://doi.org/10.1177/0956797614528522

Alpha-Band Effective Connectivity During Cued Versus Implicit Modality-Specific Anticipatory Attention: EEG-Source Analysis

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Abstract. Effective connectivity was studied in a group of 24 right-handed, healthy adults (9 male, 15 female) aged 22 ± 4.75 years during the preparation for task performance in the cued attention, implicit anticipation, and baseline conditions. Participants performed visual and auditory versions of the temporal order judgment task. Alpha-band effective connectivity was assessed by means of the directed transfer function (DTF) computed in the source space for preselected regions of interest (ROI). The results of the present study indicate the top-down influence of the right frontal eye field on the right intraparietal cortex during auditory cued attention. Moreover, a modality-specific influence of the frontal eye field on the primary auditory cortex was observed in the right hemisphere. The analysis of effective connectivity during implicit anticipation showed the influence of the primary visual cortex on the ventral premotor cortex, the intraparietal cortex, and the primary auditory cortex in the left hemisphere for the auditory modality.

Keywords: Alpha rhythm · Cued attention · EEG · Effective connectivity · Implicit anticipation

1 Introduction

Experimental paradigms for anticipatory attention research imply explicit anticipation of upcoming events caused either by cueing [10] or by the regularity of presented stimuli [1]. The analysis of the brain's mechanisms underlying anticipatory attention showed the involvement of the dorsal frontoparietal network in the deployment of spatial cued anticipatory attention [8]. Furthermore, selective changes in the activity of modality-specific cortices were shown to accompany the deployment of modality-specific anticipatory attention [1, 9, 12]. Besides the explicit type of anticipatory attention, some studies have indicated the possibility of implicit anticipation [13]. Implicit anticipation might be determined by the activity of the supplementary motor area (SMA), the presupplementary motor area (preSMA) [4], and the ventral premotor cortex (VPC) [2, 11] as well as the somatosensory and parietal cortices [7].

In the present study, we used the data obtained in [12] to investigate causal interactions (effective connectivity) [3] between preselected regions of interest (ROI) during cued and implicit types of modality-specific anticipatory attention.

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2 Method

Alpha-band effective connectivity was studied in a group of healthy right-handed adults (N = 24, 9 male, 15 female, mean age = 22 ± 4.75 years) during the preparation for task performance in three experimental conditions (cued attention, implicit learning, and baseline) that were equal in terms of stimuli, motor responses, and cognitive task. Participants performed the temporal order judgment task in visual and auditory modalities. In this task, a participant should detect which of two stimuli of the same modality was presented first and then respond manually by pressing a response key. In the cued attention condition, anticipation was caused by the presentation of a cue that informed participants about the modality of the upcoming trial. In the implicit anticipation condition, anticipation was induced by the regular alteration of modalities (visual and auditory) across trials. There was also the baseline condition that implied no development of any modality-specific anticipatory attention. The whole procedure is described in [12, Materials and Method]. Alpha-band effective connectivity was assessed by means of the directed transfer function (DTF) [6] computed in the source space for the preselected ROIs (Table 1). All experimental methods had ethical approval from the Ethics Committee of the Institute of Developmental Physiology.

Table 1. MNI coordinates of the regions of interest (ROI)

ROI	Left hemisphere			Right hemisphere		
	x	y	z	x	y	z
V1 – primary visual cortex (BA 17)	−9.8	−88.2	−8.1	9.8	−88.2	−8.1
A1 – primary auditory cortex (BA 41/42)	−40	−32.8	14.6	40	−32.8	14.6
preSMA – presupplementary motor area (BA 6a)	−6	6	70	9	6	70
VPC – ventral premotor cortex (ventral part of BA 6a)	−28	−2	50	32	−2	50
IPC – intraparietal cortex (part of BA 40)	−51.6	−55.9	44.9	51.6	−55.9	44.9
LPFC – lateral prefrontal cortex (BA 9/46)	−44	40	20	44	40	20
FEF – frontal eye field (BA 8)	−30	−4	60	30	−4	60

Note. MNI = Montreal Neurological Institute; BA = Brodmann area

3 Results

The data belonging to four participants were of poor quality and were excluded from the analysis of effective connectivity. For two other participants, we were unable to obtain a stable vector autoregression model for all experimental conditions. The data for these two participants were excluded from the analysis of variance but retained (whenever possible) for making paired comparisons. All 42 pairs of ROI were grouped in four subsets for further analysis in accordance with the results obtained in [12]. Subset 1 included the primary visual, auditory, parietal, and central areas (V1– IPC, V1–A1, V1–preSMA, V1–VPC). Subset 2 included the primary auditory, parietal, frontal, and central areas (A1–preSMA, A1–VPC, A1–LPFC, A1–FEF, A1– IPC). Subset 3 included the primary visual, parietal, and prefrontal areas (V1–LPFC, V1–FEF, IPC–LPFC, IPC–FEF). Subset 4 included centroparietal cortices (IPC– preSMA, IPC–VPC, preSMA–VPC).

For each subset, we used a general linear model (GLM) with experimental condition (cued attention, implicit learning, baseline), localization (all pairs of ROI included in a subset), and direction (top-down, bottom-up causal links) as the within-subject factors. This type of analysis was conducted separately for each sensory modality and each hemisphere.

In case of a significant interaction of condition and localization alone or in combination with direction, the effect of condition for each pair of ROI was analyzed with a probability criterion $p < 0.0167$ (0.05/3; for Subset 4), $p < 0.0125$ (0.05/4; for Subsets 1, 3) or $p < 0.0100$ (0.05/5; for Subset 2) depending on the number of ROI pairs in each subset to provide multiple testing correction.

3.1 Subset 1

Left Hemisphere. *Auditory Modality.* The statistical analysis revealed a nearly significant interaction of direction and condition, $F(2, 16) = 3.536$, $p = 0.053$, $\eta_\mathrm{p}{}^2 = 0.307$. Then the effect of condition for each pair of ROI was assessed separately for top-down and bottom-up causal links.

The bottom-up influence of the V1 on the IPC (**V1 → IPC**) was nearly significant, $F(2, 17) = 4.646$, $p = 0.025$, $\eta_p{}^2 = 0.353$. In this case, the DTF estimates during implicit learning ($M = 0.385$, $SD = 0.104$) were higher than those during both the cued attention ($M = 0.348$, $SD = 0.086$) and baseline ($M = 0.328$, $SD = 0.095$) conditions. A post hoc analysis showed a significant difference between the implicit learning and baseline conditions ($p = 0.009$).

A significant effect of condition was found for **V1 → A1**, $F(2, 17) = 9.104$, $p = 0.002$, $\eta_\mathrm{p}{}^2 = 0.517$. The DTF estimates during implicit learning ($M = 0.392$, $SD = 0.093$) were higher than those during the cued attention ($M = 0.339$, $SD = 0.084$) and baseline ($M = 0.323$, $SD = 0.096$) conditions. A post hoc analysis showed a significant difference between the implicit learning condition and the other conditions (implicit learning vs. Cued attention: $p = 0.003$; implicit learning vs. baseline: $p = 0.002$).

Moreover, the analysis showed a nearly significant effect of condition for **V1 → VPC**, F(2, 17) = 5.324, $p = 0.016$, $\eta_p{}^2 = 0.385$. The DTF estimates during implicit learning ($M = 0.380$, $SD = 0.099$) were higher than those during the cued attention ($M = 0.343$, $SD = 0.095$) and baseline ($M = 0.312$, $SD = 0.101$) conditions. A post hoc analysis showed a significant difference between the implicit learning and baseline conditions ($p = 0.004$).

Visual Modality. The GLM analysis showed no effect of condition and no significant interactions of condition and the other within-subject factors.

Right Hemisphere. For both sensory modalities, the statistical analysis showed no effect of condition and no significant interactions of condition and the other within-subject factors.

3.2 Subset 2

Left Hemisphere. For both sensory modalities, the statistical analysis showed no effect of condition and no significant interactions of condition and the other within-subject factors.

Right Hemisphere. *Auditory Modality.* The statistical analysis revealed a significant interaction of localization and condition, $F(8,\ 10) = 3.141$, $p = 0.047$, ${\eta_p}^2 = 0.715$. Then we performed the GLM analysis with condition as the only within-subject factor for top-down and bottom-up causal links. The analysis showed a significant effect of condition for **FEF → A1**, $F(2,\ 16) = 9.333, p = 0.002$, ${\eta_p}^2 = 0.538$. The DTF estimates during the baseline condition ($M = 0.204$, $SD = 0.065$) were higher than those during cued attention ($M = 0.189, SD = 0.046$) and implicit learning ($M = 0.167, SD = 0.040$). A post hoc analysis showed a significant difference between implicit learning and the other conditions (cued attention > implicit learning: $p = 0.002$; implicit learning < baseline: $p = 0.01$).

For the visual modality, no effect of condition and no significant interactions of condition and the other within-subject factors were found.

3.3 Subset 3

Left Hemisphere. *Auditory Modality.* The interaction of localization and condition was found to be nearly significant, $F(6,\ 12) = 2.615, p = 0.074$, ${\eta_p}^2 = 0.567$. However, the effect of condition did not reach the defined significance level for all causal links.

For the visual modality, no effect of condition and no significant interactions of condition and the other factors were revealed.

Right Hemisphere. *Auditory Modality.* The statistical analysis showed a significant interaction of the direction, localization, and condition factors, $F(6,\ 12) = 5.129$, $p = 0.008$, ${\eta_p}^2 = 0.719$. A significant effect of condition was shown for **FEF → IPC**, $F(2,\ 16) = 10.085$, $p = 0.001$, ${\eta_p}^2 = 0.558$. The DTF estimates during the baseline condition ($M = 0.194$, $SD = 0.046$) were higher than those during cued attention ($M = 0.178$, $SD = 0.040$) and implicit learning ($M = 0.158$, $SD = 0.037$). Significant differences were found between the cued attention and implicit learning conditions (cued attention > implicit learning: $p = 0.003$) and between the baseline and implicit learning conditions (implicit learning < baseline: $p = 0.005$).

Visual Modality. The GLM analysis revealed a nearly significant interaction of the direction, localization, and condition factors, $F(6, 12) = 2.676, p = 0.069, {\eta_p}^2 = 0.572$, and no effect of condition for either top-down or bottom-up causal links.

3.4 Subset 4

For each cross-condition, the analysis showed no effect of condition and no significant interactions of condition and the other within-subject factors.

4 Discussion and Conclusion

The results of the present study indicate the top-down influence of the FEF on the IPC during cued attention. This agrees with data concerning the involvement of the intraparietal sulcus (IPS) and FEF in the deployment of spatial cued attention [5, 8]. Moreover, a modality-specific influence of the FEF on the primary auditory cortex was observed during auditory cued attention. The observed links during implicit anticipation seem extraordinary and require additional research to be done. The obtained configuration of effective links (Fig. 1) does not really correspond to the configuration of functional links found in [12].

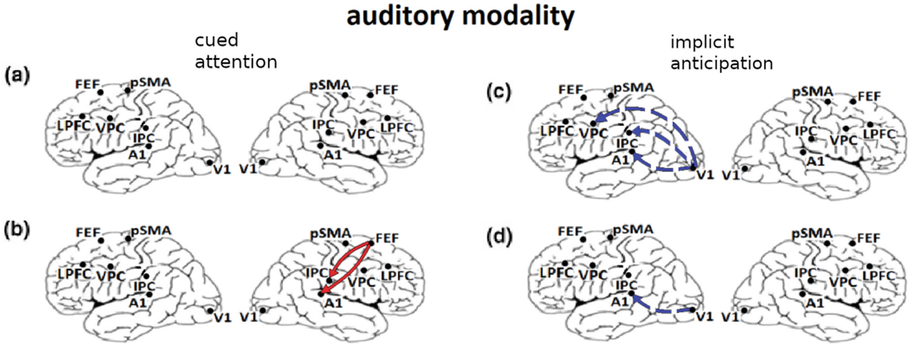

Fig. 1. A significant increase of the DTF estimates in the prestimulus period (a) during cued attention, as compared with the baseline condition; (b) during cued attention, as compared with implicit anticipation; (c) during implicit anticipation, as compared with the baseline condition; (d) during implicit anticipation, as compared with cued attention. Solid lines show top-down effective links between the cortical areas. Dashed lines show bottom-up effective links between the cortical areas.

In general, the present study revealed few effective links observed only for the auditory modality. Such results might be caused by the following:

- some "third-party" structures may influence the activity of two investigated cortices, thus causing statistical dependence (functional connectivity) and no causal interaction (effective connectivity) between them;

- the activity of different frequency bands might underlie effective connectivity during the deployment of different types of anticipatory attention;
- a different set of ROIs might better reflect effective connectivity during cued attention and implicit anticipation.

Thus, additional research should be done to detect a more comprehensive and meaningful pattern of effective connectivity during cued and implicit types of anticipatory attention. An appropriate set of ROIs should be formed, and more frequency bands should be studied.

References

1. Brunia, C.H., van Boxtel, G.J.: Anticipatory attention to verbal and nonverbal stimuli is reflected in a modality-specific SPN. Exp. Brain Res. **156**(2), 231–239 (2004). https://doi.org/10.1007/s00221-003-1780-2
2. Fiebach, C.J., Schubotz, R.I.: Dynamic anticipatory processing of hierarchical sequential events: a common role for Broca's area and ventral premotor cortex across domains? Cortex **42**(4), 499–502 (2006). https://doi.org/10.1016/S0010-9452(08)70386-1
3. Friston, K.J.: Functional and effective connectivity: a review. Brain Connectivity **1**(1), 13–24 (2011). https://doi.org/10.1089/brain.2011.0008
4. Hikosaka, O., Nakamura, K., Sakai, K., Nakahara, H.: Central mechanisms of motor skill learning. Curr. Opin. Neurobiol. **12**(2), 217–222 (2002). https://doi.org/10.1016/S0959-4388(02)00307-0
5. Huang, S., Belliveau, J.W., Tengshe, C., Ahveninen, J.: Brain networks of novelty-driven involuntary and cued voluntary auditory attention shifting. PLoS ONE **7**(8), e44062 (2012). https://doi.org/10.1371/journal.pone.0044062
6. Kamiński, M., Blinowska, K.J.: A new method of the description of the information flow in brain structures. Biol. Cybern. **65**, 203–210 (1991). https://doi.org/10.1007/BF00198091
7. Landau, S.M., D'Esposito, M.: Sequence learning in pianists and non-pianists: an fMRI study of motor expertise. Cogn. Affect. Behav. Neurosci. **6**(3), 246–259 (2006). https://doi.org/10.3758/CABN.6.3.246
8. Liu, Y., Bengson, J., Huang, H., Mangun, G.R., Ding, M.: Top-down modulation of neural activity in anticipatory visual attention: control mechanisms revealed by simultaneous EEG-fMRI. Cereb. Cortex **26**(2), 517–529 (2016). https://doi.org/10.1093/cercor/bhu204
9. Mozolic, J.L., Joyner, D., Hugenschmidt, C.E., Peiffer, A.M., Kraft, R.A., Maldjian, J.A., Laurienti, P.J.: Cross-modal deactivations during modality-specific selective attention. BMC Neurol. **8**, 35 (2008). https://doi.org/10.1186/1471-2377-8-35
10. Posner, M.I., Fan, J.: Attention as an organ system. In: Pomerantz, J.R. (ed.) Topics in Integrative Neuroscience, pp. 31–61. Cambridge University Press, New York (2008)
11. Rauch, S.L., Savage, C.R., Brown, H.D., Curran, T., Alpert, N.M., Kosslyn, S.M.: A PET investigation of implicit and explicit sequence learning. Hum. Brain Mapp. **3**, 271–286 (1995). https://doi.org/10.1002/hbm.460030403
12. Talalay, I.V., Kurgansky, A.V., Machinskaya, R.I.: Alpha-band functional connectivity during cued versus implicit modality-specific anticipatory attention: EEG-source coherence analysis. Psychophysiology **55**, e13269 (2018). https://doi.org/10.1111/psyp.13269
13. Turk-Browne, N.B., Scholl, B.J., Johnson, M.K., Chun, M.: Implicit perceptual anticipation triggered by statistical learning. J. Neurosci. **30**(33), 11177–11187 (2010). https://doi.org/10.1523/JNEUROSCI.0858-10.2010

The Selected Profession as Determinant of the Flynn Effect: Specificity of Changes in the Intelligence Structure of University Students

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Abstract. The Flynn effect presents the intelligence quotient (IQ) secular gains observed in different industrialized countries throughout the 20th century. However, in recent years the Flynn effect has reversed in some Western countries, i.e. IQ in population is declining. Several causal hypotheses have been proposed to explain the different trends in measured IQ across birth cohorts, e.g. worsening education or a person’s ability to pick an intellectually facilitating niche. Our study was aimed at the analysis of the temporal dynamics in the intelligence structure of university students who have chosen different education specialties in 1991–2011. The increase of intelligence (Flynn effect) in the last decade was found in the mathematicians for the subtests of general knowledge, numerical sequences and visual-spatial abilities. The “anti-Flynn” effect was revealed in the verbal components of IQ in the humanities students, and at the same time in the visual-spatial IQ in the engineering students. From 1991 to 2011, there was a decline in the verbal memory score. The multidirectional changes in the verbal, visual-spatial, and arithmetic components of intelligence among students who choose different education specialties apparently reflect a complex set of interconnections of biological and socio-cultural factors in the development of cognitive functions and the choice of learning environments matched to intellectual abilities.

Keywords: Structure of intelligence · Flynn effect · Professional choice

1 Introduction

The observed rise in IQ scores in the second half of the 20th century (Flynn effect) [1], began to slow down or even acquire reverse dynamics since the mid-90s [2, 3]. As plausible reasons of the inverse of the Flynn effect (i.e. anti-Flynn) were proposed environmental factors such as population migration, deterioration in education and/or nutrition, and health status [4, 5].The role of group specificity or applied psychometric techniques to assess the intellectual abilities was also noted in the manifestation of IQ effects [6, 7], although the findings at another meta-analysis of studies of the Flynn effect indicated its stability regardless of the type of sample or instrument for measuring IQ [8].

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For population studies of the Flynn effect, indices of general or fluid intelligence are used more often. However, the temporal dynamics of various IQ components is of special interest, for example, when performing verbal, visual-spatial or mathematical subtests. This is due to the close connection of learning technology and targeted development of those cognitive functions that are required for the professional effectiveness in the modern information society [9, 10].

The end of the 20th century was characterized by significant social, cultural, political and economic changes in the Russian society (the so-called "perestroika") that began in 1985. Significant changes in the education system can be associated with the introduction of the Unified State Exam (USE), the results of which since 2001–2002 are used to certify secondary school education and the subsequent freshman standing admission to higher education institutions. As an integral indicator of mental abilities, the intelligence acts as a psychometric construct for assessing brain development and the formation of adaptive behavior required for survival in any environment, and socio-economic status has a significant impact on this development [11–13]. Thus, the socio-political and informational changes in the environment caused by the "perestroika" and the transition from the unified standard education system to the variety of school curricula with a common testing schedule can be considered as a natural model for studying intelligence as an adaptation factor.

Given the above changes in the living conditions of children born in the period of 1974–1996 and the corresponding changes in social attitudes on the value of education and the development of intellectual abilities, the aim of our study was to determine the temporal dynamics of IQ taking into account its structure in students who chose to learn different professional areas. It could be assumed that the enrichment of the information environment, the expansion of the use of personal computers and the transition to testing as the main method to examine knowledge, will lead to faster thinking speed and, consequently, increased IQ. The most pronounced effect in this regard should be expected when performing arithmetic tasks by mathematicians, arithmetic and visual-spatial tasks by engineers and verbal tasks by humanitarian students.

2 Methods

A data set of IQ indices according to the Amthauer's Intelligence Structure Test was collected in the period of 1991–2011 involving 3646 students (17.6 ± 1.0 years) from different departments of the university due to three professional areas: engineers, mathematicians, humanities (Gr_E, Gr_M, and Gr_H; 1936, 975 and 735 participants in the samples, respectively).

The testing was performed for 90 min during practical classes in psychology. The structure of intelligence was presented by the indices of four verbal subtests (IQv1-IQv4), two arithmetic (IQa1, IQ2), two visuo-spatial (IQf1, IQf2), and verbal memory (IQm).

To investigate the temporal dynamics and the role of the profession factor, variance analysis of IQ indices was used. The results of the post-hoc analysis were corrected by the Bonferroni procedure to adjust for multiple comparisons. For statistical data analysis, we used R software environment with Python 3.6 language in Jupyter Notebook and pandas, sklearn, and scipy.stats libraries. Along with ANOVA, KMeans clustering and hierarchical clustering methods with the construction of cluster maps (seaborn.clustermap function) were used.

3 Results and Discussion

The analysis of the time dynamics (2 PERIODs: 1991–2000 and 2001–2011; P1 and P2) and the PROFESSION factor (3 professional areas: engineers, mathematicians and humanities, respectively, Gr_E, Gr_M and Gr_H) revealed a significant effect of PROFESSION ($F_{2.3627} = 231.75$; $p < 0.00001$; $\eta 2 = 0.11$), associated with the highest IQ in Gr_M, and the lowest IQ in Gr_H (112.9 ± 0.2; 108.9 ± 0.1 and 106.8 ± 0.2, respectively). The interaction PROFESSION x PERIOD ($F_{2.3627} = 11.01$; $p < 0.00002$; $\eta 2 = 0.01$) was also significant, due to the significant IQ increase in Gr_M and Gr_E when comparing P2 with P1, but the IQ decline per decade in Gr_H (Fig. 1).

According to post-hoc analysis of the interaction PROFESSION x PERIOD x IQ ($F_{16.29256} = 7.44$; $p < 0.00001$), the effect of IQ reduction in Gr_H was significant for IQv1, IQv3, IQa2, IQf2, and IQm, while the IQ increase was found for IQv1, IQv2, IQa1, IQa2 together with the IQm decrease in Gr_E; and Gr_M had increased values of IQv1, IQa2, and IQf1 inP2 vs. P1 (Fig. 2).

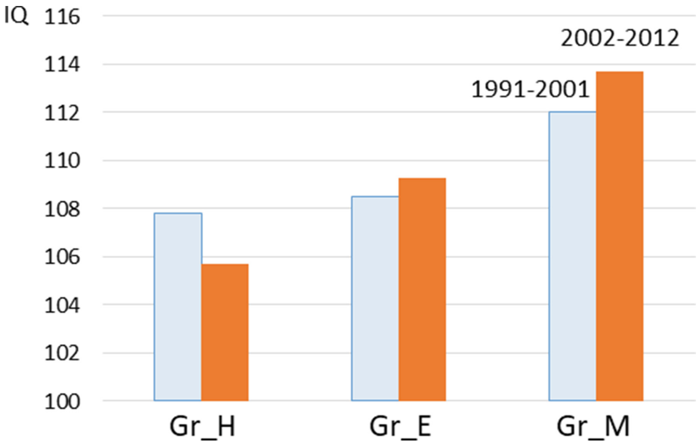

Fig. 1. The temporal dynamics of the general IQ indicators for different decades depending on the selected profession: humanities (Gr_H), engineers (Gr_E) and mathematicians (Gr_M)

To reveal a relation between the IQ level and the specificity of the temporal dynamics of the IQ components, cluster analysis of the data was carried out. The 3 clusters were formed, differing in the general level of IQ (115.8 ± 0.1; 109.5 ± 0.1 and 101.9 ± 0, respectively) and its structure: with large values of the total IQ and its arithmetic components (IQa1, IQa2) in the Cluster 1 and the predominance of memory (IQm) in the other two clusters with different ratios of the verbal and visual-spatial components of IQ (Fig. 3A).

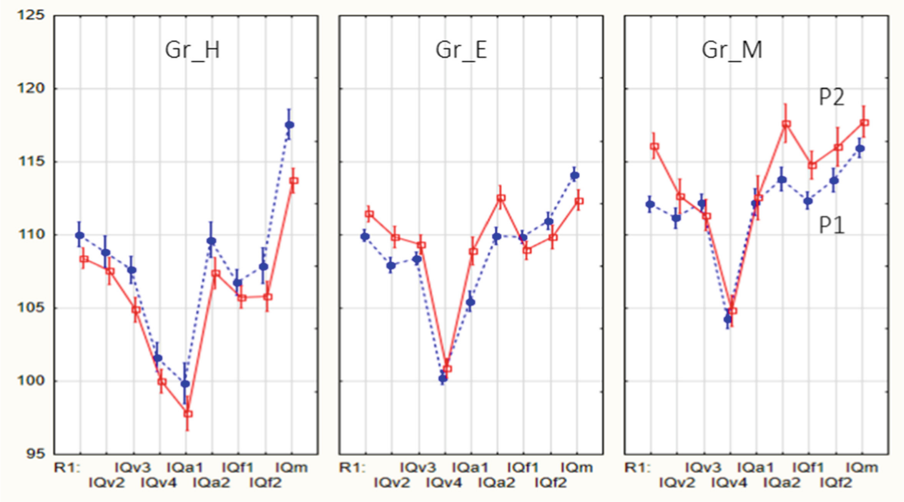

Fig. 2. The changes in the structure of intelligence depending on the period of time (dotted line for 1991–2000, solid line for 2001–2011) and profession. IQv1-IOv4 - subtests of verbal abilities, IQa1, IQa2 - arithmetic, IQf1, I Qf2 - visual-spatial, and IQm - verbal memory. The remaining notations are as in Fig. 1.

Further analysis using hierarchical clustering showed that the leading indicators in the Cluster 1 were the ability to form concepts (IQv4), visual-spatial ability (IQf2) in Cluster 2 and memory (IQm) in Cluster 3 (Fig. 3B). It should be noted that most people in Cluster 1 were represented by students from Gr_M, in Cluster 2 from Gr_E and in Cluster 3 from Gr_H.

The subsequent introduction of the CLUSTER factor into ANOVA revealed the interaction of CLUSTER x PROFESSION x PERIOD x IQ ($F_{32,29160} = 1.44$; $p < 0.051$). According to post-hoc analysis of this interaction, the decrease in IQm per decade for Gr_H and Gr_E was found regardless of the clusters (Fig. 4). An increase in IQa1 or IQa2 in P2 compared to P1 for Gr_E and Gr_M was found only for the Cluster 1, which was characterized by high IQ values. In Gr_M, large IQv1 values for P2 were revealed for the first and second clusters. It should be noted that a significant dispersion of the IQ indicators in Cluster 3 for Gr_M or in Cluster 1 for Gr_H was due to the small number of representatives in these groups (only 97 and 98 people, respectively).

Thus, the obtained results indicate that the nonexistence of the increase in the overall IQ when comparing the periods 1991–2000 and 2001–2011 (Flynn effect) is due to several factors. Namely, the temporal dynamics of intellectual abilities turned out to be related to the profession selected by students, the level, and structure of IQ differing among students in engineering, mathematical or humanitarian specialization. The Flynn effect was found in Gr_M and Gr_E whereas in Gr_H the “anti-Flynn” was revealed.

The development of information technologies and their extensive use in the 21st century seems to contribute to the enhancement of those intellectual abilities for which the speed of mental operations is especially significant. Therefore, the effect of increasing IQ should be expected for those students who have a higher level of intelligence, i.e.

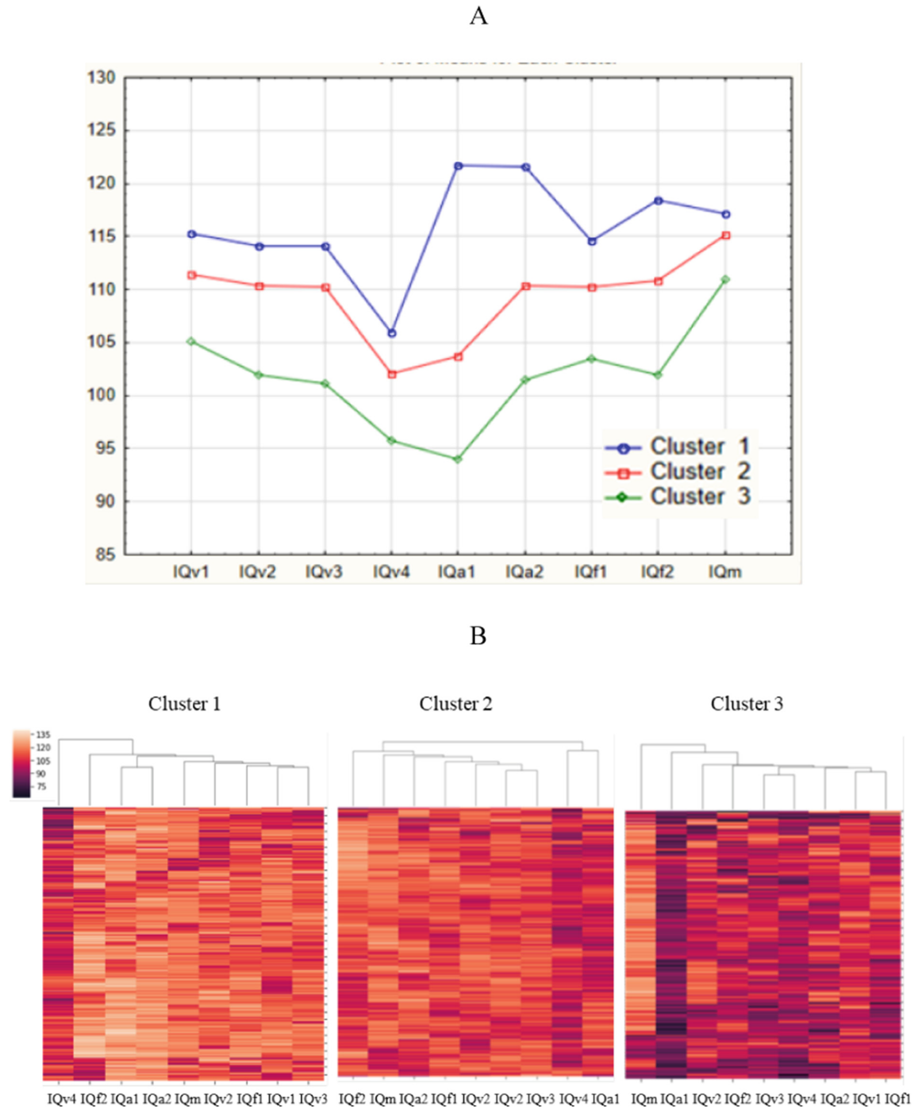

Fig. 3. The structure of intelligence in the three selected clusters (A) and the corresponding cluster maps of IQ components (B)

according to the psychometric approach is able to quickly find a solution to simple problems. Our results, however, show that this effect is not uniform and depends on the professional orientation and/or general level of IQ and is expressed differently for verbal, visual-spatial or arithmetic tasks.

Our hypothesis about the relationship between the intensity of the Flynn effect and the IQ in students of different specialties was confirmed only with respect to arithmetic abilities: an increase in these IQ components in P2 compared to P1 was shown in Gr_M

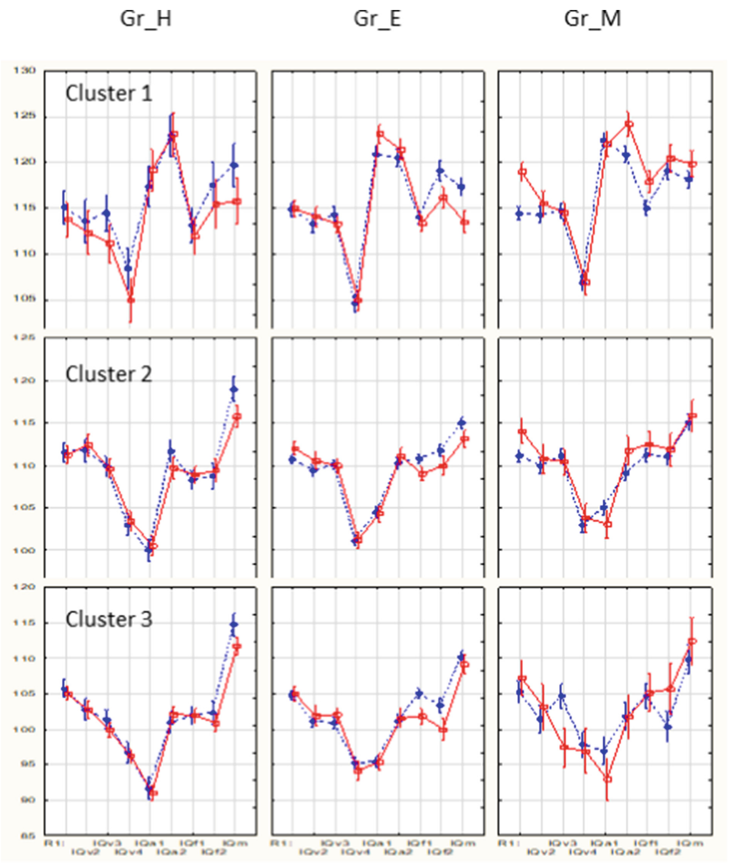

Fig. 4. The temporal dynamics of the structure of intelligence when comparing the periods 1991–2000 (dotted line) and 2001–2011 (solid line) depending on the chosen specialty in the three formed clusters.

and Gr_E. At the same time, changes in the visual-spatial components in these groups were opposite: the IQ increase in Gr_M, but a decrease in Gr_E. For the general IQ in Gr_H, we noted the "anti-Flynn" effect (Fig. 1) with a significant decrease in IQm, IQa2 and IQf2 and the tendency to this effect for all other IQ components (Fig. 2). Gr_H differed from the other groups not only in the relatively low overall IQ, but also by leading contribution of IQm to the intelligence structure (Fig. 2, 4B). It should be noted that this component is the most strongly reduced in Gr_H when comparing P2 and P1.

It can be assumed that under a penchant for the humanities occupations, often accompanied by a lack of interest in mathematics and as a consequence poor performance in arithmetic operations, the enriched information environment has rather not a stimulating effect on cognitive activity, but creates conditions for the utilitarian use of knowledge based on hints. In favor of this hypothesis, we can consider the temporal dynamics of IQm, a decrease in the level of which was noted not only in Gr_H, but also among representatives of this group, which fell into Cluster 1, formed from individuals whose mean IQ was 116.

In contrast to the evidence that the Flynn effect is more pronounced for a sample with an average or low level of intelligence [7], we found an increase in IQ over time in Gr_M which differed from Gr_E and Gr_H by high level of IQ. However, our results are in line with the findings of another study on positive temporal dynamics with a high IQ and negative with a low one [14]. Since in the analysis of IQ in the three clusters formed in the Euclidean metric based on the proximity of IQ indicators relative to K centers, a significant interaction effect of factors PERIOD and IQ was not found, but only the CLUSTER x PROFESSION x PERIOD x IQ interaction was significant, we can agree with the opinion of other researchers that the Flynn effect is associated with the complex interaction of genetic and socio-cultural factors [7, 11], affecting the development of intellectual abilities, the formation of the values of education and the choice of profession.

Considering the data on the interconnected development of mathematical abilities and executive control of behavior [9], the relatively low IQ at P1 in Gr_H, which decreases further in P2, can be explained by the insufficient level of targeted monitoring of task performance during testing of intellectual abilities. An additional factor of the "anti-Flynn" effect among humanities may be the testing procedure that is widely used in the USE, which, given the time it takes to think about the answer, leads to a superficial solution to the problem, without critical reflection of possible options.

4 Conclusion

It was found that the changes in intelligence when comparing the decade 2001–2011 to the period of 1991–2000 are dependent on the professional specialization chosen by students. The Flynn effect was revealed for mathematicians and engineers, while the "anti-Flynn" effect was shown for humanities students. The temporal dynamics of IQ was differentially presented in its structure: an increase in the intelligence among mathematicians was shown for subtests of general knowledge, numerical sequences and visual-spatial abilities, whereas the anti-Flynn effect was found for indices of verbal subtests in humanities and visual-spatial abilities among engineers at a general decrease in verbal memory. The multidirectional changes in the verbal, visual-spatial, and arithmetic components of the intelligence among students, who choose different education specialties, apparently reflect a complex set of interconnections of biological and socio-cultural factors in the development of cognitive functions and the choice of vocational training on this basis.

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References

1. Pietschnig, J., Voracek, M.: One century of global IQ gains: a formal meta-analysis of the Flynn effect (1909–2013). Perspect Psychol Sci. **10**, 282–306 (2015)
2. Bratsberg, B., Rogeberg, O.: Flynn effect and its reversal are both environmentally caused. Proc. Natl. Acad. Sci. **115**, 6674–6678 (2018)
3. Dutton, E., van der Linden, D., Lynn, R.: The negative Flynn effect: a systematic literature review. Intelligence **59**, 163–169 (2016)
4. Flynn, J.R., Shayer, M.: IQ decline and Piaget: does the rot start at the top? Intelligence **66**, 112–121 (2018)
5. Rindermann, H., Becker, D., Coyle, T.R.: Survey of expert opinion on intelligence: the Flynn effect and the future of intelligence. Pers. Individ. Differ. **106**, 242–247 (2017)
6. te Nijenhuis, J., van der Flier, H.: Is the Flynn effect on g? A meta-analysis. Intelligence **41**, 802–807 (2013)
7. Williams, R.L.: Overview of the Flynn effect. Intelligence **41**, 753–764 (2013)
8. Trahan, L., Stuebing, K.K., Hiscock, M.K., Fletcher, J.M.: The Flynn effect: a meta-analysis. Psychol. Bull. **140**(5), 1332–1360 (2014)
9. Baker, D.P., Eslinger, P.J., Benavides, M., Peters, E., Dieckmann, N.F., Leon, J.: The cognitive impact of the education revolution: a possible cause of the Flynn effect on population IQ. Intelligence **49**, 144–158 (2015)
10. Demetriou, A., Makris, N., Tachmatzidis, D., Smaragda, K., Spanoudis, G.: Decomposing the influence of mental processes on academic performance. Intelligence **77**, 10140 (2019)
11. Neisser, U.: Rising scores on intelligence tests. Am. Sci. **85**, 440–447 (1997)
12. Noble, K.G., Houston, S.M., Kan, E., Sowell, E.R.: Neural correlates of socioeconomic status in the developing human brain. Dev. Sci. **15**, 516–527 (2012)
13. Piccol, L.R., Merz, E.C., He, X., Sowell, E.R., Noble, K.G.: Age-related differences in cortical thickness vary by socioeconomic status. PLoS ONE **11**, e0162511 (2016)
14. Platt, J.M., Keyes, K.M., McLaughlin, K.A., Kaufman, A.S.: The Flynn effect for fluid IQ may not generalize to all ages or ability levels: a population-based study of 10,000 US adolescents. Intelligence **77**, 101385 (2019)

Affective Priming and Decision-Making in the Economic Game

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Abstract. Emotions are rarely studied in economic models. However, their contribution to the economic decision-making (DM) process is underestimated. The present study is based on the model of multiple regulation of DM (an interaction between cognitive, emotional, and personal processes) and investigates the influence of emotions via affective priming on DM in an economic game — the Trust Game (TG). The participants were 71 Russian students (34 men and 37 women, aged between 17 and 39 years, M age = 20.8; SD = 4.8). The masked priming paradigm is used in the experiment. Priming pictures are presented at different durations (33 or 500 ms) and valences (positive, neutral or negative). Participants played TG with three computer players (distinguished by their strategies: imitator, detective, vindictive) and they were asked to make a choice to either "trust" or "cheat" by clicking one of the buttons. The results reveal that both the computer player and the affective priming influenced DM and gain, but priming stimuli duration impacted neither the DM nor the gain. These findings reaffirm the statement that emotions can influence economic behavior.

Keywords: Emotions · Affective priming · Decision-making · Choice · Economic game · Trust game

1 Introduction

Economic behavior models rarely consider emotions as components of the decision-making (DM) process. The decision-making process is frequently described as a choice made by a person (or by a group of people) between two (or more) alternatives under uncertainty [1]. In psychology, it is crucial to know which mechanisms regulate DM process: personal (e.g. emotions, emotional intelligence (EI) or cognitive (intelligence). Based on the idea of the unity of intelligence and affect developed in cultural-historical psychology by L.S. Vygotsky, we suggests a model of dynamic regulative systems (DRSes) that includes the interaction between cognitive, emotional, and personal processes in choice regulation and the multiple regulations of DM. Our study is based on the model of dynamic regulative systems [1] and we assume that emotions along with cognitive and personal processes regulate DM. All three levels of DM regulation included in DRSes works jointly: it is difficult to define the leading level of regulation and the characteristics of the regulatory hierarchy of process for a specific person.

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Emotions include aesthetic emotions that influence DM [2, 3]. Negative aesthetic emotions, such as boredom or anger, can motivate a person to stop reading a book or to leave a performance [4]. The purpose of this study was to reveal the influence of emotional priming (EP) on decision-making in the Trust Game (TG). The affective priming paradigm, used in the experiment, worked with the vast area of stimuli: words, faces and pictures [5]. Much debate exists about priming stimulus duration. Specifically, it was shown that the priming stimulus duration of 100 ms is sufficient for a subject to perceive the affective content of artwork [6]. One of the latest researches showed that emotional priming works only when the person reports at least a brief glimpse (participants reported a brief glimpse when the priming stimulus duration was about 25–42 ms). If participant reported that he did not see anything at all, even a glimpse, then priming does not have any impact [7]. These findings challenge the "classical" interpretation of priming.

The TG is based on a social dilemma and in order to achieve higher gains, players should "trust" each other [8]. In the long run, the "cheat" strategy is the most disadvantageous in the TG [9]. However, little is known about how emotions influence DM in economic games. We hypothesized that the valence of EP (neutral, positive, negative), the priming stimuli duration (33 ms, 500 ms) and type of the computer player (imitator, detective, vindictive) strategies influence the gains and the number of "trust" decision-making strategies.

2 Experimental Method

2.1 Participants

Seventy-one healthy Russian students, among them 15 economists and 56 psychologists (who had a normal or corrected-to-normal vision) took part in the experiment (34 man and 37 women aged between 17 to 39 years, M age = 20.8; SD = 4.8).

2.2 Materials and Design

We used paintings as stimuli. We selected 36 pictures painted by artists, meeting the following criteria: a) they were a modern artist (living in the 21st century); b) their paintings were displayed in museums around the world and private collections; they had a professional art education or they were members of professional art communities. 36 paintings were rated by 23 experts.

The final set included only the paintings evaluated by experts strictly as $+ 3$ (positive valence), zero (neutral) and -3 (negative valence) on a scale from -3 to $+ 3$. The final picture set contained 18 paintings (6 - positive, 6 - negative and 6 - neutral).

Factorial design: $2 \times 3 \times 3$ was used in the experiment. There are three factors: priming stimuli duration (between-subject factor), the priming valence and a computer player (within-subject factors), and two dependent variables: gains and the number of "trust" DM strategies. There were 8 conditions: each differentiated by a sequence of priming valence and the type of computer player (forward and reverse). Each condition consisted of 9 series with 5 or 6 games (computer randomly chose the number of games in each series, and participants were blind to how many games they would play). The interval between the series was 10 s, and a countdown was presented on the screen. All participants made roughly 45 choices. There was no monetary compensation in the experiment. Before the experiment, all participants signed informed consent forms.

The strategies of computer players were as follows. The “Imitator” makes the same choices as the participant: if the participant cheats, the imitator cheats in the next game. The “Vindictive” computer strategy starts with trust strategies, but if the participant cheats, the “vindictive” computer player cheats during all the following games regardless of participants’ choices. The “Detective always starts with a trust-based strategy, then cheats, and in the last 3–4 games “trusts” a gain; if the participant cheats first, detective plays as the imitator would; if the participant cheats twice, detective plays as the vindictive computer player would. The classic masked priming paradigm was used in the experiment. Stimuli comprised of static colored images – paintings of modern artists displaying 6 neutral and 12 emotional (6 positive and 6 negative) valences.

3 Procedure

The experiment was performed in groups: each participant was sat at a computer. The first stage of the experiment included awareness of the priming stimuli: a set of priming stimuli was presented on the screen at two different durations (33 and 500 ms). Participants then reported their perceptual awareness of the stimuli, measured with the perceptual awareness scale [10] ranging from: no experience (1), brief glimpse (2), almost clear experience (3) to clear experience (4).

The instruction for the TG was presented during the second stage of the experiment. The participants played a trial game series (2 games). In the third stage, the main experiment began with a task instruction reading: “What would you choose: to trust or to cheat?” Then the following pattern of stimuli appeared sequentially: a black fixation cross on a white background (700 ms), a masked image displaying a colored pixel pattern (200 or 500 ms), the priming stimulus (33 or 500 ms), masked image (200 or 500 ms). Afterwards the screen displayed two players: the computer and the participant, with a box between them, where the players put their game coins. The screen also displayed two buttons (“trust” and “cheat”). The participant could click on one of the buttons to make the decision (DM). In the fourth stage participants filled in several questionnaires, assessing control over emotions, personal basic beliefs about trust, and impulsiveness.

4 Results

Data analysis was performed in IBM SPSS v. 22. The Kolmogorov-Smirnov test showed that data has an abnormal distribution, so we used nonparametric tests. The Friedman rank test showed a greater number of “trust” DM strategies in the game series with positive priming than in the series with neutral and negative priming: $\chi^2 = 68$; df = 2; $p < 0.001$, positive priming rank = 2.77; negative priming rank = 1.76; neutral priming rank = 1.47. Post-hoc analysis revealed that the number of “trust” DM strategies in the series of games with negative and neutral priming did not differ. Nevertheless, the series with positive priming compared to the series with neutral priming ($F = -7.720$, $p <$

0.001), and the series with positive compared to the series with negative priming ($F = 6.000$, $p < 0.001$) showed significant differences: there was a greater number of "trust" DM strategies in the series with positive priming.

The Friedman rank test also showed differences in the gains: $\chi^2 = 57$; df = 2; $p < 0.001$, negative priming rank = 2.52, positive priming rank = 2.18, neutral priming rank = 1.18. The smallest gain was in the series with neutral priming**.** Post-hoc analysis revealed that the gains in the series with positive and negative priming was approximately equal. However, the series with neutral priming compared to the series with positive priming ($F = 5.287$, $p < 0.001$) and neutral compared to negative ($F = -7.301$, $p < 0.001$) had significant differences: gains were least frequent in the series with neutral priming. The series of games were also compared according to the number of gains and "trust" DM strategies (3 priming valences × 3 players = 9 series).

The Friedman rank test showed differences in the amount of gains: $\chi^2 = 212$; df = 9; $p < 0.001$. Participants received the highest gains in the game series playing against the "imitator" and with neutral priming (rank = 5.93); the lowest gain was found in the series playing against the "detective" with negative (rank = 3.94) and positive priming (rank = 3.96). Post-hoc analysis of the game series showed that the computer player rather than the priming affects the gains, because significant differences were found in the game series with different computer players but the same priming. The Wilcoxon test showed that the gain in the series with the "detective" computer player was lower than in the series with the "imitator" for all three priming valences.

The Friedman rank test showed differences in the number of "trust" DM strategies: $\chi^2 = 77$; df = 8; $p < 0.001$. Greater number of "trust" DM strategies was found in the series with the "imitator" and neutral priming (rank = 5.64); the least number of "trust" DM strategies was seen in the series with the "detective" and negative priming (rank = 3.79) and neutral priming (rank = 3.78). Post-hoc analysis of the game series showed that the computer player rather than the priming affects the "trust" DM strategies because significant differences found in the game series with different players but the same priming. The Wilcoxon test showed that the number of "trust" DM in the series with detective less than in the series with imitator and vindictive within all priming valence. Priming stimuli durations affected neither the number of "trust" DM strategies, nor the gain.

5 Discussion

Our results show that affective priming stimuli impact DM process even via masked paradigm. The mask is necessary to ensure that priming is not perceived consciously. However, the controversial role of the mask in the effects of cognitive priming showed that: (1) a significant priming effect occurred even when it was masked and (2) the magnitude of the priming did not depend on the presence or absence of a mask. In other words, the mask reduced the accuracy of the verbal message to random that practically did not affect the value of the semantic priming effect [11]. Our results confirm that these findings are also true for affective priming.

It was an unexpected result that priming stimuli duration influenced neither the DM nor the win. However, these results can be explained by the fact that priming works only when stimuli duration 25–42 ms. It means that, if the priming duration is 25 ms or higher, then its impact increases [7]. Consequently, there is no difference between priming stimuli durations of 25 ms and 500 ms.

We also show that the type of computer player affects the number of "trust" DM strategies and the gain: the lowest gain was found in the series with the "detective" who cheated first. Our results are consistent with the findings of Japanese colleagues. Based on the Iowa Gambling Task they showed that when a person assumes that the "deck" is an unreliable partner (trying to deceive the participant), the person avoids choosing the deck symbolizing the "cheater" for a longer period of time than faced with a similar result perceived as a natural risk [12].

The hypothesis that emotions influence economic behavior was also confirmed in our experiment. Previous findings demonstrate that a person in a good mood would perform optimistic DM and vice versa [2]. We found that in the series with positive priming the number of "trust" DM strategies is greater than in the series with negative priming. Moreover, positive emotions can increase the gains, however, negative emotions have the same effect, and this finding requires further research. A possible explanation could be that negative and positive emotions influence gains indirectly via the "trust" DM strategies.

6 Conclusion

In this paper, we explore the influence of emotions via affective priming on economic behavior – the decision-making process in the Trust Game. The results partly support our hypothesis: the computer player (imitator, detective, vindictive) and the priming valence (neutral, positive and negative) influence the number of "trust" DM strategies and the gains, but the priming stimuli duration influence neither the DM nor the win.

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References

1. Kornilova, T.V.: Intellectual and Personal Potential Under Uncertainty and Risk. Nestor-Istoria, Saint Petersburg (2016).(in Russian)
2. Lerner, J.S., Li, Y., Valdesolo, P., Kassam, K.S.: Emotion and decision making. Annu. Rev. Psychol. **66**, 799–823 (2015). https://doi.org/10.1146/annurev-psych-010213-115043
3. Menninghaus, W., Wagner, V., Wassiliwizky, E., Schindler, I., Hanich, J., Jacobsen, T., Koelsch, S.: What are aesthetic emotions? Psychol. Rev. **126**(2), 171–195 (2019). https://doi.org/10.1037/rev0000135
4. Kirk, U., Skov, M., Hulme, O., Christensen, M.S., Zeki, S.: Modulation of aesthetic value by semantic context: an fMRI study. Neuroimage **44**, 1125–1132 (2009). https://doi.org/10.1016/j.neuroimage.2008.10.009

5. Garcia-Garcia, I., Kube, J., Morys, F., Schrimpf, A., Kanaan, A.S., Gaebler, M., Neumann, J.: Liking and left amygdala activity during food versus nonfood processing are modulated by emotional context. Cogn. Affective Behav. Neurosci. **20**(1), 91–102 (2020). https://doi.org/10.1101/707844
6. Nodine, C., Mello-Thoms, C., Krupinski, E., Locher, P.: Visual interest in pictorial art during an aesthetic experience. Spat. Vis. **21**(1–2), 55–77 (2008). https://doi.org/10.1163/156856807782753868
7. Lohse, M., Overgaard, M.: Emotional priming depends on the degree of conscious experience. Neuropsychologia **128**, 96–102 (2019). https://doi.org/10.1016/j.neuropsychologia.2017.10.028
8. Berg, J., Dickhaut, J., McCabe, K.: Trust, reciprocity, and social history. Games Econ. Behav. **10**, 122–142 (1995). https://doi.org/10.1006/game.1995.1027
9. Emonds, G., Declerck, C.H., Boone, C., Vandervliet, E.J.M., Parizel, P.M.: The cognitive demands on cooperation in social dilemmas: an fMRI study. Soc. Neurosci. **7**, 494–509 (2012). https://doi.org/10.1080/17470919.2012.655426
10. Ramsøy, T.Z., Overgaard, M.: Introspection and subliminal perception. Phenomenol. Cogn. Sci. **3**(1), 1–23 (2004). https://doi.org/10.1023/B:PHEN.0000041900.30172.e8
11. Cheesman, J., Merikle, P.M.: Priming with and without awareness. Percept. Psychophys. **36**(4), 387–395 (1984). https://doi.org/10.3758/BF03202793
12. Nakanishi, D., Ohtsubo, Y.: Do people react differently to natural and social risk? J. Soc. Evol. Cult. Psychol. **2**(3), 122–132 (2008). https://doi.org/10.1037/h0099350

Pupil Dilation as a Precursor of Risky Choice in Probabilistic Gambling Task

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Abstract. Human behavior in probabilistic environment is characterized by a preference for a more frequently reinforced option, yet people tend to make a few number of disadvantageous choices as well. We test the hypothesis that risky choices may reflect a bias to search for regularities in a random sequence of events. We measured pupil dilations as a marker of norepinephrine release in locus coeruleus, which may index subjects' engagement in the exploratory behavior. Fifty-two healthy participants performed two-alternative serial choice task with the reward probability of 0.7 for one stimulus and 0.3 for the other. Feedback was presented with a delay of 1 s after the response. We performed ANOVA analysis of mean pupil area in a 1400 ms time window following feedback onset. We considered three factors that could trigger pupil dilations: riskiness of the current choice, its positive or negative outcome, and the riskiness of the following choice. We found that pupil dilation predicted the future risky choice, while it did not depend on the other two factors. The amplitude of pupil dilation before a persistent risky decision negatively correlated with the total number of risky choices. Taken together, these findings indicate that the latent process of preparation for risky decisions is associated with increased norepinephrine release. We suppose that the transitory increment of norepinephrine release may result from detection of a conflict between the pragmatic model of the advantageous strategy and the planned risky action by the cingulate cortex, which sends excitatory projections to the locus coeruleus.

Keywords: Probabilistic reinforcement · Risk taking · Exploitation-to-exploration tradeoff · Pupillometry · Norepinephrine

1 Introduction

Suboptimal decision making in humans has been one of the most urgent unresolved problems in psychology, economics and psychiatry for several decades. In particular, it is known that people tend to commit a certain proportion of disadvantageous choices when outcomes of their decisions cannot be fully predicted. For example, in a typical neuroeconomic experiment participant have to choose one out of two stimuli. One of them brings a reward in 70% of trials, and the other one in 30%. Most healthy adults match relative frequencies of their choices to the expected reward probability. This

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happens despite the fact that the best strategy in such probabilistic environment would be to choose the most often rewarded stimulus on all trials. This striking example of disadvantageous decision making was well documented as “probabilistic matching law” [1].

One of the most fruitful theoretical explanations of these phenomena is the hypothesis stating that people are prone to find regularities in objectively random sequences of wins and losses in hope to increase their total gain [2]. No mechanism exists that would allow detecting random sequences directly, and the only way to detect randomness is to generate a range of hypotheses and test them. In line with this explanation, humans make disadvantageous explorative decisions and choose less rewarded alternatives simply because they attempt to follow illusory patterns they suspect.

However, it is not clear why the proportion of explorative choices closely matches the reward probability. Behavioral adaptation to uncertain conditions should be based on a proper balance between the exploratory behavior (potentially beneficial for future cumulative gains) and exploitation of known advantageous options (thus gaining immediate rewards). Theoretically, preference for the most rewarded alternative in combination with a moderate proportion of risky choices is the best strategy for most probabilistic or volatile conditions. While matching one’s behavior in probabilistic gambling tasks is disadvantageous for the subject. E.g., in the example mentioned above, following the probability-matched proportion of explorative choices decreases the total rate of wins nearly to chance level ($0.3*0.3 + 0.7*0.7 = 0.58$ vs. 0.5), while sticking strictly to the advantageous choice would ensure a much higher probability of wins (0.7). On the other hand, strong preference for advantageous options would restrict subjects’ ability to test alternative strategies.

This striking inconsistence may be explained by an essential difference between experimental and natural conditions. In the real world, most of sequentially occurring events are not mutually independent and randomly distributed, and valid hypotheses can be drawn from subjects’ prior experience. It was shown that individuals who were more prone to probabilistic matching bias were more able to discover real regularities in sequential events [3].

Here we hypothesized that risky choices in probabilistic gambling tasks may be a form of exploratory behavior. A fundamental mechanism of flexible behavioral adaptation to uncertain or volatile environment is the exploration-to-exploitation tradeoff [4]. This theoretical view describes range of adaptive behavior as a continuum between two opposite modes. Exploitation mode means a full engagement of attention to the goal. Subjects respond quickly, accurately, and easily resist to distractors. In contrast, behavioral variability and unstable reaction times characterize exploration mode. Spontaneous shifts in exploitation-to-exploitation tradeoff ensure cognitive flexibility.

Biologically, this mechanism may be based on variability in noradrenaline release from locus coeruleus neurons [4], which modulate higher-order cortical networks involved in decision making and voluntary attention shifts [5]. Behaviour accuracy depends on noradrenaline level in an inverted U-shaped shape [6]. Extremely low tonic level is characteristic of sleepiness and lacking motivation. Medium level is optimal to sustain goal-oriented attention. The further increment of noradrenaline production results in disorganized and inconsistent behavior. In an unfamiliar or volatile environment, the exploratory mode of behavior allows subjects to discover new advantageous options to exploit them in future. Individual and age-related differences as well as some clinical variations of learning based on probabilistic reinforcement may be related to specific physiological characteristics of the locus coeruleus [7].

Spontaneous risky choices in probabilistic gambling tasks may be related to noradrenaline-based shifts in exploitation-to-exploitation tradeoff balance. However, it is unclear what external or internal events trigger such shifts. One of the most probable candidate is unexpected negative feedback. In the example disused above, the unexpected negative feedback (loss) to advantageous choices occurs in 30% of trials. If subjects would follow a common reinforcement learning bias, they would shift their strategy after each loss (see [8] for review), this strategy automatically resulting in the probabilistic matching phenomena, i.e. participants would choose the disadvantageous stimulus in 30% of trials. However, our previous study [9] demonstrated that the effect of immediate feedback on subjects' future choice disappeared soon after subjects developed an adaptive preference for the more often rewarded stimulus. Yet, an unexpected negative feedback may affect human behavior in an indirect manner via automatic mobilization of noradrenaline-based attention networks. Negative violation of expectations, which is detected in the cingulate cortex, facilitates lose-shift strategy via top-down pathways to the locus coeruleus, hypothalamus and amygdala [10].

The aim of the present study was to investigate the role of two possible factors that may affect risky choices in the probabilistic gambling task: an internal proactive intention to commit the exploratory behavior, and valence of the current feedback (win or lose). We used infrared pupillometry to track pupil area as an indirect index of noradrenaline function [11]. We predicted that exploratory intention would increase pupil size in trials with advantageous choice immediately before risk. Alternatively, an unexpected negative feedback after an advantageous choice may increase pupillary size compared with to an expected gain [12, 13].

2 Method

To investigate spontaneous shifts from exploitation to exploration mode, we used a modified probabilistic learning task [14]. The task involved repeated choices between two similar abstract figures. Each choice resulted in gaining or losing several points, which were presented on the screen on each trial. Gains and losses were accumulated throughout the experiment, and converted to a sum of real money. One figure delivered a reward with a 70% probability and the other with a 30% probability. Wins and losses followed in a pseudo-random order.

The experiment included five blocks. Within each block, a new pair of stimuli was presented. Before the experiment, the participants were informed that one figure would bring a reward more often than the other. The instruction motivated participants to accumulate gains.

2.1 Participants

Fifty-two healthy volunteers (29 females; mean age 23, S. D. = 6.5, range 18–45 years) participated in the experiment. They reported no neurological disorders or severe visual impairment (visual acuity was within ± 2.5 diopters, at least for one eye). During the experiment, participants were not allowed to wear glasses or contact lenses. Before the beginning of the experiment, all participants completed a short test for visual discrimination and recognition of figures similar to experimental stimuli.

In accordance with the declaration of Helsinki, participants were informed about the experimental procedure and they gave informed consent.The experiment was approved by the ethics committee of the Moscow State University of Psychology and Education (Date of meeting: 6.02.2019, record #1).

2.2 Procedure

The experimental procedure resembled a computer game. Participants sat in a chair and placed their heads on chin rest to minimize involuntary head movements. During the game, they kept their forefinger on the left button of the gamepad, and the middle finger on the right button. To choose a stimulus, participants pressed one of two the buttons according to location of the stimuli on the screen (on the left or on the right). The experiment lasted about 30 min.

Presentation software (Neurobehavioral Systems) was used to present stimuli and record behavioral responses.

Each of five blocks consisted of 40 presentations of the same pair of figures, which were located symmetrically on the left and on the right of the screen. Location of stimuli on the screen was varied pseudorandomly with equal probability. The stimuli consisted of two Hiragana hieroglyphs rotated at different angles, with a white outline, on a black background. The size of the stimuli was 1.54 × 1.44 angular degrees, which is close to the angular size of the fovea. We equalized the stimuli in size, brightness, perceptual complexity, and spatial position. Before the stimulus onset, a fixation cross was presented on the screen for 150 ms. The stimuli stayed on the screen until the button press, then after a delay of one second, visual feedback presented for 500 ms. The feedback informed participants whether they received or lost points on the current trial. A variable time interval (800–1400 ms) was introduced between trials. At the end of each block, participants were shown their accumulated score. The procedure is shown in Fig. 1.

To investigate the spontaneous risks in each block, we identified periods in which participants' behavior reflected the exploitation of the pragmatic stimuli model. We considered such a period to begin after four consecutive choices of an advantageous stimulus and analyzed all trials until the end of the current block. During the period of usage of the pragmatic model, the percentage of advantageous stimulus choices had to stay significantly above chance (no less than 65).

2.3 Pupillometry

Pupil area of the dominant eye was recorded throughout the experiment using EyeLink 1000 Plus (SR Research) with the sampling frequency of 1000 Hz. Before each block, the eye tracker was calibrated using a standard nine-dot procedure.

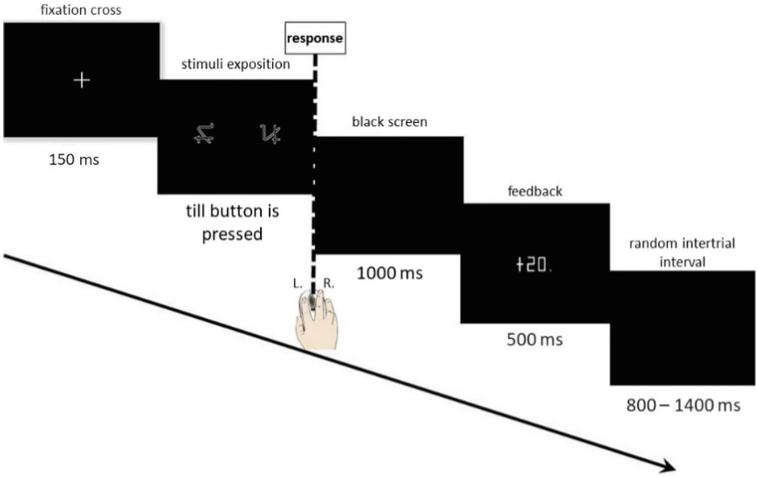

Fig. 1. Experimental procedure

The pupil area (in pixels) was calculated using the preinstalled EyeLink software during the eye fixations at the center of the screen within the span from the feedback onset up to 800 ms after the feedback cessation (1300 ms in total). Measurement errors arising due to spontaneous blinks were extrapolated by preinstalled EyeLink software.

The initial processing of the video-oculography data was performed using EyeLink DataViewer program that produces a text report. For each eye fixation, the following parameters were monitored: gaze position tracked in two coordinates on the calibration plane, the time of the onset/cessation and the duration (in ms) of each fixation, and the mean diameter of the pupil (in pixels) within the current fixation. The text reports were further processed by custom Python scripts.

2.4 Statistical Analysis

We analyzed pupil measurements using 3-way ANOVA with repeated measures, with two levels of each factor: the previous choice (advantageous/disadvantageous stimulus choice), current feedback (positive/negative) and the next choice (change/repeat of the previous choice). The analysis included data from 22 subjects who had pupil measurements for each of the 8 combinations of experimental conditions.

For a statistical analysis of the pupil measurements averaged for each condition, it was necessary to transform them to exclude the influence of different illumination conditions and individual differences in the size of the pupil. Therefore, to normalize the average pupil measurements during the feedback presentation, we divided them by the average pupil size throughout the entire experiment.

3 Results

The mean cumulative payoff for the group was 420 rubles (S.D. = 250 rubles). This was less than could be predicted if subjects would have always chosen the advantageous stimulus (1120 rubles). Proportion of risky choices in the period following the achievement of the learning criteria was 18% (range 0–35%). It means that risky choice could not be explained by the absence of a strong pragmatic model of the task. Moreover, risky choices were definitely inconsistent with the general exploitative strategy of participants' behavior.

Only 20 subjects from our sample were included in the ANOVA analysis, because of missing data (some persons avoided risky choices, or never committed two or more consecutive risky choices or never achieve learning criteria). ANOVA results revealed that out of three factors, included in the analysis, only one factor exerted a statistically significant influence on the relative pupil dilation, namely the factor of a future risky choice in the following trial (F (1,19) = 14.9; $p < 0.001$) (Fig. 2).

Nonparametric correlational analysis demonstrated that the relative pupil dilation before the repeated risk (if the previous risky choice led to a loss) negatively correlated with the total number of risky choices (Spearman R = −0.46, p = 0.003). In other words, maximal pupil dilation before disadvantageous decisions was characteristic for the subjects who tended to avoid persistent risks (Fig. 3).

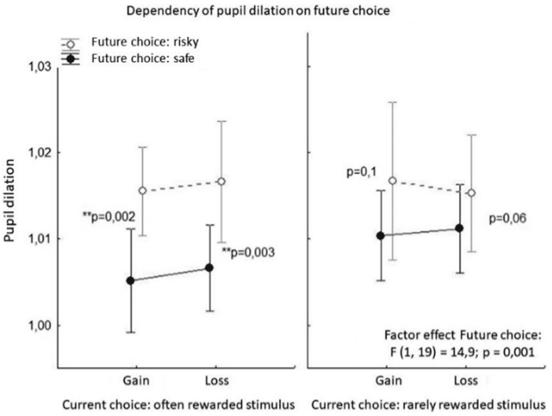

Fig. 2. ANOVA results the influence of three factors on relative pupil dilation. As can be seen in the picture, the sign of the current feedback did not affect the amplitude of pupillary response, whereas future risk in next trial did.

4 Discussion

In this study, we demonstrated that transient pupil dilation preceded spontaneous risky decisions in the probabilistic gambling task. These findings are consistent with a previous pupillometric study using a 4-armed bandit paradigm [15]. In this experiment, 4 arms with different unknown and gradually changing amounts of reward was presented to subjects for serial selection. Within several trials, most participants developed preference for the most rewarded lever, and then shifted to new options according to violations in the amount of reinforcement given. This behavioral shift was used as a model of exploitation-to-exploration tradeoff. Authors described tonic increment in the pupil size in subjects before they shifted to the unfamiliar alternatives.

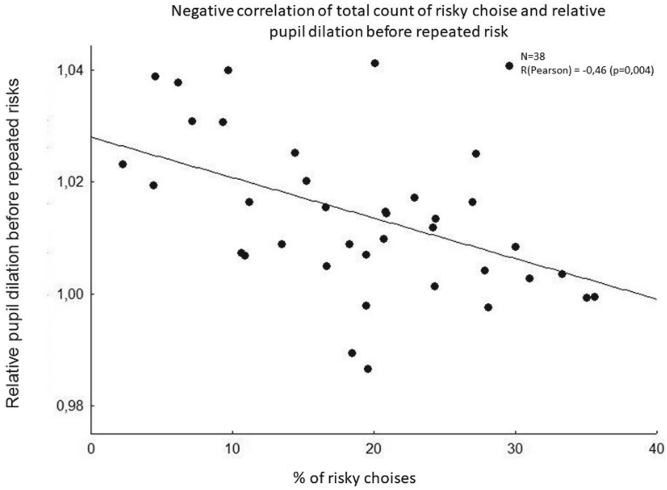

Fig. 3. Negative correlation of relative of amplitude of pupil dilation before repeated risky choice after expected lose with total count of disadvantageous choices after learning criteria is achieved.

In another study, it was shown that tonic pupil size predicts cognitive set shifting in volatile conditions [16]. In classical Wisconsin card sorting task, subjects have to switch between several selection rules according to volatile feedback. Pajkossi et al. demonstrated that enlarged pupils were characteristic of the searching period, when participants were trying to discover a new valid rule. These results are consistent with the view that pupil size is sensitive to uncertainty and surprise [11, 12].

All these investigations cited above imply an objective necessity for subjects to change their behavior. In these paradigms, participants made shifts of their strategies in accordance with informative feedback. Such design did not allow assessing the difference between the influences of reactive factors (the sign and unexpectedness of the feedback) versus proactive exploratory intentions. By contrast, the experimental procedure used in the current study did not involve any external triggers leading the subject to change their behavior for the long-term perspective. Moreover, the best cumulative gain resulted if participants behaved consistently and resisted to the influence of the feedback. We thus described spontaneous risky choices that were not induced by any violations in the task rules. Pupil dilations that preceded such occasional risky choices seem to reflect the internal proactive process of preparation to commit a risky decision.

Interestingly, we observed the negative correlation between risk aversion and pupil dilation before persistent risky choice after expected loss. This association was absent if previous risk led to an unexpected reward. This suggests that the internal trigger of pupil dilation might be a conflict detected between the imminent action and the pragmatic model of the task. Unexpected positive feedback after disadvantageous decisions may attenuate this inconsistence.

A principal brain area responding to conflict detection is the anterior cingulate cortex [17]. This structure has direct anatomical pathways to the locus coeruleus [18]. Noradrenaline released from the locus coeruleus neurons excites the frontal cortex, thus regulating selective attention functions [19]. Clarifying these complex interactions requires further research involving neuroimaging techniques.

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References

1. Guttel, E., Harel, A.: Matching Probabilities: The Behavioral Law and Economics of Repeated Behavior. The University of Chicago law review, pp. 1197–1236 (2005)
2. Wolford, G., Miller, M.B., Gazzaniga, M.: The left hemisphere's role in hypothesis formation. J. Neurosci. **20**(6), RC64–RC64 (2000). https://doi.org/10.1523/JNEUROSCI.20-06-j0003.2000.
3. West, R.F., Stanovich, K.E.: Is probability matching smart? Associations between probabilistic choices and cognitive ability. Mem. Cognit. **31**(2), 243–251 (2003). https://doi.org/10.3758/BF03194383
4. Aston-Jones, G., Cohen, J.D.: An integrative theory of locus coeruleus-norepinephrine function: adaptive gain and optimal performance. Ann. Rev. Neurosci. **28**, 403–450 (2005)
5. Bast, N., Poustka, L., Freitag, C.M.: The locus coeruleus–norepinephrine system as pacemaker of attention – a developmental mechanism of derailed attentional function in autism spectrum disorder. Eur. J. Neurosci. **47**(2), 115–125 (2018). https://doi.org/10.1111/ejn.13795
6. Unsworth, D.J., Mathias, J.L.: Traumatic brain injury and alcohol/substance abuse: a Bayesian meta-analysis comparing the outcomes of people with and without a history of abuse. J. Clin. Exp. Neuropsychol. **39**(6), 547–562 (2017)
7. Stafford, T., Thirkettle, M., Walton, T., Vautrelle, N., Hetherington, L., Port, M., Redgrave, P.: A novel task for the investigation of action acquisition. PLoS ONE **7**(6), e37749 (2012). https://doi.org/10.1371/journal.pone.0037749
8. Kozunova, G.L.: Reinforcement learning in probabilistic environment and its role in human adaptive and maladaptive behavior. J. Mod. Foreign Psychol. **5**(4), 85–96 (2016). https://doi.org/10.17759/jmfp.2016050409
9. Kozunova, G.L., Voronin, N.A., Venidiktov, V.V., Stroganova, T.A.: Reinforcement learning: a role of immediate feedback and internal model. Zh. Vyssh. Nerv. Deiat. Im. I. P. Pavlova. **5**, 603–614 (2018). https://doi.org/10.1134/S0044467718050076.
10. Arnsten, A.F.T., Goldman-Rakic, P.S.: Selective prefrontal cortical projections to the region of the locus coeruleus and raphe nuclei in the rhesus monkey. Brain Res. **306**(1–2), 9–18 (1984). https://doi.org/10.1016/0006-8993(84)90351-2
11. Preuschoff, K., Hart, B.M., Einhauser, W.: Pupil dilation signals surprise: evidence for noradrenaline's role in decision making. Front. Neurosci. **5**, 115 (2011)
12. Lavín, C., San Martín, R., Rosales Jubal, E.: Pupil dilation signals uncertainty and surprise in a learning gambling task. Front. Behav. Neurosci. **7**, 218 (2014). https://doi.org/10.3389/fnbeh.2013.00218

13. Simonovic, B., Stupple, E.J., Gale, M., Sheffield, D.: Pupil dilation and cognitive reflection as predictors of performance on the Iowa gambling task. In: Gunzelmann, G., Howes, A., Tenbrink, T., Davelaar, E.J. (eds.) Proceedings of the 39th Annual Conference of the Cognitive Science Society, pp. 3180–3185 (2017)
14. Frank, M.J., Seeberger, L.C., O'reilly, R.C.: By carrot or by stick: cognitive reinforcement learning in parkinsonism. Science **306**(5703), 1940–1943 (2004)
15. Jepma, M., Nieuwenhuis, S.: Pupil diameter predicts changes in the exploration–exploitation trade-off: evidence for the adaptive gain theory. J. Cogn. Neurosci. **23**(7), 1587–1596 (2011). https://doi.org/10.1162/jocn.2010.21548
16. Pajkossy, P., Szőllősi, Á., Demeter, G., Racsmány, M.: Tonic noradrenergic activity modulates explorative behavior and attentional set shifting: evidence from pupillometry and gaze pattern analysis. Psychophysiology **54**(12), 1839–1854 (2017). https://doi.org/10.1111/psyp.12964
17. Ebitz, R.B., Platt, M.L.: Neuronal activity in primate dorsal anterior cingulate cortex signals task conflict and predicts adjustments in pupil-linked arousal. Neuron **85**(3), 628–640 (2015). https://doi.org/10.1016/j.neuron.2014.12.053
18. Botvinick, M.M., Cohen, J.D., Carter, C.S.: Conflict monitoring and anterior cingulate cortex: an update. Trends Cogn. Sci. **8**, 539–546 (2004). https://doi.org/10.1016/j.tics.2004.10.003
19. Seidman, L.J., Valera, E.M., Makris, N., Monuteaux, M.C., Boriel, D.L., Kelkar, K., Kennedy, D.N., Caviness, V.S., Bush, G., Aleardi, M.: Dorsolateral prefrontal and anterior cingulate cortex volumetric abnormalities in adults with attention-deficit/hyperactivity disorder identified by magnetic resonance imaging. Biol. Psychiat. **60**, 1071–1080 (2006). https://doi.org/10.1016/j.biopsych.2006.04.031

Language, Speech, and Semantics

Cognitive Mechanisms of Semantic Derivation in the Domain of Visual Perception

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Abstract. The cognitive mechanisms underlying language conceptualization can be revealed using the notion of a *semantic shift*, understood as the association of two distinct linguistic meanings in the form of synchronic polysemy, diachronic semantic evolution, cognates and some others. The data collected in the "Database of semantic shifts in languages of the world" (www.datsemshift.ru) allows us to conclude that the linguistic meaning of visual perception serves as the source for the denotation of all the basic mental states, i.e. knowledge, understanding, belief, expectation and intention, as well as of some complex meanings which include mental and actional components. The paper discusses three cognitive mechanisms of semantic shifts in the domain of visual perception, namely the "metaphorical", "inferential" and "metonymical" ones.

Keywords: Semantic shift · Cognitive mechanisms of semantic derivation · Visual perception · Mental state · Polysemy · Metaphor · Inference

1 Introduction

The cognitive mechanisms underlying language conceptualization can be revealed using the notion of a *semantic shift*, understood as the association of two distinct linguistic meanings within one word (in a broad sense), namely in form of synchronic polysemy, diachronic semantic evolution, cognates and some others (see [18, 19]). The "Database of semantic shifts in languages of the world" (hereafter referred to as Datsemshift), built on this principle, contains more than 4000 semantic shifts, each of which is represented by a number of realizations belonging to languages from different language families and linguistic areas (the database is available at: www.datsemshift.ru). This article uses language data collected in Datsemshift.

The potential of the verbs with the initial meaning 'to see' for synchronic and diachronic semantic derivation and its realization in different languages has been widely discussed in the literature (see [1; 2: 475–485; 8; 9; 11: 197–255; 14: 32–45; 16]). This article will focus solely on the cognitive mechanisms that are observed in this domain of sematic derivation. The analysis of the data contained in Datsemshift allows for the

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identification of three basic mechanisms that can be referred to as “metaphorical”, “inferential” and “metonymical”. The formation of a given derivative meaning may also result from the simultaneous operation of several cognitive mechanisms.

The paths of the semantic derivation of lexemes denoting active and passive visual perception partially coincide: some of the derivative meanings are based on the initial meaning ‘to look (at)’ (e.g. ‘to take care of smb.’), while others may stem from both the meanings ‘to look (at)’ and ‘to see’ (e.g. ‘to have an opinion’). Datsemshift thus combines the two initial meanings in the label ‘to see/to look at’; the database at present contains more than 30 semantic shifts with this source meaning.

2 Semantic Shifts

2.1 The Metaphorical Mechanism

The metaphorical cognitive mechanism of semantic derivation implies that a given situation which cannot be *seen* in the strict sense is interpreted as being seen by “inner” or “mental” vision, i.e. *as if it were seen* (cf. The notion of “mental vision” in [14: 33] and the Russian word *umozritel’nyj,* lit. ‘viewed by the mind’). The metaphorical mechanism transfers the meaning from the perceptive source domain to the mental target domain (cf. *Transfield I* type of metaphorical extension in [13: 3]), thus the component of visual perception is lost. This metaphor is deeply rooted in language; cf. [14: 42, 13: 17–42].

The metaphorical mechanism produces the meaning of acquiring an image of the situation seen by the “mental vision”, which in fact corresponds to a large scope of mental states lacking distinct inner demarcation. The mental state ‘to understand’ is the easiest to distinguish among these; cf. the definition of the first derivative meaning of the verb *to see* in [12: 2736]: “Perceive mentally (an idea, quality, etc.), attain to comprehension of, to understand”. The metaphorical mechanism is realized in the context of a non-observed situation, such as the sense of another person’s words (cf. *I see what you mean*) or a non-verifiable judgment (*I saw that perhaps he was right*). Cf. several realizations of the semantic shift ‘to see’ – ‘to understand’ from the Datsemshift.[1]

(0746) ‘to see’ → ‘to understand’:

- < polysemy >: En. (*to see*): *Can’t you* ***see****that he’s taking advantage of you?* [10]; *I don’t see what you have against her* [12]
- < polysemy >: Rus. (*videt’*): *Teper’ vy* ***vidite****svoju oshibku?* ‘Do you understand your mistake?’ [2: 483]
- < polysemy >: Anc.Greek (ὁράω): ὁ**ρῶ** μ´ ἔργον δεινὸν ἐξειργασμένην ‘I understand that I did a terrible thing’
- < polysemy >: It. (*vedere*): ***vedo****bene che non ci riesco* – ‘I understand that I cannot do it’

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[1] The semantic shifts are presented in the same form as in Datsemshift, with the ID of the shift in brackets. The following information is provided for each example: the type of the semantic shift (<polysemy >, < (semantic) evolution >, < cognates >, < (morphological) derivation >), the language, the word or the two words denoting both meanings; the example that illustrates the derivative meaning in question. The examples from Datsemshift are given without reference.

- < polysemy >: Norw. (*se*): *så vidt jeg kan* ***se****, skulle det gå bra* – ‘as far as I understand it, everything should be fine’

The metaphorical mechanism allows also for the shift from the meaning ‘to see/to look at’ to ‘to have an opinion, to believe, to regard in a particular way’; cf. the following examples:

(0035): ‘to see/to look at’ → ‘to have an opinion’.

- < polysemy >: En. (*to see*): *he* ***saw****himself as a good teacher* [10]; *America* ***is seen****as the land of opportunity* [12]; cf. also: *point of view*
- < polysemy >: Rus. (*videt’*): *On* ***videl****v nem razumnogo, strogo mysljaschego, ogromnogo uma cheloveka* ‘He saw in him a reasonably thinking person, a man of great mind’ [2: 483]; *Ja ne* ***vizhu****v etom nichego durnogo* ‘I do not see anything bad about that’; cf. also *tochka zrenija* ‘point of view’
- < polysemy >: Rus. (*rassmatrivat’*): *Ya* ***rassmatrivaju****etu rabotu kak pervyj etap* ‘I regard this work as the first stage’
- < polysemy >: Sp. (*ver*) *es su manera de* ***ver****las cosas* ‘This is his way of seeing things’
- < polysemy >: Norw. (*betrakte*): *vi* ***betrakter****saken som oppgjort* ‘we consider this matter to be settled’
- < polysemy >: Hung. (*néz*): *jó embernek* ***nézem*** ‘I consider him a good person’
- < polysemy >: Amharic (*ayyä*): *əndä nəgus* ***əyyäw*** ‘consider him as a king’

The “mental vision” of the situation which appears due to the metaphorical mechanism may further serve as a component in a range of more complex derivative meanings, the formation of which also involves other cognitive mechanisms, see below.

2.2 The Inferential Mechanism

The inferential mechanism of semantic derivation implies that the derivative meaning is a conclusion drawn by the subject on the basis of their observation. The visual perception is known to be the main source of our knowledge (cf. [3]); therefore, the main conclusion that can be drawn from observing the situation P is that the situation P actually takes place. The meaning ‘to know’ which is proper to the Indo-European lexemes traced back to the root **ueid-* ‘to see’ is generally considered to be the result of the inference ‘I saw it, therefore I know it’ (cf. [17: 1304]). This opinion builds mainly upon the fact that the Ancient Greek infinitive (ἰδεῖν) and the aorist 2 (εἶδον) both denote ‘to see’, while the perfect form of the same verb functions as the present tense of the verb ‘to know’. The perfect form is indeed used to refer to a state resulting from a given situation: ‘I saw it, therefore I know it’; cf. also the perfect form of the Old English *wāt* ‘I knew (because I saw it)’ [4: 145].

The semantic shift ‘to see’ → ‘to know’ is common to numerous Indo-European languages. The Germanic lexemes that are traced back to the root **ueid-* only have the meaning ‘to know’: cf. the German *wissen*, the Old English *witan* ‘to know’, the English *wit* etc. (However, some derivatives of the Icelandic verb *vita* ‘to know’ have meanings derivative from ‘to see’: *vita upp* ‘to be turned (see) upward’, *vita út* ‘to overlook (of windows etc.)'; *gluggin veit út að götunni* 'the window looks out onto the street', the verb *vitja* means 'to visit' [5].) In the Russian language this semantic shift is realized in the cognates *videt'* 'to see' and *vedat'* 'to know'; cf. also the Belarusian *vedats'*, the Polish *wiedzieć*, the Slovene *vem*, etc. 'to know'.

E. Sweetser [14: 33–48] suggests another, namely metaphorical, interpretation of the semantic evolution 'to see' → 'to know'; cf. also [13: 47]. Actually, the derivative meaning may result from the operation of two different mechanisms: the inference and the metaphor. The inferential mechanism 'I saw it, therefore I know it' comes into play in the case of observable phenomena, and results in the knowledge *stricto sensu*, i.e. "being in possession of the truth". The metaphorical mechanism '*as if* I saw it', or 'I see it with my *mental sight*' operates when the situation in question cannot be actually seen (e.g. *the solution of a problem*; *what went wrong*). Further on, the inferential mechanism that comes into play, just as in the case of actual visual perception. This scheme underlies the semantic development 'to see' → 'to know' in various modern languages.

For instance, according to Apresjan [2: 475–485] one of the derivative meanings of the Russian verb *videt'* is 'to know' (cf. *Ja ne vizhu prichin dlja otkaza* 'I do not see any reason to refuse'; *Ja ne vizhu, kak eto mozhno sdelat'* 'I do not see how it can be done', etc.). This meaning is defined as follows: *A1 sees A2*: 'The person A1 knows A2 *because* it is *as if* A1 saw A2′ [ibid.: 484]. The component "as if" indicates that the starting point of the semantic derivation is the metaphorical transfer: I know it *as if* I saw it, I see it with my "mental sight". Further on, the inferential mechanism 'I saw it, therefore I know it' comes into play (cf. the component "because" in the definition.).

The lexicographic descriptions of the English verb *to see* usually do not include the meaning 'to know' (e.g. in [12]), but in the contexts like *It is necessary to see what could be done* the verb *to see* actually denotes a mental state which includes knowledge ('to find out, to get knowledge').

In modern languages, the inferential mechanism with the real visual perception as the starting point only produces an implicature, cf.: – *Otkuda ty eto znaesh'? – Ja eto videl svoimi glazami* 'How do you know it? – I saw it with my own eyes' (→ 'therefore I know it'); *Ja videl kak on vkhodil v pod"ezd* 'I saw him entering the building' (→ 'therefore I know it'). In this case the verb *videt'* 'to see' does not develop a new lexical meaning and still denotes visual perception – while the meaning 'to know' derivative from 'to see' by means of the metaphorical mechanism (cf. *I do not see any reason to refuse*) lacks the component of actual visual perception.

However, the inference 'I saw it, therefore I know it' is not the only one possible. It has often been pointed out that the fact that something is "visible" might mean two things which are in a sense opposite: it may be true or, to the contrary, it may only be something "apparent", "seeming". Therefore, inferential semantic derivation in the domain of visual perception may also have a different result, the target meaning being an opinion with varying degrees of certainty; cf. the semantic shift (0045). The meaning 'opinion' based on the inferential mechanism results from the interpretation of visually perceived data (cf. *Ja vizhu, chto ty ne rad etomu izvestiju* 'I see that you are not happy about these news'= 'your reaction, facial expression etc. allows for such a conclusion'). Cf. also the meaning (6a) of the verb *to see* in [12: 2736] "[p]erceive or realize the nature of something, esp. by visual signs": *Don't you see I am tired to death?*

(0045) ‘to see/to look at’ → ‘to seem’:

- < polysemy >: En. (*to look*): *It* ***looks*** *like rain*(*ing*)
- < polysemy >: Dan. (*se*): *De* ***ser*** *ud til at have det godt* ‘looks like they’re fine’
- < derivation >: Germ. (*sehen* ‘to see’ – *aussehen* ‘to seem’): *es* ***sieht*** *nach Regen* ***aus*** ‘looks like it will rain’
- < derivation >: Lat. (*video* ‘to see’ – *videor* ‘to seem’): *abesse a periculo* ***videntur*** ‘It seems to them that they are out of danger’

2.3 The Metonymic Mechanism

The metonymic mechanism of semantic derivation implies that the situation of visual perception is combined with a contiguous situation which then comes into focus: it may be: 1) the **goal** (e.g. ‘to keep someone out of danger’), 2) the **means**, i.e. certain actions resulting in visual perception (e.g. ‘finding something’); 3) an **inner state** which accompanies the visual perception. The semantic component of visual perception may remain part of the derivative meaning (as in the case of ‘to visit’) or be transformed into “mental vision” via the metaphorical mechanism (within one meaning; e.g. one can look for a lost object or for the solution to a problem).

1. **The “goal” metonymy.** The aims pursued by the action ‘to look at’ can vary. One may look at someone or something in order to maintain their health and well-being (cf. (0384) ‘to care for, look after < for smb. >’); to protect someone from external risks and/or prevent them from escaping (cf. (1807) ‘to guard < smb. >’); to protect oneself from possible risks (cf. (2186) ‘to beware, be careful’); to get (secret) information about someone’s actions (cf. 4274 ‘to spy’); to have personal communication with somebody (cf. (3503) ‘to meet, to visit < smb. >’). All these (and some other) goals can be part of the meaning derivative from that of visual perception.
   (0384) ‘to look at’ → ‘to care for, look after < smb./smth. >’.

- < derivation >: En. (*to look – to look after*): *to* ***look after*** *the children*
- < derivation >: Rus. (*smotret’– smotret’ za*): ***smotret’ za*** *det’mi* ‘to look after the children’
- < derivation >: Hung. (*néz* ‘to look’ – *utána néz* ‘to look after someone’)
- < polysemy >: Tigre (*ʔattaḳbala*): mǝndi lǝddarre dib šābrā; ʔadugātu ***lattaḳbǝl*** ‘when he descends to Shabra, he watches his donkeys’
  (1807) ‘to look at’ → ‘to guard’.
- < polysemy >: En. (*to watch*): *to* ***watch*** *the prisoner all day*
- < cognates >: It. *Guardare* ‘to look at’ – Fr. *Garder* ‘to guard’
- < polysemy >: Middle High Germ. *wārten* [6: 915]
  (4274) ‘to look at’ → ‘to spy’.
- < derivation >: Rus. (*gljadet’* ‘to look’ – *sogljadataj* ‘a spy’)
- < cognates >: Kurux (*ērnā*) – Kui (*ēra*)
  (2186) ‘to look at’ → ‘to beware, be careful’.
- < derivation >: Rus. *Smotret’* ‘to look’ – *osmotritel’nyj* ‘prudent’ Cf. also the construction *smotri ne* (lit. ‘watch not to’) + Perfective Imperative in the meaning of warning: *smotri ne upadi* ‘watch out, you might fall’

- < derivation >: En. *watch – watch out*
  (3503) ‘to see/to look at’ → ‘to meet, to visit < smb. >’.
- < polysemy >: En. (*to see*) ***See****you later*; *I went to* ***see****Caroline*; *You need to see a doctor*.
- < derivation > Rus. (*videt’* ‘to see’ – *videt’sja* ‘to meet’): *Kak davno my ne* ***videlis’****!* We haven’t met for such a long time!
- < polysemy > Rus. (*videt’*): *Mozhno* ***videt’****glavnogo redartora?* ‘May I see the chief editor?’ [2: 476]
- < derivation >: Lat. (*videre* ‘to see’– *visitare* ‘to visit’)

2. **The “means” metonymy.** The visual perception may also be the goal of certain actions. For instance, in order to find something (to actually see the object or to have the mental vision of it), the subject has to carry out certain actions or mental operations:
   (0984) ‘to see/to look at’ → ‘to search, to look for’.

- < derivation > En. (*to look – to look for*): *What are you* ***looking for****here?*
  (2017) ‘to see/to look at’ → ‘to find’.
- < polysemy >: Komi (*addzyny*): ***addzyny****udzh* ‘to find a job’

3. **The “concomitant inner state” metonymy.**
   (0987) ‘to see/to look at’ → ‘to like, to please’:

- < polysemy >: En. (*to see*): *I don’t know what I* ***see****in you* [12: ‘find good or attractive qualities in smb.’]
- < derivation >: Serbo-Croat. (*videti* ‘to see’ – *svideti se* ‘to please’)
- < derivation >: Old Rus. (*viděti* ‘to see’ – *naviděti* ‘to look at with pleasure’ [15, III: 63]); cf. Rus. *nenavidet’* (with negation marker) ‘to hate’
- < derivation >: Lat. (*video* ‘to see’ – *videor* ‘to please’): *quid tibi* ***visa est****Chios?* ‘Did you like Chios?’ [7: 1078].
- < derivation >: Rus. (*gljadet’* ‘to look’ – *prigljanut’sja* ‘to please’); cf. *nenagljadnyj* ‘darling, beloved’

(1174) ‘to see/to look at’ → ‘to be surprised/delighted’.

- < cognates >: Ukr. (*divitisja* ‘to look at’) – Rus. (*udivit’sja* ‘to be surprised)
- < derivation >: Sp. (*mirar* ‘to look at’– *admirar* ‘to be delighted’; ‘to surprise’)

(1176) ‘to see/to look at’ → ‘to envy’.

- < derivation >: Lat. (*video – invidia*)
- < derivation >: Rus. (*videt’ – zavidovat’*)
- < derivation >: Lithuan. (*veizdėti – pavydeti*)

(0037) ‘to see/to look at’ → ‘to wait’.

- < derivation > En. *to look forward*
- < derivation > Class. Arabic: (*naẓara – ʔintaẓara*)
- < evolution > Germ. (*warten*) [6: 915]

Provided that the situation seen by the mental vision is a controlled action carried out by the subject, the idea of the intention to carry it out may also be actualized:

(0990) ‘to see/to look at’ → ‘to intend’.

- < derivation >: Germ. (*sehen – beabsichtigen*)
- < polysemy > Tamil (*pār*)
- < polysemy > Malayalam (*nōkkuka*)
- < cognates > Kannada (*nōḍu*) – Tulu (*nōṭa*)

(0036): ‘to see/to look at’ → ‘to try, to attempt’.

- < polysemy >: Serb. (*gledati*): ***gledaj****da doђesh* ‘try to come’
- < polysemy >: Japan. (*miru*): *Dewa, sassoku, chīzu o tsukutte* ***miru****koto ni shimashō* ‘And now let’s try making cheese’
- < polysemy >: Karaim (*bakh*): *eger avalgъylarymyz* ***bakhtylar****achma yashyryn syoz’lyarin’ aziz’ til’nin’* ‘If our ancestors were trying to discover the secret meaning of the words of the holy language’

3 Conclusion

To sum up, the data collected in Datsemshift shows that the linguistic meaning of visual perception serves as source for the denotation of all the basic mental states – knowledge, understanding, belief (including a potentially false one), expectation and intention, as well as some complex meanings which include mental and actional components. The initial meaning of visual perception may be maintained or completely lost in the derivative meaning. Semantic derivation in the domain of visual perception may be realized by means of three cognitive mechanisms – the metaphorical, the inferential and the metonymical ones; it may as well result from the operation of several mechanisms at a time.

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References

1. Andrews, E.: Seeing is believing: visual categories in the Russian lexicon. In: Contini-Morava, E., Goldberg, B.S., Kirsner, R.S. (eds.) Meaning as Explanation: Advances in Linguistic Sign Theory, pp. 363–377. Mouton de Gruyter, Berlin (1995)
2. Apresjan, J.D.: Investigations in semantics and lexicography, Paradigmatics, vol. 1. Nauka, Moscow (2009). (in Russian)
3. Arnheim, R.: Visual Thinking. University of California Press, Berkeley (1969)
4. Benvenist, E.: On several forms of development of Indo-European perfect [О некоторых формах развития индоевропейского перфекта] In: Benvenist, E. (ed.) General Linguistics, Nauka, Moscow, pp. 141–147 (1974). (in Russian)

5. Berkov, B.P.: Islandic-Russian Dictionary. Nauka, Moscow (1962).(in Russian)
6. Duden, Bd.7. Herkuftsworterbuch, 3. Auflage. Dudenverlag: Mannheim
7. Dvoretskij, K.H.I.: Latinsko-russkij slovar' [Дворецкий И.Х. Латинско-русский словарь], Moscow (1976) (in Russian)
8. Haser, V.: Metaphor in semantic change. In: Barcelona, A. (ed.) Metaphor and Metonymy at the Crossroads. A Cognitive Perspective. Topics in English Linguistics. vol., 30, pp.171–194. Mouton de Gruyter, Berlin-New York (2003)
9. Kubota, M.A.: Cognitive Linguistic Analysis of Visual Perception Verbs in Natural Language – With Special Reference to English Verbs "Look" and "See" (2016). https://www.kansaigaidai.ac.jp/common/pdf/info.disclosure.theses.ko59_dissertation.pdf
10. Oxford Dictionary of English, 3rd Edition. Oxford University Press, Oxford (2010)
11. Paducheva, E.V.: Dynamic models of lexical semantics. Nauka, Moscow (2004).(in Russian)
12. Shorter Oxford English Dictionary. Fifth edition. Oxford University Press, Oxford (2002)
13. Speed, L.J., O'Meara, C., San Roque, L., Majid, A. (eds.): Perception metaphors. John Benjamins, Amsterdam-Philadelphia (2019)
14. Sweetser, E.E.: From etymology to pragmatics. In: Cambridge Studies in Linguistics. vol., 54. Cambridge University Press, Cambridge (1990)
15. Vasmer, M.: Etymological Dictionary of Russian. Nauka, Saint Petersburg (1996).(in Russian)
16. Viberg, Å.: The verbs of perception: a typological study. In: Butterworth, B., Comrie, B., Dahl, Ö. (eds.) Explanations for Language Universals, pp. 123–162. Mouton, Berlin (1984)
17. Viberg, Å.: Verbs of perception. In: Haspelmath, M., König, E., Oesterreicher, W., Raible, W. (eds.) Language Typology and Language Universals: An International Handbook, vol. 2, pp. 1294–1309. De Gruyter, Berlin-Boston (2001)
18. Zalizniak, A.A.: The catalogue of semantic shifts: 20 years later. Russ. J. Linguist. **22**(4), 770–786 (2018)
19. Zalizniak, Anna A., Bulakh, M., Ganenkov, D., Gruntov, I., Maisak, T., Russo, M.: The Catalogue of semantic shifts as a database for lexical semantic typology. In: Koptjevskaja-Tamm, M., Vanhove, M. (eds.) New Directions in Lexical Typology. Linguistics, **50**(3), 633–669 (2012)

Concreteness/Abstractness Concept: State of the Art

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Abstract. In recent years, several scientific disciplines – linguistics, psychology, psycholinguistics, neurophysiology, medicine, philosophy, education – have paid considerable attention to studying the concreteness/abstractness concept. Existing reviews on this topic cover only one area of research. This article provides an interdisciplinary overview from a general cognitive perspective and gives a general integral idea of this area. It is brief by necessity, but covers the main results obtained. First of all, this is the so-called "concreteness effect", which consists in faster and more efficient processing of concrete words in comparison with abstract ones. The main theories explaining the effect of concreteness – the dual-coding theory and the context-availability theory – are considered. The problem of representing abstract and concrete words is one of the central problems in cognitive studies of the organization of concepts in our mind. The results of the search for neurophysiological correlates of concreteness/abstractness are discussed. In linguistics, fundamentally new research ideas and results have emerged due to large text corpora and large lexical ontologies. For research in these areas, it is important to have dictionaries with concreteness/abstractness ratings. The article provides data on the most significant dictionaries with human ratings for different languages, and also discusses how to extrapolate human ratings using machine learning methods. These methods, including deep learning of neural networks, can help quickly generate large dictionaries of near human quality, which can facilitate research in the field and extend it to many languages.

Keywords: Concreteness · Abstractness · Cognition · Neuroimaging · Dictionaries · Concreteness effect · Dual-coding theory

1 Introduction

Modern approaches to the study of concreteness/abstractness originate from the fundamental paper [1]. It is considered that one of the central problems in cognitive studies of the organization of concepts is precisely the problem of representing abstract and concrete words [2], which poses a serious challenge to any theory of cognition [3].

The problem of concreteness/abstractness of words (concepts) is interdisciplinary and multidisciplinary, studied from a cognitive standpoint in linguistics, psychology, psycholinguistics, neurophysiology, medicine, philosophy, education, and has various practical applications. Thousands of publications are devoted to it making an exhaustive

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review quite impossible. However, some problems that most studies are devoted to can be identified.

First of all, this is the so-called “concreteness effect”, demonstrating greater ease of processing concrete words in the human mind. The “concreteness effect” is well-established and the aim of the research is to explain it. Further, a large complex of neurophysiological studies aims to find out which parts of the brain are responsible for processing concrete words, and which ones – for processing abstract ones. Psycholinguistic experiments with patients suffering from various forms of brain damage pursue the same goal. Finally, it is important to provide the aforementioned studies with dictionaries with ratings of abstract and concrete words. Such dictionaries are created for different languages and by different methods: by interviewing informants and by the method of computer extrapolation of human evaluations. The article will also pay attention to other areas of research – linguistics, education. We’ll mention some significant specialized reviews devoted to certain aspects of concreteness/abstractness: an approach from the standpoint of cognitive linguistics and embodiment theory [3], functional brain mapping [4], acquisition of concrete and abstract concepts in childhood [5], neuroimaging [6].

Let us look into definitions of concreteness and abstractness. The main approach to defining these concepts is the following [7]. Concrete concepts are those that are perceived by the senses. Examples of concrete words are cat, chair, mountain. Abstract concepts are not perceived by the senses. For example, responsibility, relationships, misunderstanding. Similar interpretations are found in many works. For instance, the following definition is given in the paper [8]: “abstract nouns are those nouns whose denotata are not part of the concrete physical world and cannot be seen or touched”. However, these definitions greatly simplify the situation, characterizing prototypes of concreteness and abstractness. In fact, experimental studies have shown that this is not a dichotomy, but a continuum of concreteness/abstractness [4].

2 Concreteness Effect

In a series of works, it was established that concrete words have advantages over abstract ones in terms of ease of processing. Concrete words are better remembered [9], better recognized [10], read faster [11], learned faster [12]. Dictionary definitions are easier to write for them, and they will be more detailed [13]. Concrete words evoke associations more easily [14].

There are two fundamental parameters associated with the concreteness/abstractness continuum: Imageability (IMG) is a measure of how easily a word evokes a mental image and Context availability (CA) is a measure of how easy it is to think about the context of a word. In the paper [15], the correlation of these parameters with a degree of words concreteness is experimentally shown. Note that to obtain this result, a quantitative assessment of all three properties of words compared is required. Other parameters were considered in the literature as well, in particular, in the paper [24] it was shown that the way a concept is assimilated – through experience or through language – is a good predictor of concreteness/abstractness. In the paper [24], such parameters as the age of concept acquisition, the degree of word familiarity were also considered.

Several theories have been proposed to explain the concreteness effect. The most developed and frequently cited are two: the dual-coding theory (DCT) [16] and the context-availability theory (CAT) [11].

According to the DCT, there are two functional systems associated with semantic memory: verbal and image. Moreover, while the verbal system can be responsible for the linguistic coding of both concrete and abstract concepts, the non-verbal image system, first of all, is involved in the coding of concrete, but not abstract concepts. DCT makes certain predictions about the localization of the processing of concrete and abstract words in the brain. The processing of abstract words relies solely on the verbal system, therefore it is carried out in the left hemisphere, while the processing of concrete words also involves the image system and requires the participation of both hemispheres.

According to the CAT, concrete and abstract concepts have a different number of semantic associations: concrete concepts have stronger associative links with fewer contexts, while abstract concepts have weaker associative links with more contexts. CAT predicts that the processing of abstract and concrete words will depend on the same neural networks with stronger activation by concrete words because knowledge of words is context-dependent.

Other hypotheses about the cognitive organization of concrete/abstract concepts have been proposed in the literature. In the paper [17] it is proposed to distinguish the type of their semantic connections. According to the paper [17], concrete words have a hierarchical semantic structure, which is based on categorical ontological links (synonyms, hypernyms, hyponyms), while abstract words are connected by associative links. In the work [25], it is argued that emotional experience is critical for the assimilation of abstract concepts. This is not explained by the DCT and CAT theories. In the work [25], the approach adopted in cognitive linguistics is developed, which presupposes the embodiment of linguistic concepts concerning the semantics of abstract concepts. This approach has been criticized in the work [26], which presents additional arguments in favor of DCT. In the paper [3], it is suggested that the representation of abstract concepts is at least partially based on the sensorimotor system, which is supported by the theory of embodiment. Confirmation is presented in the results of the paper [5], which shows the absence of specific mechanisms for the acquisition of abstract knowledge. Following these ideas, in the work [18] both concrete and abstract concepts are presented in a multidimensional space of both linguistic and empirical features.

3 Neurophysiological Correlates

The DCT postulates the processing of concrete and abstract words in various parts of the brain. A significant number of neurophysiological studies have been devoted to testing this assumption, using the entire arsenal of modern methods of brain research: EEG, MEG, fMRI, PET, TMS, tDCS [6]. Neuroimaging has shown that processing abstract concepts leads to greater activation in areas such as the middle and superior temporal gyrus (MTG, STG) and the left inferior frontal gyrus (IFG). Concrete concepts, in turn, activated the ventral anterior part of the fusiform gyrus [10, 19].

The processing of abstract and concrete concepts in different parts of the brain has been confirmed by numerous studies [20, 21], which supports the dual-coding theory.

However, for some areas of the brain, conflicting data have been obtained in some works. In the area of the anterior temporal region (ATL), an increased activity associated with abstract concepts was mentioned in the paper [22], and in the paper [23] – with concrete ones.

Observations of patients with various types of brain damage are an important source of data. Concrete words are more resistant to various types of brain damage than abstract words, which suggests, at least in part, different neural systems that support these types of knowledge [6]. This is consistent with the concreteness effect and also provides partial support for the dual-coding theory. However, the reverse concreteness effect has also been found, that is, better processing of abstract words as compared to concrete ones. The reverse concreteness effect occurs in some patients with brain damage. It is observed in patients with semantic dementia, as well as with herpetic encephalitis that are characterized by disorders in the anterior temporal regions [2].

If patients undergo brain surgery, this makes other research methods available – direct electrical stimulation of the brain (DES), as well as studies of the effects of anesthesia. In the course of such studies, it was shown that impact on the inferior frontal gyrus (Brodmann's area, BA 44) negatively affects the processing of abstract words, while the impact on the anterior temporal cortex (Brodmann's area, BA 38) affects the processing of concrete words [2]. This is consistent with the model of differentiating neural substrates of concrete and abstract words in the left hemisphere.

These studies have not only theoretical but also practical significance. For example, the paper [27] describes the use of abstract verbs in the treatment of aphasia.

4 Linguistics and Education

Concreteness and abstractness concepts in themselves have been subjects of study in linguistics for a long time, however, recently with the advent of large text corpora and large lexical ontologies, fundamentally new research ideas and results have emerged.

The article [28] compares categories of concreteness and specificity. The specificity of a word is determined by its position in the hierarchy of a well-known lexical ontology – WordNet [29]. It turned out that these are two independent categories, with only a moderate correlation between them.

When studying the compatibility by text corpora, it was shown that abstract words are often combined with abstract ones, and concrete words with concrete ones [30, 31].

Analysis of diachronic data on the Corpus of Historical American English (COHA, [32]) showed that the degree of concreteness of words tends to increase over time [33].

In [34], the density of neighborhoods (sets of semantically close words) in corpus data was investigated. It was shown that the neighborhoods are denser for concrete words than for abstract words. Apparently, this result correlates in a certain way with the results of [17] described above.

In [35], the following categorization is presented: concrete concepts are artifacts, foods, animals, people, substances, plants, or body parts, abstract concepts are cognition, action, shapes, communication, relations, states, events, time, or motives.

In some papers [36, 37] it was shown that the share of abstract words in texts is an indicator of the complexity of their understanding. Thus, the automatically estimated share of abstract words together with other parameters can be used in education to assess the complexity of texts to make an adequate choice of educational materials.

5 Dictionaries

To conduct psychological experiments, lists of words with evaluations of the degree of their concreteness/abstractness are needed. Evaluations are obtained by interviewing native speakers. For the English language, the first large dictionary of this kind was created in 1981 [38]. It contains almost 4,000 words and is freely available from the MRS psycholinguistic database (https://websites.psychology.uwa.edu.au/school/MRCDatabase/uwa_mrc.htm). Later, a dictionary was created for almost 40 thousand words [39]. Each word gets at least 30 ratings from respondents, which are averaged. Apart from the English language, a dictionary of the comparable volume was created only for the Dutch language [40]. The obvious problem is the great labor intensity of creating such dictionaries. For German, the dictionary [41] contains only 4 thousand words, and for Russian – only 1 thousand [42].

In this regard, the problem of automatic extrapolation of human evaluations obtained from a small set of words to a larger set is urgent. One of the first papers to present a computer dictionary with concreteness/abstractness ratings was [43]. The main idea in extrapolating human evaluations to previously non-evaluated words is to use the vector semantics of words, built on large texts corpora, and to obtain new evaluations based on the semantic proximity of words in the constructed semantic space. Thus, for the creation of a computer dictionary in any language, a necessary condition is the existence of large texts corpora, based on which vector semantics can be built.

There are two main approaches to implementing this idea.

Using classifiers, including neural networks. Classifiers are trained on a part of the accessible dictionary with human evaluations and tested on the rest of the dictionary.

Using small sets of “reference” abstract and concrete words (called a seed). Further, for each word in the constructed dictionary, distances to these sets are calculated and on this basis, an assessment of the degree of abstractness/concreteness of a word is made.

Most researchers take the first approach. It is very convenient because of the development of the theory and technology of classifiers, especially taking into account the progress in deep learning in recent years. Its obvious disadvantage is that it takes a lot of data to train classifiers, i.e. large dictionaries with expert evaluations are needed.

Evaluation of the quality of machine dictionaries is of fundamental importance. They are assessed by comparison with human ones with the calculation of the correlation coefficient of two dictionaries, most often by Spearman. To date, the best-achieved result – a machine dictionary of the English language in the paper [44] has a correlation coefficient with the human one of 0.900. The dictionary is built using fastText to build semantic space and SVM as a classifier. The algorithm is trained on 90% of the dictionary of 40 thousand words [39] and tested on the remaining 10%. In [39], two human dictionaries were compared and it turned out that the correlation coefficient between them was 0.920. The result of 0.900 is almost the utmost possible.

In the paper [45], attention is drawn to the fact that the quality of evaluations depends on the frequency of words: evaluations for high-frequency words are obtained more accurately than for low-frequency ones. A study of the effect of size is given in [47].

Another way to solve the problem of creating large dictionaries with concreteness/abstractness ratings is to transfer ratings from one language, where they are already built, to another. This idea was implemented in the paper [46].

6 Conclusion

The concepts of concreteness/abstractness turned out to be very complex and interesting for research and attracted the attention of scientists from various fields. The concreteness effect has been reliably established in psycholinguistic experiments and consists in easier processing of concrete concepts as compared to abstract ones. To explain it, some competing hypotheses have been put forward, none of which explains the entire set of experimental data. Neurophysiological methods were used to solve the problem of localizing the areas processing concrete and abstract concepts in the brain. Given the partial success achieved, it cannot be said that this problem has already been solved. Also, neurophysiological data support DCT in part. Substantial challenges in carrying out such studies do not allow hope for a quick solution to the aforementioned problems. Unlike psychology and neurophysiology, research in linguistics is more fragmented, not united by a global research task. Dictionaries with concreteness/abstractness ratings are an important means of supporting these studies. Due to the great laboriousness of creating dictionaries with human ratings, significant efforts have been directed towards the automatic creation of dictionaries using machine learning methods. Much progress has been made in this direction, in particular, thanks to the recently developed word embedding and deep learning techniques. It is likely that in the near future large dictionaries of comparable with human quality will be created for different languages.

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References

1. Paivio, A.: Abstractness, imagery, and meaningfulness in paired-associate learning. J. Verbal Learn. Verbal Behav. **4**, 32–38 (1965). https://doi.org/10.1016/s0022-5371(65)80064-0
2. Orena, E.F., Caldiroli, D., Acerbi, F., Barazzetta, I., Papagno, C.: Investigating the functional neuroanatomy of concrete and abstract word processing through direct electric stimulation (DES) during awake surgery. Cogn. Neuropsychol. **36**(3–4), 167–177 (2018). https://doi.org/10.1080/02643294.2018.1477748
3. Borghi, A.M., Binkofski, F., Castelfranchi, C., Cimatti, F., Scorolli, C., Tummolini, L.: The challenge of abstract concepts. Psychol. Bull. **143**, 263–292 (2017)
4. Mkrtychian, N., Blagovechtchenski, E., Kurmakaeva, D., Gnedykh, D., Kostromina, S., Shtyrov, Y.: Concrete vs. abstract semantics: from mental representations to functional brain mapping. Front. Hum. Neurosci. **13**, 267 (2019). https://doi.org/10.3389/fnhum.2019.00267
5. Vigliocco, G., Ponari, M., Norbury, C.: Learning and processing abstract words and concepts: insights from typical and atypical development. Top. Cogn. Sci. **10**, 533–549 (2018). https://doi.org/10.1111/tops.12347

6. Montefinese, M.: Semantic representation of abstract and concrete words: a minireview of neural evidence. J. Neurophysiol. **121**, 1585–1587 (2019). https://doi.org/10.1152/jn.00065.2019
7. Spreen, O., Schulz, R.W.: Parameters of abstraction, meaningfulness, and pronunciability for 329 nouns. J. Verbal Learn. Verbal Behav. **5**, 459–468 (1966)
8. Schmid, H.-J.: English Abstract Nouns as Conceptual Shells: From Corpus to Cognition. Topics in English Linguistics. De Gruyter Mouton (2000)
9. Schwanenflugel, P.J., Akin, C., Luh, W.-M.: Context availability and the recall of abstract and concrete words. Mem. Cogn. **20**, 96–104 (1992). https://doi.org/10.3758/bf03208259
10. Fliessbach, K., Weis, S., Klaver, P., Elger, C.E., Weber, B.: The effect of word concreteness on recognition memory. Neuroimage **32**, 1413–1421 (2006). https://doi.org/10.1016/j.neuroimage.2006.06.007
11. Schwanenflugel, P.J., Shoben, E.J.: Differential context effects in the comprehension of abstract and concrete verbal materials. J. Exp. Psychol. Learn. Mem. Cogn. **9**, 82–102 (1983). https://doi.org/10.1037/0278-7393.9.1.82
12. Mestres-Missé, A., Münte, T.F., Rodriguez-Fornells, A.: Mapping concrete and abstract meanings to new words using verbal contexts. Second Lang. Res. **30**, 191–223 (2014)
13. Sadoski, M., Kealy, W.A., Goetz, E.T., Paivio, A.: Concreteness and imagery effects in the written composition of definitions. J. Educ. Psychol. **89**(3), 518–526 (1997). https://doi.org/10.1037/0022-0663.89.3.518
14. de Groot, A.M.: Representational aspects of word imageability and word frequency as assessed through word association. J. Exp. Psychol. Learn. Mem. Cogn. **15**(5), 824–845 (1989). https://doi.org/10.1037/0278-7393.15.5.824
15. Rosa, P.A.D., Catrical, E., Canini, M., Vigliocco, G., Cappa, S.F.: The left inferior frontal gyrus: A neural crossroads between abstract and concrete knowledge. Neuroimage **175**, 449–459 (2018). https://doi.org/10.1016/j.neuroimage.2018.04.021
16. Paivio, A.: Dual coding theory. In: Broadbent, D.E., McGaugh, J.L., Mackintosh, N.J., Posner, M.I., Tulving, E., Weiskrantz L. (eds.) Mental Representations: A Dual Coding Approach, pp. 53–83. Oxford University Press, Oxford (1990). https://doi.org/10.1093/acprof:oso/9780195066661.003.0004
17. Crutch, S.J.: Qualitatively different semantic representations for abstract and concrete words: further evidence from the semantic reading errors of deep dyslexic patients. Neurocase **12**, 91–97 (2006). https://doi.org/10.1080/13554790500507172
18. Myachykov, A., Fischer, M.H.: A hierarchical view of abstractness: grounded, embodied, and situated aspects. Phys. Life Rev. (2019). https://doi.org/10.1016/j.plrev.2019.04.005
19. Pexman, P.M., Hargreaves, I.S., Edwards, J.D., Henry, L.C., Goodyear, B.G.: Neural correlates of concreteness in semantic categorization. J. Cogn. Neurosci. **19**, 1407–1419 (2007). https://doi.org/10.1162/jocn.2007.19.8.1407
20. Binder, J.R., Westbury, C.F., McKiernan, K.A., Possing, E.T., Medler, D.A.: Distinct brain systems for processing concrete and abstract concepts. J Cogn Neurosci. **7**(6), 905–917 (2005). https://doi.org/10.1162/0898929054021102
21. Dhond, R.P., Witzel, T., Dale, A.M., Halgren, E.: Spatiotemporal cortical dynamics underlying abstract and concrete word reading. Hum. Brain Mapp. **28**(4), 355–362 (2007). https://doi.org/10.1002/hbm.20282
22. Wang, J., Conder, J.A., Blitzer, D.N., Shinkareva, S.V.: Neural representation of abstract and concrete concepts: a meta-analysis of neuroimaging studies. Hum. Brain Mapp. **31**, 1459–1468 (2010). https://doi.org/10.1002/hbm.20950
23. Robson, H., Zahn, R., Keidel, J.L., Binney, R.J., Sage, K., Ralph, M.A.L.: The anterior temporal lobes support residual comprehension in Wernicke's aphasia. Brain **137**, 931–943 (2014). https://doi.org/10.1093/brain/awt373

24. Pasquale, A., Rosa, D., Catricala, E., Vigliocco, G., Cappa, S.F.: Beyond the abstract–concrete dichotomy: mode of acquisition, concreteness, imageability, familiarity, age of acquisition, context availability, and abstractness norms for a set of 417 Italian words. Behav. Res. Meth. **42**(4), 1042–1048 (2010). https://doi.org/10.3758/BRM.42.4.1042
25. Kousta, S.T., Vigliocco, G., Vinson, D.P., Andrews, M., Del Campo, E.: The representation of abstract words: why emotion matters. Exp Psychol Gen. **140**(1), 14–34 (2011). https://doi.org/10.1037/a0021446
26. Paivio, A.: Dual coding theory, word abstractness, and emotion: a critical review of Kousta et al. (2011). J. Exp. Psychol. Gen. **142**(1), 282–287 (2013). https://doi.org/10.1037/a0027004
27. Bailey, D.J., Nessler, C., Berggren, K.N., Wambaugh, J.L.: An aphasia treatment for verbs with low concreteness: a pilot study. Am. J. Speech Lang. Pathol. **29**(1), 299–318 (2020)
28. Bolognesi, M., Burgers, C., Caselli, T.: On abstraction: decoupling conceptual concreteness and categorical specificity. Cogn. Process. **21**, 365–381 (2020). https://doi.org/10.1007/s10339-020-00965-9
29. Fellbaum, C.: WordNet: An Electronic Lexical Database. MIT Press (1998)
30. Frassinelli, D., Naumann, D., Utt, J., Schulte m Walde, S.: Contextual characteristics of concrete and abstract words. In Proceedings of the 12th International Conference on Computational Semantics, Montpellier (2017)
31. Naumann, D., Frassinelli, D., Schulte im Walde, S.: Quantitative semantic variation in the contexts of concrete and abstract words. In: Proceedings of the 7th Joint Conference on Lexical and Computational Semantics, New Orleans, LA, pp. 76–85 (2018)
32. Davies, M.: Expanding Horizons in historical linguistics with the 400 million word corpus of historical American English. Corpora **7**, 121–157 (2012)
33. Snefjella, B., Généreux, M., Kuperman, V.: Historical evolution of concrete and abstract language revisited. Behav. Res. **51**, 1693–1705 (2019)
34. Reilly, M., Desai, R.H.: Effects of semantic neighborhood density in abstract and concrete words. Cognition **169**, 46–53 (2017). https://doi.org/10.1016/j.cognition.2017.08.004
35. Feng, S., Cai, Z., Crossley, S.A., McNamara, D.S.: Simulating human ratings on word concreteness. In: FLAIRS Conference (2011)
36. Sadoski, M.: Resolving the effects of concreteness on interest, comprehension, and learning important ideas from text. Educ. Psychol. Rev. **13**(3), 263–281 (2001)
37. McNamara, D.S., Graesser, A.C., McCarthy, P.M., Cai, Z.: Automated Evaluation of Text and Discourse with Coh-Metrix. Cambridge University Press, Cambridge (2014)
38. Coltheart, M.: The MRC psycholinguistic database. Q. J. Exp. Psychol. **33A**, 497–505 (1981)
39. Brysbaert, M., Warriner, A.B., Kuperman, V.: Concreteness ratings for 40 thousand generally known English word lemmas. Behav. Res. Methods **46**(3), 904–911 (2014)
40. Brysbaert, M., Stevens, M., De Deyne, S., Voorspoels, W., Storms, G.: Norms of age of acquisition and concreteness for 30,000 Dutch words. Acta Physiol. (Oxf) **150**, 80–84 (2014). https://doi.org/10.1016/j.actpsy.2014.04.010
41. Köper, M., Schulte im Walde, S.: Automatically generated affective norms of abstractness, arousal, imageability and valence for 350 000 German lemmas. In: Proceedings of the 10th International Conference on Language Resources and Evaluation, LREC 2016, pp. 2595–2598 (2016)
42. Solovyev, V.D., Ivanov, V.V., Akhtiamov, R.B.: Dictionary of abstract and concrete words of the Russian language: a methodology for creation and application. J. Res. Appl. Linguist. **10**, 215–227 (2019)
43. Theijssen, D., Van Halteren, H., Boves, L., Oostdijk, N.: On the difficulty of making concreteness concrete. In: Computational Linguistics in the Netherlands, CLIN 21 (2011)
44. Charbonnier, J., Wartena, C.: Predicting the concreteness of German Words. In: Proceedings of the 5th Swiss Text Analytics Conference (SwissText) and 16th Conference on Natural Language Processing (KONVENS), CEUR-WS, vol. 2624 (2020). Paper 8

45. Solovyev, V.D., Bochkarev, V.V., Khristoforov, S.V.: Generation of a dictionary of abstract/concrete words by a multilayer neural network. J. Phys. Conf. Ser. **1680**, 012046 (2020)
46. Thompson, B., Lupyan, G.: Automatic estimation of lexical concreteness in 77 languages. In: The 40th Annual Conference of the Cognitive Science Society, pp. 1122–1127. Cognitive Science Society (2018)
47. Solovyev, V., Ivanov, V.: Automated compilation of a corpus-based dictionary and computing concreteness ratings of Russian. In: Karpov, A., Potapova, R. (eds.) Speech and Computer, SPECOM 2020. Lecture Notes in Computer Science, vol 12335, pp. 554–561. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-60276-5_53

Short Definite Descriptions and Referent Activation

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Abstract. We test the claim that the use of short definite descriptions (SDDs) for referent mentions in discourse (e.g. *the country*) corresponds to a specific range of referent activation in the speaker's working memory, lower than the activation level necessary for pronoun use and higher than the level corresponding to proper names (PNs). Data from the WSJ MoRA 2020 corpus of English written texts suggest that the use of SDDs and PNs corresponds to one and the same activation range. Referential distance is highly correlated with activation, and we compare the distribution of two distance metrics, linear distance and rhetorical distance, across SDDs and PNs. We have found the differences to be statistically insignificant. Furthermore, we demonstrate on the corpus data that at least four factors operate that affect the choice between SDDs and PNs, while not being directly related to activation, namely: referent animacy, referent number, relative length of the SDD and the PN for the given referent, and prior mentions of the referent by means of an SDD within the current text.

Keywords: Referential choice · Referential distance · Referent activation · Short definite descriptions · Proper names · Corpus linguistics

1 Introduction

When a speaker chooses an appropriate expression to mention a referent in discourse, the primary choice s/he has to make is to choose the basic expression type: a lexically full referential device (an NP headed by a noun) or a reduced one (a pronoun or a zero expression). Following Kibrik [1], we call such choice basic referential choice. In the research of reference, it is widely accepted that basic referential choice is influenced by the current degree of the referent's activation in the speaker's working memory (or another functionally equivalent cognitive component) [2–7]. There is a certain threshold of referent activation above which the use of a reduced referential device is preferable, and a lexically full NP is superfluous. If this threshold has not been attained and thus a full NP must be used, how is the choice made between different subtypes of full NPs, such as proper names and descriptions?

It has been proposed by Ariel [8] that the use of descriptions corresponds to a level of activation (or accessibility, in Ariel's terminology) lower than that corresponding to

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pronouns (e.g. *it*) and higher than that corresponding to proper names (e.g. *Spain*). In addition, various types of definite descriptions serve to mark distinct levels of activation, in the order of decreasing accessibility: demonstrative descriptions (e.g. *this country*), short definite descriptions (e.g. *the country*), and long definite descriptions (e.g. *the southernmost European country*). Similarly, according to the givenness hierarchy proposed by Gundel et al. [9], the use of pronouns requires a higher activation level than the level sufficient for demonstrative descriptions, and the use of demonstrative descriptions – a higher activation level than the level sufficient for definite *the*-descriptions.

Among these options, the most fundamental one is short definite descriptions, consisting of a common noun and a definite article.[1] In the present study, we focus on the choice between **short definite descriptions** (SDDs) and **proper names** (PNs) and test the hypothesis that this choice again depends on referent activation. We here exclude demonstrative descriptions (DemDs) and long definite descriptions (LDDs) from consideration for the following reasons. DemDs are infrequent in the corpus (5.4% of all descriptions in the corpus, cf. Table 1), and as Krasavina [10] states, DemDs are extremely rare as referring to discourse protagonists, which means that obtaining a representative data sample would be problematic. LDDs are much more numerous in the corpus (27.4% of all descriptions), but this category is heterogeneous, which may make it difficult to obtain clear results concerning activation. Also, at least in some cases, LDDs convey novel information on the referent (e.g. *Spain's seventh largest bank*), and such usages are difficult to tell apart from the cases conditioned by activation as such. SDDs, in contrast, are a homogeneous class.

Is it possible to directly measure activation in the instances when SDDs and PNs are used? A technique ensuring a precise measurement is labor-intensive (cf. Chapters 12 and 13 of [1]), but for the present purposes it suffices to use an easily measurable parameter that can serve as a rough assessment of activation. Specifically, we use the distance from the current mention of a referent (anaphor) to its previous mention in discourse (antecedent). In the present study, we consider two distance metrics: linear and rhetorical distance (LinD and RhD, respectively), both measured in clauses. LinD captures plain linear discourse structure, while RhD takes hierarchical discourse structure into account.

It was observed in [11] that:

1. in the task of modeling *basic referential choice* by means of machine learning algorithms, distance factors demonstrated the highest contribution to the overall success of prediction among all the factors used in the model;
2. the set of factors predicting basic referential choice with a high accuracy may also be used for predicting the *three-way choice* between PNs, descriptions and pronouns, even though with a significantly lower accuracy.

This suggests that distance factors may indeed be correlated with the choice between PNs and SDDs.

The rest of the paper is organized as follows. Section 2 reports an analysis of LinD and RhD distribution in the classes of SDDs and PNs. In Sect. 3, several non-activation

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[1] In the present study, we make some exceptions to this definition, see Sect. 2.1 for details.

factors of SDD usage are explored. Section 4 contains concluding remarks and outlines directions for further research.

2 Short Definite Descriptions and Distance

2.1 Corpus and Data

The analysis here is based on the data from the WSJ MoRA 2020 corpus, which is a collection of newspaper articles from the Wall Street Journal annotated according to the so-called MoRA scheme [11], in the version modified in 2020. The annotation of the corpus includes the following layers:

- referring expressions (markables),
- relations of coreference between markables,
- numerous features of markables,
- hierarchical (so-called rhetorical) discourse structure, obtained from the RST Discourse Treebank [12].

Table 1. Breakdown of anaphor-antecedent pairs in the corpus by anaphor expression type

	In the corpus	Selected for analysis
Pronouns	**826**	**826**
PNs	**719**	**719**
Descriptions	**825**	**386**
SDDs	386 (46.8% of descriptions)	386
LDDs	226 (27.4% of descriptions)	–
DemDs	45 (5.4% of descriptions)	–
Indefinite descriptions	168 (20.4% of descriptions)	–
Total pairs	**2370**	**1931**

The annotation was carried out in the MMAX2 annotation tool [13]. The values of some factors were extracted automatically.[2]

A total of 2370 anaphor-antecedent pairs are found in the corpus, and 1931 of them are used in the analysis reported here. Table 1 provides the breakdown of these anaphors by expression type.

We define SDD as an NP that consists of: the definite article plus exactly one noun (e.g. *the unit*) and, optionally, a cardinal numeral (e.g. *the five senators*). An exception to the one-noun requirement is made for the instances such as *the vice president*, where the two-word term is indivisible, contrary to the instances such as *the plane crash*, treated as LDDs.

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[2] We express our gratitude to Grigory B. Dobrov who developed scripts for these purposes.

Also, 16 examples of bare NPs were included in the SDD category for the reason that they were reliably identified as co-referring with an SDD containing the same head noun and a definite article. In most cases, that was due to the grammatical role of attribute (cf. *the company's shares* – *company shares*).

2.2 Results

Table 2 and Table 3 show how the values of LinD and RhD are distributed within the classes of pronouns, SDDs and PNs in the corpus. LinD only assumes integer values. RhD may also have values of 0.5, 1.5, etc. [14], but in the tables, those are rounded up to integer values, for the purposes of comparability with LinD.

Table 2. Distribution of linear distance values in pronouns, SDDs and PNs

LinD	Pronouns		SDDs		PNs	
	n	%	n	%	n	%
0	214	25.91%	17	4.40%	12	1.67%
1	418	50.61%	90	23.32%	144	20.03%
2	101	12.23%	84	21.76%	141	19.61%
3	50	6.05%	41	10.62%	115	15.99%
4	24	2.91%	45	11.66%	59	8.21%
5	13	1.57%	25	6.48%	53	7.37%
6	3	0.36%	19	4.92%	43	5.98%
7	0	–	11	2.85%	26	3.62%
8	0	–	11	2.85%	18	2.50%
9	1	0.12%	8	2.07%	21	2.92%
10	0	–	7	1.81%	12	1.67%
11–15	2	0.24%	19	4.93%	52	7.22%
16–20	0	–	8	2.08%	20	2.78%
21–25	0	–	1	0.26%	3	0.42%
TOTAL	**826**	**100%**	**386**	**100%**	**719**	**100%**

As can be seen from Table 2 and Table 3, pronouns become extremely rare at LinD and RhD values above 6, in comparison with full NPs that are rather frequent at distance values above 6. If the claim is true that SDDs correspond to a higher activation range than PNs, then it must be expected that above a certain distance value, i.e. below a certain activation threshold, SDDs must occur more rarely compared to PNs. But as statistical analysis demonstrates, the differences in the distance distributions of SDDs and PNs are not significant.

We conducted unpaired *t*-tests, limiting the dataset to instances in which distance values were equal to 2 and above. The cases with distances of 0 and 1 are not pertinent to our analysis, since these are cases in which the antecedent is located in the same

Table 3. Distribution of rhetorical distance values in pronouns, SDDs and PNs

RhD	Pronouns		SDDs		PNs	
	n	%	n	%	n	%
0	223	27.00%	19	4.92%	16	2.23%
1	329	39.83%	86	22.28%	103	14.33%
2	141	17.07%	104	26.94%	184	25.59%
3	101	12.23%	72	18.65%	163	22.67%
4	21	2.54%	41	10.62%	104	14.46%
5	6	0.73%	31	8.03%	67	9.32%
6	3	0.36%	19	4.92%	42	5.84%
7	0	–	7	1.81%	23	3.20%
8	2	0.24%	1	0.26%	9	1.25%
9	0	–	3	0.78%	4	0.56%
10	0	–	0	–	1	0.14%
11–15	0	–	3	0.78%	3	0.42%
16–25	0	–	0	–	0	–
TOTAL	**826**	**100%**	**386**	**100%**	**719**	**100%**

clause as the anaphor, or in the immediately preceding clause (in terms of linear or rhetorical structure). These contexts normally require a pronoun, and referent activation level is expected to be high. Accordingly, if a full NP is used in this context, this is due to special conditions such as referential conflict [1, 15], rather than to insufficient activation. The factors guiding the choice between PNs and definite descriptions in these contexts require a separate investigation.

Table 4 shows the results of the *t*-tests; *p*-values below 0.05 are marked in boldface. *p*-values for the whole dataset and different subsets are provided for comparison. Note that starting from the subset with distance values of 0 and 1 eliminated (line 3), statistical significance of the differences in the distance distributions of SDDs and PNs is not confirmed.

Table 4. *p*-values for *t*-tests, PNs vs. SDDs at different thresholds

	LinD	RhD
Whole dataset	**0.023169555**	**0.00041527**
Distance values of 0 are eliminated	0.068387056	**0.002861141**
Distance values of 0 and 1 are eliminated	0.204953338	0.171664547
Distance values of 0 to 2 are eliminated	0.580578004	0.819044445
Distance values of 0 to 3 are eliminated	0.112348106	0.991416212
Distance values of 0 to 4 are eliminated	0.65972398	0.881422687

We also conducted an additional series of t-tests, with the difference that PNs and SDDs were combined into a single class of full NPs and were compared to pronouns. The difference in distribution is confirmed for all tests (with all p-values below 0.05 and mostly below 10^{-10}). This result conforms to the claim that basic referential choice is mainly guided by activation, and supports our assumption that LinD and RhD are adequate substitutes for activation levels.

Thus our analysis revealed no evidence of SDDs and PNs corresponding to different activation levels.

3 Factors of SDD Usage Unrelated to Activation

Having found that activation is unlikely to account for the distribution of SDDs and PNs in our corpus, we now search for alternative factors that may be responsible for this choice.

3.1 Animacy

Fraurud [16] demonstrated that humans are denoted by means of definite descriptions significantly more rarely than inanimate referents. The data from the WSJ MoRA 2020 corpus support this finding. For human referents, 78.35% of full NPs are PNs, and 21.65% are SDDs; for inanimate referents, the ratio is roughly the opposite: 20.45% PNs and 79.55% SDDs.

Animacy is known to be a factor of basic referential choice, that is contribute to referent activation; see [1, 17]. If SDDs corresponded to a higher activation level than PNs, we would observe a frequency distribution converse to the one observed in our data. Therefore, we conclude that in the case of the SDD vs. PN choice the factor of animacy plays a separate role, unrelated to activation processes.

3.2 Number

The effect of animacy described above, however, is overridden if the referent is a group of persons and the NP is in the plural (e.g. *the leaders; the women*). In this case, SDD mentions surpass PNs strongly (24 vs. 2 instances, respectively).

Thus the combination of a referent's grammatical number and its animacy is a good predictor of referential choice between PNs and SDDs.

3.3 Relative Length of PNs and SDDs

The observation that, for some referents, their basic proper name (e.g. *Banco Exterior*) is perceptibly longer than their mention via the corresponding common noun (e.g. *the bank*), lead us to the hypothesis that at least in some instances, this might be a reason for the writer to prefer an SDD over a PN, and, conversely, if a referent has a compact PN, such as an acronym (e.g. *the U.S.*), the SDD option (e.g. *the country*) is less likely to be chosen.

It is difficult to define the conditions under which one expression may be judged to be “lighter” than another one. How substantial must be the difference? In what units must it be measured? We compared lengths of expressions in characters, omitting the definite article and punctuation marks. In the present study, our goal is to test whether the tendency proposed above exists in principle, so our priority is to have simple and objective heuristics rather than to find an optimal metric.

To test the hypothesis, we selected a sample of 78 referential chains from the corpus, based on the following criteria:

- for the given referent, both expression types are available: PN and SDD;
- the referential chain contains at least three anaphors in the form of either a PN or an SDD;
- animate referents are excluded due to the effects of animacy and number discussed above.

For each referent, all of its PN and SDD mentions were determined, and the character lengths of those were compared. The PN and the SDD were taken in their respective shortest (basic) modifications attested in the text (e.g. *P&G* and not *Procter & Gamble*; *state* and not *country*). The SDD for quite a few referents was not present in the texts, in which case the most basic variant was selected for comparison, corresponding to the category of the referent (*country, company*).

Finally, the sample was divided into two subgroups based on whether the SDD was shorter than the PN or not (40 and 38 instances, respectively), and they were compared in terms of the share of SDDs in the referential chain.

The results are presented in Fig. 1. Values within each of the groups are sorted in descending order. Although in each of the groups, the values ranged from 0 to 0.8 and above, still the group in which the SDD was shorter than the PN demonstrated a tendency toward higher SDD rates, and an unpaired t-test showed this difference to be statistically significant ($p = 0.466143$).

These results suggest that relative length is another factor of referential choice between PNs and SDDs: shorter SSDs have more chances to be preferred over the corresponding PNs.

3.4 SDDs Among the Prior Mentions Within the Referential Chain

In the case of certain referents, SDDs are used extensively, and for some other referents they are not, even though these referents do not differ in terms of relative length of their respective PNs and SDDs. This becomes especially evident with long referential chains comprising about 10 full NP mentions and more: in some of such chains the share of SDDs among all full NPs reaches 0.75 (e.g. *California – state*), while in some other only 0.36 (e.g. *Boston Co – unit*).

A closer analysis of such referential chains in the corpus reveals that this effect cannot be accounted for by different activation levels, since in the referential chains that were analyzed, SDDs do not appear preferably at shorter distances, as well as PNs do not appear preferably at longer distances. This suggests that a certain referent within a certain text may be generally more or less prone to the use of SDDs.

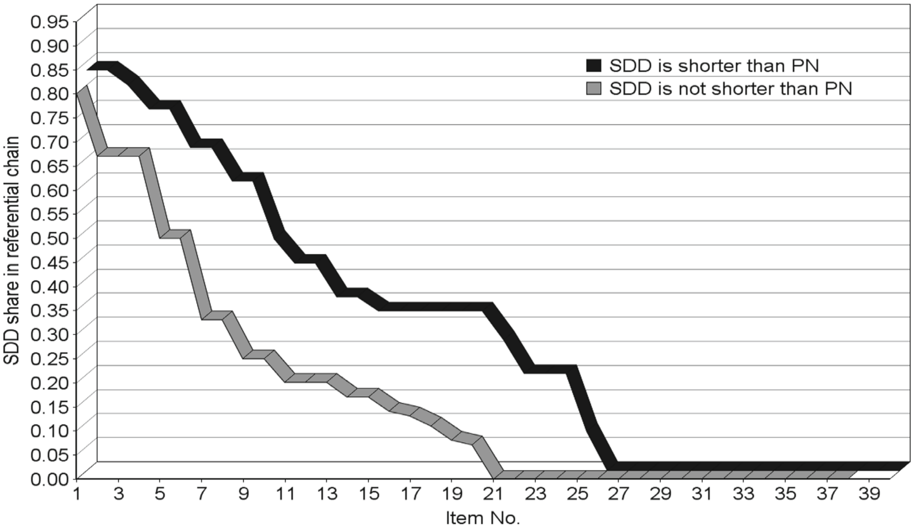

Fig. 1. SDD usage rate depending on relative length of PNs and SDDs

A referent's propensity to the use of SDDs discussed here is reflected in the frequency of SDDs within the referential chain. Accordingly, the *probability* that the referent will be mentioned by means of an SDD at a given point in discourse is predicted, in addition to other factors, by the frequency of SDDs among the prior mentions of the referent within the chain.

4 Conclusion

The prediction that SDDs correspond to a particular range of activation distinct from that of PNs was not confirmed by our data. Distance metrics in the anaphor-antecedent pairs were used as an approximation of referent activation, and the difference in distribution of their values observed for SDDs and PNs was not found to be statistically significant.

We suggest that instances of PNs and SDDs correspond to one and the same range of referent activation, while there are additional factors of semantic and usage-based nature that influence the choice between them.

These results are important for the exploration of the larger issue of modeling the choice between various types of full NPs.

Directions for further research on the topic include:

- usage of SDDs and PNs under referential conflict;
- exploration of the specific contexts that favor the use of DemDs, LDDs, and indefinite descriptions;
- factors leading to the variation of SDD forms within the referential chain (cf. *the company/the unit/the manufacturer* all pertaining to the same referent).

References

1. Kibrik, A.A.: Reference in Discourse. Oxford University Press, Oxford (2011)
2. Tomlin, R.S.: Linguistic reflections of cognitive events. Coherence Ground. Discourse **11**, 455–479 (1987). https://doi.org/10.1075/tsl.11.20tom
3. Chafe, W.L.: Discourse, Consciousness, and Time: The Flow and Displacement of Conscious Experience in Speaking and Writing. University of Chicago Press, Chicago, IL (1994)
4. Wardlow Lane, L., Ferreira, V.S.: Speaker-external versus speaker-internal forces on utterance form: do cognitive demands override threats to referential success? J. Exper. Psychol. Learn. Mem. Cogn. **34**, 1466–1481 (2008). https://doi.org/10.1037/a0013353
5. Arnold, J.E.: How speakers refer: the role of accessibility. Lang. Linguist. Compass **4**, 187–203 (2010). https://doi.org/10.1111/j.1749-818X.2010.00193.x
6. Martin, R.C., Slevc, L.R.: Language production and working memory. In: Goldrick, M., Ferreira, V.S., Miozzo, M. (eds.) The Oxford handbook of language production, pp. 437–450. Oxford University Press, Oxford (2014). https://doi.org/10.1093/oxfordhb/9780199735471.013.009
7. Hendriks, P.: Cognitive modeling of individual variation in reference production and comprehension. Front. Psychol. **7**, 187–203 (2016). https://doi.org/10.3389/fpsyg.2016.00506
8. Ariel, M.: Accessing Noun-Phrase Antecedents. Routledge, London (1990)
9. Gundel, J.K., Hedberg, N., Zacharski, R.: Cognitive status and the form of referring expressions in discourse. Language **69**, 274–307 (1993). https://doi.org/10.2307/416535
10. Krasavina, O.N.: Korpusno-orientirovannoe issledovanie referencii (principy annotacii i analiz dannyx). Корпусно-ориентированное исследование референции (принципы аннотации и анализ данных). [A corpus-oriented study of reference (principles of annotation and data analysis)]. Ph.D. thesis. Dept. of Theoretical and Applied Linguistics, Moscow State University, Moscow (2006)
11. Kibrik, A.A., Khudyakova, M.V., Dobrov, G.B., Linnik, A., Zalmanov, D.A.: Referential choice: Predictability and its limits. Front. Psychol. **7**, 204–224 (2016). https://doi.org/10.3389/fpsyg.2016.01429
12. Carlson, L., Marcu, D., Okurowski, M.: RST Discourse Treebank. Linguistic Data Consortium, Philadelphia, PA (2002)
13. Müller, C., Strube, M.: Multi-level annotation of linguistic data with MMAX2, In: Braun, S., Kohn, K., Mukherjee, J. (eds.) Corpus Technology and Language Pedagogy. New Resources, New Tools, New Methods, Peter Lang, Frankfurt, pp. 197–214 (2006)
14. Kibrik, A.A., Krasavina, O.N.: A corpus study of referential choice: the role of rhetorical structure. In: Kobozeva, I.M., Narin'jani, A.S., Selegey, V.P. (eds.) Papers from the Annual International Conference "Dialogue": Computational Linguistics and Intellectual Technologies, Nauka, Moscow, pp. 561–569 (2005)
15. Arnold, J.E., Griffin, Z.M.: The effect of additional characters on choice of referring expression: everyone counts. J. Mem. Lang. **56**, 521–536 (2007). https://doi.org/10.1016/j.jml.2006.09.007
16. Fraurud, K.: Cognitive ontology and NP form. In: Fretheim, T., Gundel, J.K. (eds.) Reference and Referent Accessibility, pp. 65–88. Benjamins, Amsterdam (1996)
17. Dahl, Ö., Fraurud, K.: Animacy in grammar and discourse. In: Fretheim, T., Gundel, J.K. (eds.) Reference and Referent Accessibility, pp. 47–64. Benjamins, Amsterdam (1996)

Voxel-Wise Localization of Brain Activity While Comprehending Oral Russian-Language Stories

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Abstract. We have implemented neurosemantic analysis to identify voxel-wise representations of lexical items in brain's reaction of native participants on Russian spoken narratives and these representations possible global asymmetries in the brain. Twenty-five subjects took part in this study. Five texts with personal life stories were presented as audio stimuli. Each story was 2 min long. Ultra-fast MRI sequences (TR = 1000 ms) were used to scan brain activity. Scanning was performed on 3 T MRI (Siemens). Seven subjects were selected for further analysis following the control of their cognitive involvement into listening and the level of their registered brain activity. As in an earlier our study with these narratives, twelve lexical clusters were found, with different but coherent semantic fields: from time-and-space concepts to human actions and mental states. The individual semantic maps of each subject look similar in terms of their broad brain activity distribution. Clusters demonstrated nearly symmetrical localization. This fact implies that the left and right hemispheres are both involved in the neural representation of mental lexicon.

Keywords: Neurosemantics · Narratives · Russian language

1 Introduction

While speech processing in the cerebral cortex demonstrates significant left-side lateralization [1], the comprehension of natural text and processing of speech semantics is a higher order cognitive function and thus may demonstrate more compound and distributed brain localization [2, 3]. Indeed, language may designate any aspect of the observed world or of subjective experience. Speech may refer to visual, tactile, haptic, or olfactory representation of real or imaginary objects, as well as to the emotional experience or its conceptual processing [4–6]. Thus, speech comprehension mechanisms in

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the human brain can interact with other processing and representation systems during the analysis of an oral text [7]. In our study, we examine the localization in processing of semantic categories, assigned to text words, during the comprehension of oral narratives. This study used the methodology proposed by Alexander Huth and colleagues [8], where it was for the first time shown how semantic information is represented in the entire neurocognitive system as compared to the studies, that tested only a handful of stimulus conditions (living things, tools, food and others) [9, 10]. The study by Huth et al. presented the semantic maps of the English language on the cerebral cortex. Naturally spoken biographical texts in English were used as audio stimuli with simultaneous recording of the brain neural networks activity with functional MRI for seven subjects. Researchers found that the English language semantic map almost symmetrically covers the cortex surface of the right and left hemispheres of the brain.

Recently, we published results of several studies addressing methodology of neurosemantic research in difference to the common method of cognitive subtraction [11, 12]. In the current work, the question of localization of neurosemantic representations will be further considered on material of the Russian spoken narratives. In two related works, we discuss at more length lexical [13] and communicative [14] aspects of this study. We repeat here some details of our method for the sake of better understanding.

2 Methods

2.1 Participants and stimuli

We have produced five original narrated stories as stimulus material. These five stories were first-person narratives that describe personal life events: each was a small emotional story of the same author. Texts were recorded by a professional performer and orally presented to subjects in fMRI. All texts were accompanied by linguistic markup: each word was annotated by a semantic vector, depending on the distance of the word to 997 feature words (see below).

The study involved 25 people (native Russian speakers, all right-handed). Informed consent was obtained from each participant prior to the experiment. Participation in the study was not paid. Ethical approval for the study was provided by the local Ethics Committee of the National Research Center “Kurchatov Institute”. Most of participants were excluded from the analysis following the two criteria. First, it was important to verify that a person in tomographic scanner was really listening to the texts and was involved in them. To control the involvement, we asked subjects to fill out a questionnaire after the experiment. Subjects were to evaluate the significance of each text on a five-degree scale. For further analysis we have selected subjects, who gave 4 or 5 points to at least three texts out of five. Second, the significance of the registered BOLD-signal was controlled as compared to the resting state. The activity of the brain in some significant zones such as hippocampi and amygdalae, was chosen as the criteria. Following these two principals, we selected seven people for the further analysis (5 female, mean age 23.8).

2.2 Stimuli Markup

Semantics of the stimulus material has to be formalized and represented for further analysis, so each word within the texts got semantic and temporal markup. For time alignment, start and end time of each oral word were manually annotated in ELAN speech annotation software – in milliseconds from the start of the text. For the semantic markup we attributed to each word a 300-dimensional word2vec vector, automatically extracted basing on the joint occurrence of words in The Russian National Corpus and Russian Wikipedia [15]. Thereafter we selected feature words: 500 most frequent Russian nouns and 497 most frequent Russian verbs [16]. All these feature words were marked up using the same word2vec distributional semantic model. Basing on the word2vec vectors, for each original text word we calculated similarities to each of the feature words as cosine distances of their vectors. Further, each text word has received a 997-dimensional representation vector as the similarities of the word to each of the 997 feature words.

The MRI data was acquired using a 3T SIEMENS Magnetom Verio MR tomograph. The T1-weighted sagittal three-dimensional magnetization-prepared rapid gradient echo sequence was acquired with the following imaging parameters: 176 slices, TR = 1,900 ms, TE = 2.19 ms, slice thickness = 1 mm, flip angle = 9°, inversion time = 900 ms, FOV = 250 × 218 mm. fMRI data was acquired with the following parameters: 30 slices, TR = 2,000 ms, TE = 25 ms, slice thickness = 3 mm, flip angle = 90°, FOV = 192 × 192 mm. The obtained anatomical and fMRI data were processed using the SPM8 program [17], in which the following processing steps were carried out: bringing the center of anatomical and functional images to the front commissure (AC); correction of field heterogeneity for functional data; calculation of the motion vector of the head and the correction of data using the obtained vector; co-registration of functional images with anatomical; correction of time offset between slices (slice-timing correction); segmentation of anatomical images into gray and white matter, cerebrospinal fluid; spatial normalization of anatomical and functional images.

2.3 Advanced Pre-processing

In an earlier work, we have already described all steps of pre-processing [11]. In these steps, we firstly formed the stimuli matrix [Features × Time samples (Words)], where stimuli were represented as a variation of each feature value over time. The standard scores (z-scores) for the stimuli matrix rows were calculated. These scores are dimensionless quantities, what allowed us to compare them with the BOLD signal, for which z-scores were also found.

For further calculations, it was necessary to bring the time series of semantic vectors to the fMRI time scale (with a repetition time of TR = 1.1 s), that is, to resample. For resampling, the Lanczos filter is used with a cut-off frequency set to the Nyquist frequency of the fMRI acquisition. The last step of pre-processing the stimuli matrix was to consider time delays of the fMRI scanning nature. The BOLD signal increases and decreases in accordance with the well-known non-linear graph of Haemodynamic Response Function. To approximate this curve, 5-point delays were used, 3.3, 4.4, 5.5, 6.6 and 7.7 s. Accordingly, 5 copies of time series of each feature were created and concatenated.

To estimate how 997 features affect the BOLD response in each voxel in the cortex and the subcortical structures of the brain, we applied a specially prepared atlas mask to all the voxels in the data. The mask represents neocortical gray-matter voxels of both hemispheres, as well as those of some subcortical structures, e.g. amygdalae, brainstem, and cerebellum. After applying the mask only about 100,000 voxels (from 900,000 initially) remained.

We used the regularized linear regression (or ridge regression) procedure for the estimation of the weights of each feature for each voxel. The OLS regression does not work directly because the features number (4985) is greater than the time samples number (467). This problem is solved by regularization. The matrices formula of it is as following: $Y = X\beta$, where Y is the BOLD signal matrix (t × m), X is the stimuli matrix (t × p), β is the weight matrix; t is time samples, m is the voxel number, p is the feature number.

$$E = \|Y - X\beta\|^2 + \alpha\|\beta\|^2 \tag{1}$$

The cross-validation method was used to find the regularizing coefficient α. For this purpose, the data set was divided into two parts: in the first part the weights are estimated for a given α, in the second part these weights are tested. The procedure is repeated for each α of interest. Thereafter α with the best prediction is selected and weights are calculated using the entire dataset and this α.

In order to find the best voxels to accommodate the semantic features represented by our stimulus words, we chose 10,000 voxels with the highest correlation between predicted responses to the fifth text and the actual BOLD responses. The correlation coefficients range between 0.16 and 0.54. These voxels are distributed approximately equally across the hemispheres and across the gray matter. The principal component analysis (PCA) method was applied to the weight matrices [Voxels × Features]. Before that, the features were averaged over time of hemodynamic responses (that is, out of 4985 features, 997 features were again obtained). For the resulting 10,000 voxels, matrices of scores and loadings were constructed in the principal components space, whereby first four factors of the PCA were used as respective dimensions. After that, we projected the stimuli words into this principal component space by multiplying each word vector by the feature vector in PCA space. Then we chose the most important words in this space implying their significance is the distance from all words cloud center. We selected 80% of the words randomly and found their convex hull in this space. By repeating this procedure 1,000 times, we constructed the set of words that appeared on the hull at least once.

After the convex hull procedure, there were 162 words left for cluster analysis. We used hierarchical clustering, the complete linking method. A cutoff threshold of 1 was selected, as a result, we got 12 clusters, with a cardinality from 5 to 23 words. Some words had comparable distances to the centers of several clusters and, thus, could not be attributed to a single cluster. This is an expected result as in natural languages words may belong to several semantic domains at the same time. However, in this paper, we attempted a more formal approach with additional filtering of words for clustering by choosing words that had a similarity to the center of one cluster 15% more than to the centers of all other clusters. This filtering reduced the word count to 111. After a recalculation of cluster centers, the new clusters were more compact: the distance of each word to the center of its cluster was over 2 times less than to the center of any other cluster. These derivate clusters were named in accordance with the semantics of words within each cluster but basically they had the same meaning on the first sight and therefore preserved their old names – rebuilding, city, threat, event, function, confrontation, deprivation, experience, goal, creation (space), order, and try (moving).

3 Results

As each cluster can be represented by its words and the weight matrix contains the significance of each voxel for each feature, we used the stimuli matrix as a transformation matrix from features to words and multiplied it by the weight matrix. Then each word was weighted for each voxel. We found 250 most representative voxels for each word in every cluster, and further – voxel representations for each cluster.

These voxels representations sometimes had common voxels for different clusters. For thorough identification of such voxels, intersection procedure was used. The voxels were intersected between subjects for each cluster and between clusters for each subject. Some of the voxels were represented in all the clusters, while other voxels, on the contrary, belonged only to a single cluster.

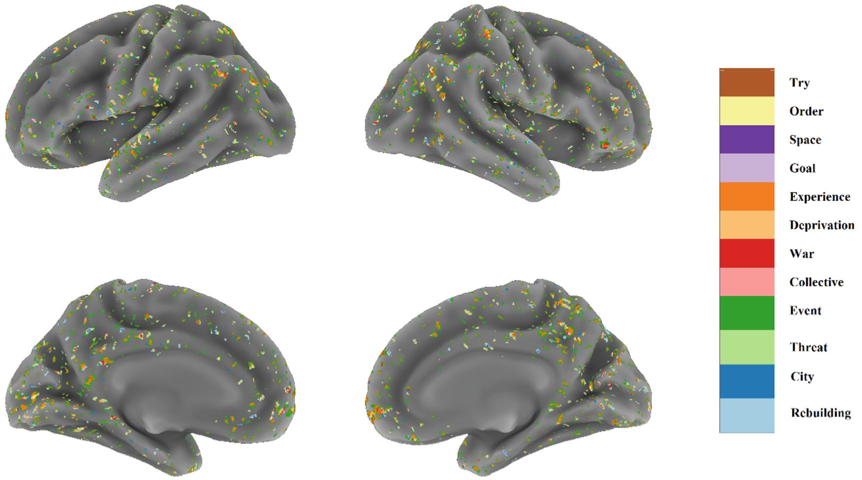

Fig. 1. Maps of active voxels of the brain for all subjects across all clusters.

Automated Anatomical Labeling (AAL) atlas [18] was used to count the number of voxels in four major zones: cortex, subcortical structures, brain stem and cerebellum. These four zones were constructed directly from unification of the AAL zones.

On our view, it was inappropriate to compare directly the absolute number of voxels in different brain areas, because even for the best 10000 voxels, their number differed from zone to zone (Table 1). To consider this difference, we have calculated the ratio of the cluster voxels in a given zone to the subset of the best 10,000 voxels, represented in the same zone (Table 2). The individual data for all clusters are presented in Appendix (Table 3).

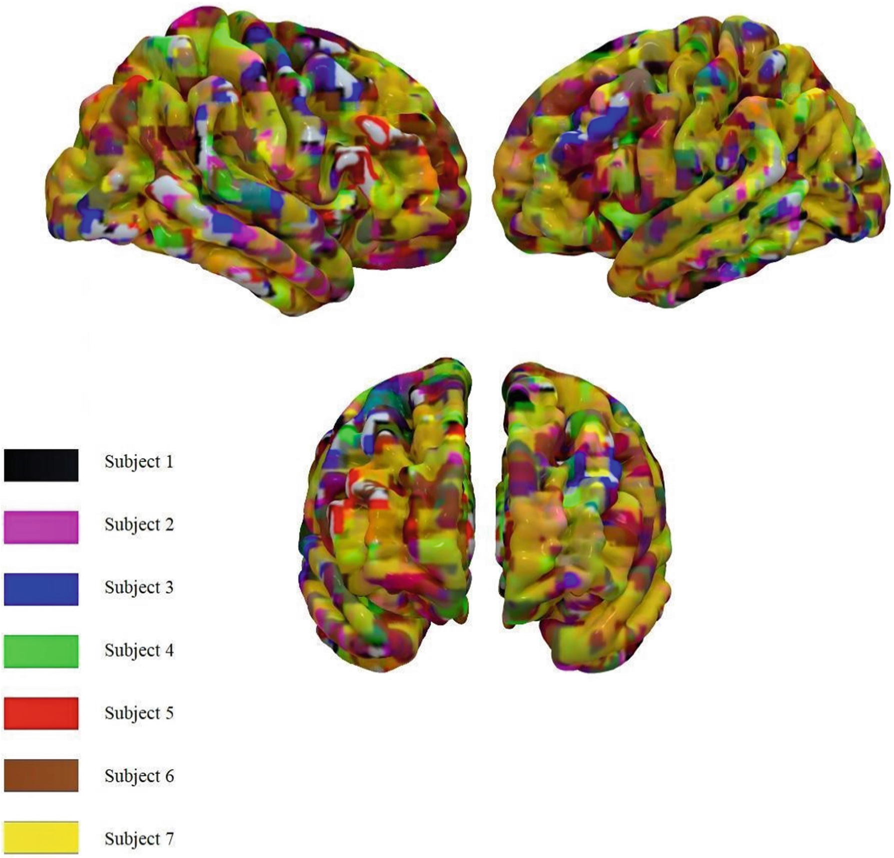

Fig. 2. Maps of brain voxels active in any clusters.

4 Discussion

As can be seen from the data presented in Figs. 1 and 2 and Table 1, the representation of semantic groups has nearly equal distribution over the gray matter of the brain for all subjects. The individual semantic maps of each subject look similar in terms of even distribution. The localization of words that are specific and nonspecific for clusters was analyzed, respectively. In case of words, non-specific to individual clusters, there is an equal distribution of activations. In case of specific words, clusters with localization zones with significant size can be observed in individual brain structures. Although stimuli texts were situational in nature, the activation of neural networks of the brain was spatially distributed throughout the cortex, which corresponds to the results by Huth et al. [8].

Table 2 shows data on 4 regions of the brain – the gray matter of the cerebral cortex, subcortical structures, cerebellum, and brainstem. Semantic maps for the English language [8] also had approximately symmetry along the long axe of cerebral cortex. Our preliminary analysis for 132 brain structures according to the AAL anatomical Atlas

Table 1. Distribution of the 10,000 best voxels in the brain for all subjects (L and R correspond to left and right hemispheres).

Brain Region	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7
Cortex (L)	3494	3505	4444	3757	3331	3481	3942
Cortex (R)	3639	3535	3715	3561	3872	4379	3442
Subcort. (L)	319	279	190	263	283	269	243
Subcort. (R)	242	189	149	180	209	185	185
Stem (L)	98	95	46	81	101	92	95
Stem (R)	127	159	57	119	158	99	136
Cerebel. (L)	885	1030	350	786	836	636	844
Cerebel. (R)	912	941	826	1018	952	629	837

Table 2. Number of active voxels for intersection of all the clusters and ratio of these voxels to the number of the best 10,000 voxels, represented in the same zone for each subject (L and R correspond to left and right hemispheres; percentages are given in parentheses)

Brain Region	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7
Cortex (L)	101 (2.9)	93 (2.7)	128 (2.9)	121 (3.2)	109 (3.3)	122 (3.5)	113 (2.9)
Cortex (R)	107 (2.9)	92 (2.6)	91 (2.5)	90 (2.5)	154 (4,0)	92 (2.1)	102 (3,0)
Subcort. (L)	9 (2.8)	11 (3.9)	7 (3.7)	7 (2.7)	3 (1.1)	8 (3,0)	4 (1.7)
Subcort. (R)	4 (1.7)	5 (2.7)	3 (2)	6 (3.3)	6 (2.9)	2 (1.1)	6 (3.2)
Stem (L)	2 (2.0)	7 (7.4)	2 (4.4)	2 (2.5)	0 (0)	3 (3.3)	2 (2.1)
Stem (R)	2 (1.6)	6 (3.8)	3 (5.3)	10 (8.4)	2 (1.3)	7 (7.1)	1 (0.7)
Cerebel. (L)	17 (1.9)	40 (3.9)	9 (2.6)	21 (2.7)	12 (1.4)	14 (2.2)	9 (1.1)
Cerebel. (R)	25 (2.7)	32 (3.4)	21 (2.5)	20 (2)	4 (0.4)	20 (3.2)	13 (1.6)

[18] showed that voxel activation for any structure was nearly symmetrical for the left and right hemispheres for each subject. Frontal, prefrontal, and temporal brain, both left and right, was involved, as well as the regions around temporoparietal junction, precuneus and other structures. In our study, such symmetry is also observed for the subcortical structures and the cerebellum. The involvement of internal structures in linguistic processing has been previously discussed [19, 20]. Also, on the basis of semantic contrasts, the role of cerebellar structures in language processing was registered [6]. The hypothesis of the modulating role of the cerebellum in speech processing and in various non-motor language processes such as lexical retrieval, syntax, and language dynamics was proposed [21, 22]. According to our results, the activity of the cerebellar zones is spatially different for different clusters that may indicate specific conceptual processes. Such conceptual processes could be evolutionarily programmed, and their specificity could be determined during the formation of individual experience [23–26]. Formed

clusters of semantic groups at different cognitive levels in the left and right hemispheres could correspond to the conceptual structures.

An important part of semantic information processing is the identification of the common concept or understanding of the narrative. Such processes may also be non-specific to clusters of semantic groups. There is increased brain activity in the area of the cerebellum, as well as in the area of the default mode network (DMN) zones: the medial prefrontal cortex (MPFC), posterior cingulate cortex (PCC) and the inferior parietal cortex of left (LIPC) and right (RIPC) hemispheres. New work [27] also underlined the role of the DMN in the neurosemantic encoding of narratives. It has been shown that this generalization is executed at higher levels than those, withholding individual semantic units, and that this encoding is systematic for both individuals (Americans, Iranians, Chinese) and three languages (English, Chinese, and Farsi). Thus, our study testifies to the important role playing by structures of both hemispheres – the cerebrum as well as cerebellum – in advanced linguistic processes.

5 Conclusions

Based on a neurosemantic approach for meaningful narrated texts, we have constructed voxel-wise maps of the cerebral cortex and subcortical structures and identified the same 12 semantic clusters as previously even in more stringent clustering procedure [11, 13]: *rebuilding, city, threat, event, function, confrontation, deprivation, experience, goal, space/ creation, order, try/ moving*. These semantic clusters demonstrate nearly symmetrical distribution across the cerebral cortex. However, we were able to find their slight asymmetry in a related work [13]. Interestingly, overall processing of semantic information seems to be similar in Russian and English languages, which presumably indicates the universal nature of the mechanism, forming cognitive groups based on individual experience. In addition to cortical regions, subcortical structures, cerebellar, and stem structures were involved in the formation of these semantic clusters. At the end of the paper, we speculate that the resulting clusters, within the framework of modern linguistic and neurocognitive theories, can be characterized as the conceptual structures.

Acknowledgements. The study has been in part supported by the Russian Science Foundation, grant 17-78-30029.

Appendix

Table 3. Number of active voxels for all the clusters and ratio of these voxels to the number of the best 10,000 voxels, represented in the same zone for each subject (L and R correspond to left and right hemispheres; percentages are given in parentheses)

Subject 1	**Rebuilding**	**City**	**Threat**	**Event**	**Collective**	**War**	**Deprivation**	**Experience**	**Goal**	**Space**	**Order**	**Try**
Cortex (L)	224 (6.4)	323 (9.2)	220 (6.3)	249 (7.1)	225 (6.4)	244 (7)	227 (6.5)	306 (8.7)	268 (7.7)	249 (7.1)	260 (7.4)	251 (7.2)
Cortex (R)	233 (6.4)	324 (8.9)	260 (7.14)	261 (7.2)	229 (6.3)	270 (7.4)	233 (6.4)	336 (9.2)	290 (8)	245 (6.7)	272 (7.5)	270 (7.4)
Subcort. (L)	15 (4.7)	24 (7.5)	23 (7.2)	23 (7.2)	22 (6.9)	20 (6.3)	19 (6)	28 (8.8)	23 (7.2)	21 (6.6)	26 (8.2)	24 (7.5)
Subcort. (R)	16 (6.6)	20 (8.3)	18 (7.4)	16 (6.6)	13 (5.4)	18 (7.4)	17 (7)	23 (10)	20 (8.3)	22 (9.1)	21 (8.7)	14 (5.8)
Stem (L)	3 (3.1)	5 (5.1)	2 (2)	3 (3.1)	4 (4.1)	4 (4.1)	4 (4.1)	6 (6.1)	4 (4.1)	4 (4.1)	3 (3.1)	4 (4.1)
Stem (R)	4 (3.2)	7 (5.5)	5 (4)	5 (4)	5 (4)	7 (5.5)	5 (4)	8 (6.3)	7 (5.5)	5 (3.9)	5 (3.9)	8 (6.3)
Cerebel. (L)	41 (4.6)	69 (7.8)	50 (5.7)	52 (5.9)	47 (5.3)	56 (6.3)	53 (6)	75 (8.5)	61 (6.9)	65 (7.3)	48 (5.4)	56 (6.3)
Cerebel. (R)	65 (7.1)	87 (9.5)	71 (7.8)	78 (8.6)	66 (7.2)	72 (7.9)	66 (7.2)	88 (9.7)	83 (9.1)	67 (7.4)	78 (8.6)	73 (8)
Subject 2	**Rebuilding**	**City**	**Threat**	**Event**	**Collective**	**War**	**Deprivation**	**Experience**	**Goal**	**Space**	**Order**	**Try**
Cortex (L)	197 (5.6)	258 (7.4)	218 (6.2)	215 (6.1)	196 (5.6)	235 (6.7)	188 (5.4)	257 (7.3)	235 (6.7)	231 (6.6)	232 (6.6)	213 (6.1)
Cortex (R)	185 (5.2)	259 (7.3)	215 (6.1)	187 (5.3)	179 (5.1)	221 (6.3)	176 (5)	278 (7.9)	240 (6.8)	217 (6.1)	196 (5.5)	222 (6.3)
Subcort. (L)	15 (5.4)	19 (6.8)	14 (5)	16 (5.7)	17 (6.1)	13 (4.7)	18 (6.5)	18 (6.5)	18 (6.5)	20 (7.2)	17 (6.1)	18 (6.5)
Subcort. (R)	10 (5.3)	17 (9)	12 (6.4)	13 (6.9)	11 (5.8)	15 (7.9)	12 (6.4)	19 (10)	19 (10)	15 (7.9)	14 (7.4)	13 (6.9)
Stem (L)	15 (15.8)	16 (16.8)	13 (13.7)	13 (13.7)	16 (16.8)	15 (15.8)	10 (10.5)	20 (21)	18 (19)	12 (12.6)	12 (12.6)	12 (12.6)
Stem (R)	17 (10.7)	15 (9.4)	14 (8.8)	14 (8.8)	13 (8.2)	13 (8.2)	10 (6.3)	18 (11.3)	17 (10.7)	13 (8.2)	15 (9.4)	14 (8.8)
Cerebel. (L)	76 (7.4)	121 (11.8)	98 (9.5)	96 (9.3)	88 (8.5)	120 (11.7)	96 (9.3)	120 (11.7)	116 (11.3)	98 (9.5)	105 (10.2)	95 (9.2)
Cerebel. (R)	55 (5.8)	80 (8.5)	56 (6)	60 (6.4)	52 (5.5)	70 (7.4)	59 (6.3)	78 (8.3)	72 (7.7)	67 (7.1)	57 (6.1)	68 (7.2)

(continued)

Table 3. (*continued*)

Subject 3	**Rebuilding**	**City**	**Threat**	**Event**	**Collective**	**War**	**Deprivation**	**Experience**	**Goal**	**Space**	**Order**	**Try**
Cortex (L)	287 (6.5)	383 (8.6)	312 (7)	356 (8)	296 (6.7)	340 (7.7)	303 (6.8)	433 (9.7)	351 (7.9)	309 (7)	333 (7.5)	363 (8.2)
Cortex (R)	218 (5.9)	312 (8.4)	239 (6.4)	256 (6.9)	227 (6.1)	276 (7.4)	236 (6.4)	326 (8.8)	291 (7.8)	233 (6.3)	268 (7.2)	267 (7.2)
Subcort. (L)	20 (10.5)	19 (10)	14 (7.4)	19 (10)	14 (7.4)	23 (12.1)	12 (6.3)	29 (15.3)	21 (11)	18 (9.5)	16 (8.4)	17 (9)
Subcort. (R)	7 (4.7)	16 (10.7)	11 (7.4)	13 (8.7)	13 (8.7)	13 (8.7)	11 (7.4)	23 (15.4)	17 (11.4)	11 (7.4)	12 (8)	13 (8.7)
Stem (L)	4 (8.7)	7 (15.2)	6 (13)	5 (10.9)	4 (8.7)	7 (15.2)	2 (4.4)	10 (21.7)	5 (10.9)	4 (8.7)	5 (10.9)	6 (13)
Stem (R)	4 (7)	5 (8.8)	5 (8.8)	5 (8.8)	4 (7)	6 (10.5)	3 (5.3)	6 (10.5)	6 (10.5)	7 (12.3)	4 (7)	5 (8.8)
Cerebel. (L)	23 (6.6)	35 (10)	25 (7.1)	25 (7.1)	24 (6.9)	29 (8.3)	29 (8.3)	29 (8.3)	33 (9.4)	30 (8.6)	27 (7.7)	34 (9.7)
Cerebel. (R)	43 (5.2)	73 (8.8)	62 (7.5)	59 (7.1)	50 (6)	69 (8.4)	49 (5.9)	121 (14.7)	64 (7.8)	61 (7.4)	61 (7.4)	67 (8.1)
Subject 4	**Rebuilding**	**City**	**Threat**	**Event**	**Collective**	**War**	**Deprivation**	**Experience**	**Goal**	**Space**	**Order**	**Try**
Cortex (L)	211 (5.6)	299 (8)	237 (6.3)	251 (6.7)	219 (5.8)	260 (6.9)	219 (5.8)	289 (7.7)	288 (7.7)	258 (6.9)	250 (6.7)	264 (7)
Cortex (R)	190 (5.3)	275 (7.7)	213 (6)	217 (6.1)	214 (6)	217 (6.1)	196 (5.5)	272 (7.6)	235 (6.6)	219 (6.2)	227 (6.4)	216 (6.1)
Subcort. (L)	15 (5.7)	24 (9.1)	14 (5.3)	16 (6.1)	12 (4.6)	20 (7.6)	11 (4.2)	25 (9.5)	18 (6.9)	17 (6.5)	17 (6.5)	17 (6.5)
Subcort. (R)	12 (6.7)	13 (7.2)	11 (6.1)	12 (6.7)	9 (5)	11 (6.1)	14 (7.8)	13 (7.2)	13 (7.2)	12 (6.7)	14 (7.8)	13 (7.2)
Stem (L)	5 (6.2)	5 (6.2)	3 (3.7)	6 (7.4)	4 (4.9)	4 (4.9)	7 (8.6)	7 (8.6)	5 (6.2)	5 (6.2)	5 (6.2)	4 (4.9)
Stem (R)	18 (15.1)	18 (15.1)	18 (15.1)	18 (15.1)	16 (13.5)	16 (13.5)	14 (11.8)	19 (16)	18 (15.1)	20 (16.8)	18 (15.1)	20 (16.8)
Cerebel. (L)	52 (6.6)	71 (9)	56 (7.1)	54 (6.9)	58 (7.4)	61 (7.7)	49 (6.2)	72 (9.2)	59 (7.5)	48 (6.1)	57 (7.3)	52 (6.6)
Cerebel. (R)	46 (4.5)	52 (5.1)	43 (4.2)	50 (4.9)	48 (4.7)	47 (4.6)	40 (3.9)	60 (5.9)	54 (5.3)	48 (4.7)	49 (4.8)	51 (5)

(*continued*)

Table 3. (*continued*)

Subject 5	**Rebuilding**	**City**	**Threat**	**Event**	**Collective**	**War**	**Deprivation**	**Experience**	**Goal**	**Space**	**Order**	**Try**
Cortex (L)	197 (5.9)	269 (8.1)	212 (6.4)	231 (6.9)	214 (6.4)	218 (6.5)	220 (6.6)	270 (8.1)	253 (7.6)	224 (6.7)	239 (7.2)	218 (6.5)
Cortex (R)	255 (6.6)	355 (9.2)	262 (6.8)	291 (7.5)	285 (7.4)	300 (7.8)	267 (6.9)	325 (8.4)	309 (8)	286 (7.4)	283 (7.3)	290 (7.5)
Subcort. (L)	10 (3.5)	15 (5.3)	11 (3.9)	11 (3.9)	7 (2.5)	10 (3.5)	12 (4.2)	11 (3.9)	12 (4.2)	11 (3.9)	13 (4.6)	10 (3.5)
Subcort. (R)	8 (3.8)	15 (7.2)	10 (4.8)	8 (3.8)	10 (4.8)	9 (4.3)	11 (5.3)	13 (6.2)	11 (5.3)	17 (8.1)	8 (3.8)	10 (4.8)
Stem (L)	1 (1)	6 (5.9)	1 (1)	2 (2)	3 (3)	0 (0)	3 (3)	5 (5)	0 (0)	6 (6)	3 (3)	2 (2)
Stem (R)	3 (2)	4 (2.5)	3 (2)	2 (1.3)	4 (2.5)	4 (2.5)	2 (1.3)	4 (2.5)	4 (2.5)	3 (2)	3 (2)	5 (3.2)
Cerebel. (L)	27 (3.2)	41 (4.9)	31 (3.7)	29 (3.5)	32 (3.8)	27 (3.2)	29 (3.5)	33 (4)	28 (3.4)	32 (3.8)	29 (3.5)	27 (3.2)
Cerebel. (R)	20 (2.1)	37 (3.9)	26 (2.7)	28 (2.9)	23 (2.4)	22 (2.3)	32 (3.4)	37 (3.9)	37 (3.9)	33 (3.5)	32 (3.4)	20 (2.1)
Subject 6	**Rebuilding**	**City**	**Threat**	**Event**	**Collective**	**War**	**Deprivation**	**Experience**	**Goal**	**Space**	**Order**	**Try**
Cortex (L)	253 (7.3)	367 (10.5)	257 (7.4)	282 (8.1)	256 (7.4)	315 (9)	265 (7.6)	338 (9.7)	316 (9.1)	321 (9.2)	287 (8.2)	292 (8.4)
Cortex (R)	253 (5.8)	347 (7.9)	319 (7.3)	300 (6.9)	271 (6.2)	343 (7.8)	238 (5.4)	371 (8.5)	309 (7.1)	283 (6.5)	337 (7.7)	303 (6.9)
Subcort. (L)	16 (6)	22 (8.2)	19 (7.1)	20 (7.4)	15 (5.6)	16 (6)	17 (6.3)	23 (8.6)	17 (6.3)	18 (6.7)	17 (6.3)	18 (6.7)
Subcort. (R)	10 (5.4)	10 (5.4)	7 (3.8)	8 (4.3)	8 (4.3)	7 (3.8)	6 (3.2)	9 (4.9)	10 (5.4)	13 (7)	4 (2.2)	9 (4.9)
Stem (L)	7 (7.6)	10 (10.9)	8 (8.7)	8 (8.7)	6 (6.5)	8 (8.7)	8 (8.7)	11 (12)	8 (8.7)	7 (7.6)	7 (7.6)	6 (6.5)
Stem (R)	13 (13.1)	12 (12.1)	13 (13.1)	13 (13.1)	11 (11.1)	14 (14.1)	13 (13.1)	16 (16.2)	13 (13.1)	11 (11.1)	12 (12.1)	14 (14.1)
Cerebel. (L)	43 (6.8)	58 (9.1)	41 (6.5)	46 (7.2)	38 (6)	41 (6.5)	35 (5.5)	61 (9.6)	59 (9.3)	41 (6.5)	46 (7.2)	38 (6)
Cerebel. (R)	49 (7.8)	76 (12.1)	56 (8.9)	56 (8.9)	45 (7.2)	45 (7.2)	43 (6.8)	85 (13.5)	75 (11.9)	60 (9.5)	53 (8.4)	54 (8.6)

(*continued*)

Table 3. (*continued*)

Subject 7	**Rebuilding**	**City**	**Threat**	**Event**	**Collective**	**War**	**Deprivation**	**Experience**	**Goal**	**Space**	**Order**	**Try**
Cortex (L)	283 (7.2)	388 (9.8)	336 (8.5)	339 (8.6)	288 (7.3)	363 (9.2)	292 (7.4)	410 (10.4)	381 (9.7)	330 (8.4)	331 (8.4)	362 (9.2)
Cortex (R)	239 (6.9)	358 (10.4)	251 (7.3)	279 (8.1)	248 (7.2)	290 (8.4)	236 (6.9)	394 (11.5)	336 (9.8)	290 (8.4)	299 (8.7)	289 (8.4)
Subcort. (L)	10 (4.1)	16 (6.6)	14 (5.8)	15 (6.2)	9 (3.7)	12 (4.9)	16 (6.6)	13 (5.4)	16 (6.6)	9 (3.7)	15 (6.2)	13 (5.4)
Subcort. (R)	16 (8.7)	19 (10.3)	15 (8.1)	17 (9.2)	13 (7)	20 (10.8)	15 (8.1)	24 (13)	20 (10.8)	13 (7)	21 (11.4)	14 (7.6)
Stem (L)	2 (2.1)	8 (8.4)	10 (10.5)	6 (6.3)	5 (5.3)	6 (6.3)	7 (7.4)	8 (8.4)	5 (5.3)	8 (8.4)	11 (11.6)	8 (8.4)
Stem (R)	4 (2.9)	6 (4.4)	6 (4.4)	5 (3.7)	8 (5.9)	5 (3.7)	3 (2.2)	8 (5.9)	6 (4.4)	4 (2.9)	7 (5.2)	6 (4.4)
Cerebel. (L)	24 (2.8)	37 (4.4)	22 (2.6)	33 (3.9)	21 (2.5)	25 (3)	31 (3.7)	34 (4)	28 (3.3)	24 (2.8)	31 (3.7)	26 (3.1)
Cerebel. (R)	48 (5.6)	62 (7.4)	56 (6.7)	56 (6.7)	46 (5.5)	53 (6.3)	50 (6)	77 (9.2)	60 (7.2)	47 (5.6)	65 (7.8)	40 (4.8)

References

1. Ardila, A.: A proposed neurological interpretation of language evolution. Behav. Neurol. **2015**, 872487 (2015). https://doi.org/10.1155/2015/872487
2. Luria, A.R.: Language and brain: towards the basic problems of neurolinguistics. Brain Lang. **1**, 1–14 (1974). https://doi.org/10.1016/0093-934X(74)90022-4
3. Luria, A.R.: Basic Problems in Neurolinguistics. Mouton, The Hague (1976)
4. Grabowski, T.J., Damasio, H., Tranel, D., Ponto, L.L.B., Hichwa, R.D., Damasio, A.R.: A role for left temporal pole in the retrieval of words for unique entities. Hum. Brain. Mapp. **13**, 199–212 (2001). https://doi.org/10.1002/hbm.1033
5. Damasio, H., Tranel, D., Grabowski, T., Adolphs, R., Damasio, A.: Neural systems behind word and concept retrieval. Cognition **92**, 179–229 (2004). https://doi.org/10.1016/j.cognition.2002.07.001
6. Binder, J.R., Desai, R.H., Graves, W.W., Conant, L.L.: Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. Cereb. Cortex **19**, 2767–2796 (2009). https://doi.org/10.1093/cercor/bhp055
7. Assaf, M., Calhoun, V.D., Kuzu, C.H., Kraut, M.A., Rivkin, P.R., Hart, J., Pearlson, G.D.: Neural correlates of the object-recall process in semantic memory. Psychiatry Res. Neuroimaging **147**, 115–126 (2006). https://doi.org/10.1016/j.pscychresns.2006.01.002
8. Huth, A.G., de Heer, W.A., Griffiths, T.L., Theunissen, F.E., Gallant, J.L.: Natural speech reveals the semantic maps that tile human cerebral cortex. Nature **532**, 453–458 (2016). https://doi.org/10.1038/nature17637
9. Caramazza, A., Shelton, J.R.: Domain-specific knowledge systems in the brain the animate-inanimate distinction. J. Cogn. Neurosci. **10**, 1–34 (1998). https://doi.org/10.1162/089892998563752
10. Mummery, C.J., Patterson, K., Hodges, J.R., Price, C.J.: Functional neuroanatomy of the semantic system: divisible by what? J. Cogn. Neurosci. **10**, 766–777 (1998). https://doi.org/10.1162/089892998563059
11. Velichkovsky, B.M., Zaidelman, L.Y., Kotov, A.A., Nosovets, Z.A., Ushakov, V.L., Zabotkina, V.I.: The nature of neurosemantic representation: Stimuli, meaning, and personal sense. Quest. Psychol. (Вопросы психоло гии) **66**(3), 132–146 (2020). (in Russian)
12. Velichkovsky, B.M., Zabotkina, V.I., Nosovets, Z.A., Kotov, A.A., Zaidelman, L.Y., Nosovets, Z.A., Kartashov, S.I., Korosteleva, A.N., Malakhov, D.G., Orlov, V.A., Zinina, A.A., Goldberg, E., Ushakov, V.L.: Towards semantic brain mapping methodology based on a multidimensional markup of continuous Russian-language texts. STM **12**(2), 14–25 (2020). https://doi.org/10.17691/stm2020.12.2.02
13. Zaidelman, L.Y., Nosovets, Z.A., Kotov, A.A., Ushakov, V.L., Zabotkina, V.I., Velichkovsky, B.M.: Russian-language neurosemantics: clusterizing of words meaning and sense from the oral narratives. Cogn. Syst. Res. **67**, 60–65 (2021)
14. Velichkovsky, B.M., Kotov, A.A., Zabotkina, V.I., Nosovets, Z.A., Goldberg, E., Zaidelman, L.Y.: Heteroglossia in Neurosemantics: The Case of a Word Cluster with Mentalist Content. In: Velichkovsky, B., et al. (eds.) Advances in Cognitive Research, Artificial Intelligence and Neuroinformatics. Advances in Intelligent Systems and Computing, vol. 1358, pp. 307–318 (2021)
15. Kutuzov A., Kuzmenko E.: WebVectors: a toolkit for building web interfaces for semantic vector models. In: Ignatov, D., et al. (ed.) AIST 2016. CCIS, vol. 661, pp. 155–161. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-52920-2
16. Lyashevskaya, O.N., Sharov S.A.: Frequency Dictionary of the Modern Russian Language (The Russian National Corpus). Azbukovnik (2009)
17. SPM8 Software. https://www.fil.ion.ucl.ac.uk/spm/software/spm8

18. Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., Mazoyer, B., Joliot, M.: Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. Neuroimage **15**, 273–289 (2002). https://doi.org/10.1006/nimg.2001.0978
19. Price, C.J.: The anatomy of language: a review of 100 fMRI studies published in 2009. Ann. N.Y. Acad. Sci. **1191**, 62–88 (2010). https://doi.org/10.1111/j.1749-6632.2010.05444.x
20. Price, C.J.: A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. Neuroimage **62**, 816–847 (2012). https://doi.org/10.1016/j.neuroimage.2012.04.062
21. Mariën, P., Engelborghs, S., Fabbro, F., De Deyn, P.P.: The lateralized linguistic cerebellum: a review and a new hypothesis. Brain Lang. **79**, 580–600 (2001). https://doi.org/10.1006/brln.2001.2569
22. Argyropoulos, G.P.D.: The cerebellum, internal models and prediction in 'non-motor' aspects of language: a critical review. Brain Lang. **161**, 4–17 (2016). https://doi.org/10.1016/j.bandl.2015.08.003
23. van den Hurka, J., Baelena, M.V., de Beecka, H.P.O.: Development of visual category selectivity in ventral visual cortex does not require visual experience. PNAS **114**, 4501–4510 (2017). https://doi.org/10.1073/pnas.1612862114
24. Jackendoff, R.: Meaning and the Lexicon. Oxford University Press, Oxford, UK (2010)
25. Jackendoff, R.. : Defence of theory. Cogn. Sci. **41**(2), 185–212 (2017). https://doi.org/10.1111/cogs.12324
26. Tononi, G., Boly, M., Massimini, M., Koch, C.: Integrated information theory: from consciousness to its physical substrate. Nat. Rev. Neurosci. **17**, 450–461 (2016). https://doi.org/10.1038/nrn.2016.44
27. Dehghani, M., Boghrati, R., Man, K., Hoover, J., Gimbel, S., Vaswani, A., Zevin, J., Immordino-Yang, M., Gordon, A., Damasio, A., Kaplan, J.: Decoding the neural representation of story meanings across languages. Hum. Brain. Mapp. **38**, 6096–6106 (2017). https://doi.org/10.1002/hbm.23814

Heteroglossia in Neurosemantics: The Case of a Word Cluster with Mentalist Content

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Abstract. In this study, we used neurosemantic analysis to identify the brain representation of words in Russian-language spoken narratives. 25 participants listened to five stories, first person narratives of the same author describing threatening episodes of recent history. Their brain BOLD (blood-oxygen-level dependent) activation was registered by a 3T MRT (magnetic resonance tomograph). We selected seven subjects, who were the best in terms of their engagement, memory for details of narratives and parameters of brain reactions, for further PCA (Principal Component Analysis) analysis. 12 lexical clusters were found with similar brain activation patterns and coherent semantics, which ranged from time-and-space concepts to those of human actions and mental states. A new cluster "author" emerged from the "mentalist" cluster 8, when we extended the number of clusters from 13 to 16. The words in this new cluster described –quite accurately– the narratives author's profession and attitudes towards life. While most of the clusters demonstrated a small left-hemispheric lateralization, involvement of the right hemisphere was apparent in case of cluster "author". Our results support the view of non-modular and widely distributed nature of semantic representations. These results also demonstrated possible relevance of the ideas in the works of Vladimir Propp and Mikhail Bakhtin to modern neuroimaging of narrated stories.

Keywords: Narrative · Lexical semantics · Functional magnetic resonance imaging (fMRI) · Brain lateralization · Cluster analysis · Dialogic imagination

1 Introduction

Sporadic reports about semantic selectivity of some brain areas have existed for decades, based on clinical observations [1, 2]. Experimental study of the neural basis of semantics was made possible by the advent of neuroimaging. At early stages of neuroimaging research, the dominant methodology was based on cognitive subtraction methodology, where the data of the control (or baseline) condition is subtracted from that of the experimental condition. As the control condition, one usually considers another cognitive task, similar to the experimental task in every respect except for the variable of immediate

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interest or the resting state – a state in which brain presumably stays at the minimum of its energy and cognitive facilities. However, this last presumption turned out to be wrong: rest leads to a significant rise of activity in some of the brain's structures called the Default Mode Network (DMN), which structures seem to be crucial for our thinking and inner life [3, 4]. The cognitive subtraction methodology is mostly appropriate in studies of brain activity if one deals with examples of modular architectures. In cases of higher symbolic processes, as for example in neurosemantics, the assumption of modular organization seems doubtful [5].

The question about general distribution of language semantics in the human brain was formulated only relatively recently, in the work of Huth, De Heer, Griffiths, Theunissen, Gallant [6]. They have implemented a new paradigm in investigation of meaning and in so doing substantially enriched the old psycholinguistic approach that was initiated in neobehaviorism and expanded in psychosemantics. Huth and colleagues studied brain representation of the English language with the help of functional magnetic resonance imaging (fMRI) in seven participants in response to orally presented narratives. The authors reported two main results. Firstly, brain mapping of natural language categories on an idealized two-dimensional surface of the cortex showed a similarity to the outlines of the DMN, characteristic of the "resting" state. Secondly, these representations demonstrated broad distribution across the brain with no obvious signs of the initially expected left hemispheric asymmetry.

In a recent paper, we reported neurosemantic mapping on the material of Russian-language texts [7]. In the current work, we examine brain laterality of neurosemantic representations from a thematic perspective. In a difference to other publications on this topic, we also for the first time present data, which connects this line of modern experimental research in cognitive neuroscience with the classical tradition of literary studies by Propp [8] and Bakhtin [9].

2 Method

2.1 Participants, Ethical Approval, and Stimulus Material

25 subjects (17 females; mean age of 22 years 7 months; 23 subjects reported to be right-handed) participated in the experiment. All subjects were native speakers of Russian. As students at the State University for the Humanities they were nonpaid for their participation. Informed consent was obtained from each subject prior to the experiment. Ethical approval for this study was provided by the local Ethics Committee of the National Research Center "Kurchatov Institute" (Protocol No.10 from the 1st of August 2018). We asked subjects to maintain wakefulness with closed eyes during the study.

Stimulus material consisted of five original texts in Russian composed by one of the authors of this article. The texts had an autobiographical character (1500 word-forms). Each text was a story addressing significant social problems of contemporary life. To produce the stimuli material for oral presentation, texts were recorded by a professional broadcaster. We expected that the emotional first-person narratives, as well as the addressed topics would ensure interest and involvement of at least a subgroup of subjects. Cognitive involvement was controlled by a questionnaire, subsequent memory test, and brain imaging. The order of stories presentation was randomized. In contrast to the work by Huth et al. [6]) and typical neuroimaging experiments, every stimulus narrative was presented only once in order to prevent semantic saturation of the material and overall habituation.

2.2 Linguistic Markup

The semantics of each word was represented as a 997-dimensional vector. These dimensions (features) were numeric estimations of similarity of a stimulus word meaning to those of 997 most frequent Russian nouns and verbs [10], evaluated as cosine distances between their word2vec vectors. The particular word2vec model was created within the frames of RusVectōrēs project and trained on the National Russian Corpus and the Russian segment of Wikipedia [11]. Temporal allocations of the words in the audio-presentations were annotated in ELAN speech annotation software[1] and double-checked by experts.

2.3 Brain Imaging

We used a 3T SIEMENS Magnetom Verio MRI scanner where BOLD (blood-oxygen-level dependent) signal was continuously registered. The scanning process had two stages: capturing high-resolution anatomical data and recording functional data by a parallel scanning protocol with ultrafast EPI-sequence ($TR = 1100$ ms, $TE = 33$ ms, 56 slices, slice thickness $-$ 2 mm, spatial resolution in each slice $-$ 2×2 mm). Professional audio-equipment was used to represent audio-stimuli and to suppress the noise of tomography.

2.4 Data Processing

We evaluated the influence of each of 997 features on each of 103,163 voxels of individual brains' grey matter over the whole time of texts presentation divided into 490 epochs. This allowed us to transform the matrix of word feature vectors in time into voxel activity vectors in time for every subject. We then selected seven subjects (all right-handed; mean age 23 years 8 months; five females) maximally engaged in listening and comprehension of the texts according to a questionnaire, memory performance, and imaging data such as activation of auditory areas as well as hippocampi and amygdalae related to memory functioning and emotion.

Further, we performed principal component analysis (PCA) on the weight matrix [Voxels X Features]. The first four components of the PCA scores matrix were used as respective spatial dimensions for projecting stimulus words. We did this projecting by multiplying each word vector by the feature vector in the PCA space. We chose words in this space implying that their significance was the distance from the center of the word cloud. We randomly selected 80% of the words and found their convex hull in this space. Repeating this procedure 1000 times, we constructed a set of 163 words that appeared on the hull at least once. We proceeded with hierarchical agglomerative clustering (single-linkage technique) on words from this set. After studying the tree diagram, we have

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[1] See: https://archive.mpi.nl/tla/elan

selected a cutoff threshold (the maximum distance for objects located within the same cluster) equal to 1. Thus, 12 lexical clusters were formed with cardinality from 5 to 23 words. To check for stability of this clustering, we also performed the division of the relevant word set on 13, 14, 15, and 16 clusters.

3 Results

While four axes of PCA, according to Huth et al. [6], were difficult to interpret, the 12 basic clusters from the neurosemanic analysis permitted a relatively straightforward interpretation [12]. For example, clusters 2, 9 and 10 were connected with "space and time" of actions described in the narratives, while clusters 1, 3 and 11 – with topics of threats, deprivation, and overt conflicts (war), respectively. Lexical items with modality of intention such as *have to do*, action optionality and goals were concentrated within cluster 5. Notions overtly related to the subjective experience such as *conscious, intelligence, feeling*, were mapped by the cluster analysis of word semantics and brain activity to the cluster 8, which we called "experience". This selection of 12 initial clusters was confirmed by a *post hoc* Pearson correlation of the loci of their brain activation. These correlations were highly significant and varied with precision of only one voxel in every direction of MNI (Montreal Institute of Neurology) coordinates in pairwise intersubjective comparisons from 62.4 to 78.3% (average 74.4%).

With respect to the issue of brain lateralization, the "mentalist" cluster 8 was the only one that demonstrated on average slight right-hemispheric localization in the number of significantly activated voxels. In all other clusters, brain localization had a left-hemispheric bias or was approximately symmetrical (see Table 1). A three-way ANOVA showed a significant dependency of the number of active voxels from each single factor of subject, hemisphere, and cluster ($p < 0.02$ and better). This analysis proved a dominant left-hemispheric asymmetry for the majority of clusters in the number of activated voxels. It could also be easily seen from mean data in Table 1, where paired mean measurement data differed significantly according to Wilcoxon Rank Sum test ($n = 12$, $W = 2$, $p < 0.01$). All two-ways interactions of ANOVA were highly significant ($p < 0.01$) as well, with exception of hemisphere X cluster interaction, which was approaching significance ($p < 0.06$). Three-way interaction was non-significant.

In additional clustering into 13, 14, 15, and 16 clusters, the initial distribution of words demonstrated an overall stability. However, the mentalist cluster 8 "experience" was divided into two clusters we called cluster 13 "author" and 14 "resources". The first included the following words: *life, knowledge, study, material, world, scientific, neuropsychologist, simultaneously, permanently, work*. The second cluster consisted of such words as *elderly. Robust, illness, clinical, brain, conscious, food, reaction, child, conscious, feeling, emotion.* This division remained in the same lexical composition in all additional steps of cluster analysis, in divisions from 14 to 16 clusters. We analyzed the brain lateralization of active voxels representing these new clusters in two different ways shown in Table 2. In the first two columns of the table, we present the same type of data as in Table 1. In the following three columns, we present data from a more rigorous analysis. First, we show here the number of voxels uniquely belonging to either "author" or "resources". In the last column of the Table 2, we present the number of voxels, shared

Table 1. Number of active voxels for 12 initial clusters depending on subjects and hemisphere

Subj	Hemi	Rebuilding	City	Threat	Event	Collective	War	Deprivation	Experience	Goal	Space	Order	Try
1	Left	290	458	345	359	341	451	310	469	456	346	383	386
	Right	326	485	396	387	381	478	328	512	520	345	425	428
2	Left	313	452	396	374	364	496	321	479	478	365	416	401
	Right	275	399	336	303	296	392	266	444	425	319	322	367
3	Left	350	492	432	445	434	539	361	589	557	377	454	491
	Right	283	449	375	380	361	491	310	546	491	325	400	424
4	Left	298	446	362	368	365	462	305	472	474	349	382	412
	Right	271	388	325	320	325	398	269	419	407	307	344	346
5	Left	238	360	283	280	290	369	266	359	362	276	316	306
	Right	291	434	335	346	360	449	315	424	451	343	354	374
6	Left	322	502	374	393	369	483	329	495	501	393	404	429
	Right	329	493	464	404	409	572	303	551	516	374	449	430
7	Left	332	487	433	442	398	563	361	560	555	381	458	481
	Right	309	478	383	380	384	491	306	558	522	358	443	402
Mean	Left	306	457	375	380	366	480	322	489	483	355	402	415
Mean	Right	298	447	373	360	359	467	300	493	476	339	391	396

by both these clusters. Thus, the trend towards right hemisphere involvement was present only in cluster “author”.

Table 2. Number of active voxels as well as unique and common voxels for two clusters derived from the cluster 8 “experience” depending on subject and hemisphere (see text for explanation).

Subj	Hemi	Author	Resource	Author unique	Resource unique	Common
1	Left	387	347	122	82	265
	Right	442	394	118	88	306
2	Left	398	383	96	81	302
	Right	367	348	96	77	271
3	Left	486	434	155	103	331
	Right	448	382	164	98	284
4	Left	399	446	109	73	290
	Right	346	388	103	73	243
5	Left	299	363	84	60	215
	Right	363	316	88	61	275
6	Left	425	275	123	70	302
	Right	451	336	140	100	311
7	Left	430	448	112	130	318
	Right	451	414	144	107	307
Mean	Left	403	374	114	86	280
Mean	Right	407	371	122	86	285

In a voxel-wise analysis, we also attempted to find statistical significance for activation of voxels uniquely related to clusters “author” or “resources”. Few, from 1 (subject 2) to 19 (subject 6), such voxels could be discovered ($p < 0.05$, uncorrected), but these data did not survive a stringent control with appropriate statistical correction for multiple comparisons. Obviously, a more holistic approach is needed in neurosemantic studies. To this end, in visualization of data, we smoothed each of the voxels unique to the cluster "author", as well as the common voxels across clusters. We used the box kernel of the size 3 because the significant voxel correlation among subjects was achieved with the precision of one neighboring voxel for each coordinate axis in MNI space. Then we summed the voxel matrices of all subjects into one. If the threshold number 7 was achieved for a voxel, it meant that all subjects had this voxel somewhere within a cube with an edge of 3 voxels. We rejected voxels with the threshold number less than 7 and thus came up with a generalized visualisation for all subjects with the precision of a 3-by-3-by-3 voxel cube. The resulting representations are shown in Fig. 1 for the cluster "author” and in Fig. 2 for the cluster "resources". In these figures, common voxels are colored in red and unique voxels in yellow.

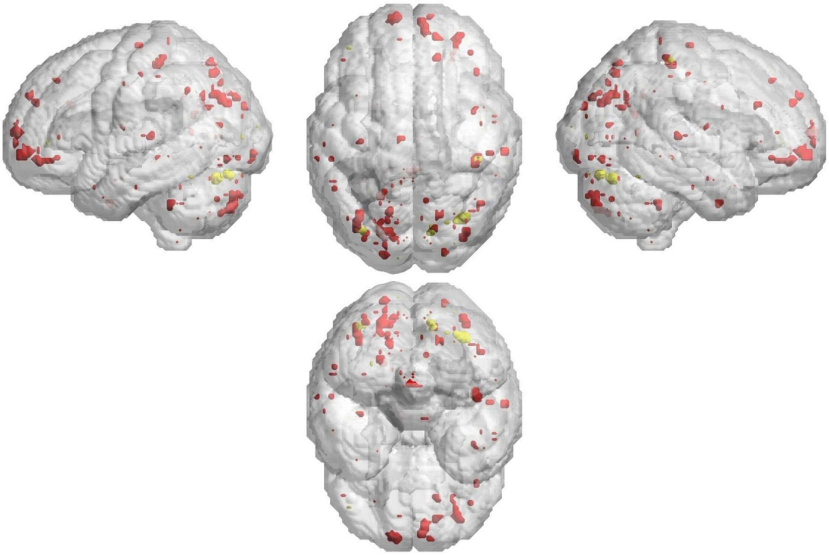

Fig. 1. Voxels representing cluster "author" (see text for details).

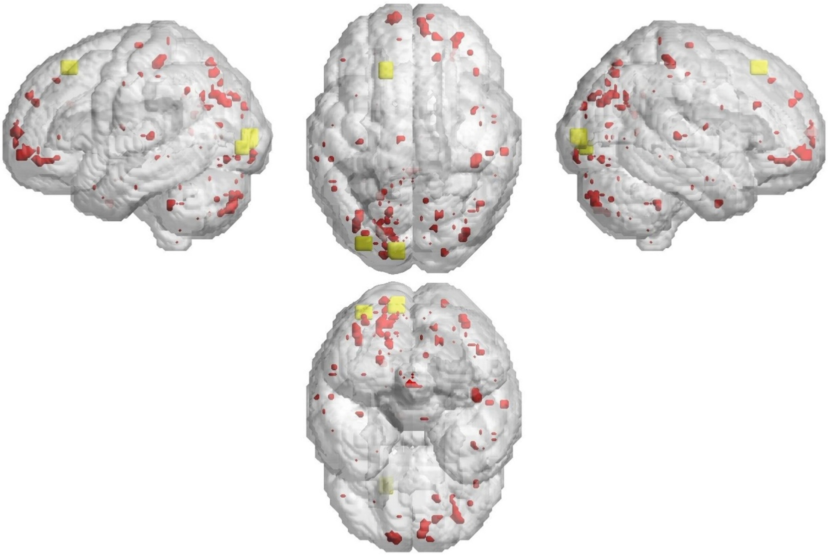

Fig. 2. Voxels representing cluster "resources" (see text for details).

Due to a high proportion of common voxels, the two figures look similar. Their dominant feature is the activity in the right prefrontal region and around the left parieto-occipital junction. Our general impression from the visualization of the data is that unique voxels of the cluster "author" concentrated in the prefrontal and parietal-occipital regions of the brain, while for the cluster “resources” in the posterior and lateral aspects of the left cortex. No activation was apparent in the temporal lobes, in contrast with the majority of initial clusters. In both cases, traces of activation were found across the whole cortex as well as in the cerebellum and subcortical regions.

4 Discussion

In the results section, we initially noted that PCA dimensions are notoriously difficult for interpretation. However, in our case they can be related, for example, to the art of timing and evolution of events. The first dimension, which had the heaviest loading, seems to differentiate events occurring here and now, “in the moment,” from those characterized by an extended and continuous unfolding. Trying to find the best word for naming this major dimension of PCA, we discovered the notion of “chronotope” proposed by Mikhail Bakhtin [9]. In a speculative vein, tree other dimensions of PCA were then interpreted as appropriate complexity vs. Relaxed simplification, some focal part vs. Undifferentiated whole, and, finally, as hints triggering socially important recollections vs. Something of complete irrelevance. Perhaps, this relative transparence of the PCA dimensions is one of specificities of our stimulus material and subjects in contrast to that of Huth et al. [6] who have no coherent stories by the same author and did not select the engaged subjects from a larger group.

The most important result of our study is the demonstration that maps of brain semantic activation strongly follow the principle of conceptual similarity, reminiscent of Donald Hebb’s famous decoding of abbreviation CNS as “Conceptual Nervous System”. The 12 basic clusters build up a relatively closed system of reference resembling the ‘narratemes’ system in organization of fairytales known from the works of Vladimir Propp and his followers [8, 13]. Propp has deconstructed the storylines of Russian fairytales and suggested a list of basic units to describe their plot structure. The units (like for example, “prohibition → breach of prohibition by protagonist”) suggested the conceptualization for any fairytale situation, regardless of the particular details or actors. In this sense, the allocated clusters may offer a similar conceptualization scheme for situations in the presented personal narratives.

This central role of conceptual similarity is obvious from studies on memory illusions [14, 15], and from our results. It even allowed us to compute possible brain localization for representation of words, which were not explicitly presented as stimuli in the current experiment [16]. Interestingly some words from the set of 997 feature words – such as *fame*, *bank*, *name*, and *card* – could not be processed in this way because their similarity to the centers of 12 referent clusters was too low by the criteria of closeness to the center of at least one of them. In our view, the explanation is their minimal or altogether absent role in thematic set of our limited pool of narrated stories.

Of particular interest is cluster 13. We called it “author” as the words in this cluster described the author, his profession, and attitudes toward life more precisely than it was done in any of the separate stories. One of the hallmarks of the Russian literary tradition is the Bakhtin’s ideas about dialogical imagination and heteroglossia in understanding a novel. To have a dialogue one needs at least one other person and, according to Bakhtin, such an additional voice belongs to the author of the novel who, somehow, has to be present in the mind of the reader/ listener [9]. Neurosemantic ‘envelope’ of the author’s model is the cluster 8, with its reference to factors of mentality. Secondly, the representation is special in purely neurophysiological sense of the word. Most of the clusters dealing with objective and even subjective (“goal”) settings of narrated stories show in our study a left-sided lateralization. This is not surprising as language perception and production are traditionally attributed – at least in the right-handed persons – to the left hemisphere [1, 17]. More central is the fact that the left-hemispheric lateralization is not apparent in the initial cluster 8; and that in further clustering the new cluster 13 demonstrated, in the group data, up to 58% of its uniquely activated voxels as localized within the right hemisphere.

As a rule, the theories of semantic hemispheric differences stem from clinical observations and studies. For example, one of them, the ‘hub-and-spoke’ model, is the authoritative model of conceptual knowledge, which is based on data gathered in patients with semantic dementia. In its classical version [18], this model stipulated that conceptual representations are stored in a unitary “amodal” format in the left and right anterior temporal lobes (ATL), because in semantic dementia the disorder cuts across modalities and categories. Partial specialization occurs across the ATL hub as a consequence of graded differential connectivity across the region. The role of the left hemisphere was repeatedly emphasized due to connectivity with the left-lateralized speech output module in prefrontal and motor cortices [17, 19]. At the same time, the idea placing conceptual representations in such a focal area can easily be wrong since this region is not even a part of heteromodal association cortex.

Thus, the novel results of our study are the merely symmetrical localization of activity in case of clusters “experience” and “threat” in the initial set of 12 clusters and also an increased involvement of the right hemisphere activity in case of newly discovered cluster “author”. This cannot be explained simply by the fact that these clusters refer to mental states because clusters “deprivation” and “goal” can be considered “mental” as well. However, both latter clusters demonstrated a clear left-hemispheric bias. The pattern is reminiscent of the results of levels-of-processing studies where semantic encoding was compared with self-and-other referential effects on memory performance [20] in a positron emission tomography study [21] showed a prefrontal localization in the left hemisphere for semantic categorization and a symmetrical localization or a trend towards the frontopolar right hemisphere in self-reference. Perhaps, the crucial difference here seems to be the reflective consciousness in perceiving and understanding subject-matter of narratives and personality of their author [22].

This is especially critical in building the model of author of narrated stories represented neurosemantically by cluster 13. Here and in case of the cluster “resources”, we noted activation in the right prefrontal and left parieto-occipital regions. This diagonal of brain organization is known as Yakovlevian Torque and its frontal components are characterized by a particularly rapid development in anthropogenesis. For example, frontal structures anterior to the right Sylvian fissure are anatomically ‘torqued forward’ relative to their counterparts on the left. Structures on the left pole of occipital lobe may be involved in the processes of imagination [23, 24]. First described after WW2, Yakovlevian Torque phenomenon is supported by modern ontogenetic [25] and paleoneurological findings [26]. With respect to underlying architecture, we encounter in such studies widely distributed networks not limited to the Default Mode Network or some parts of neocortex such as ATL. In fact, temporal lobes were not specifically involved in representing the clusters “author” and “resources”. The existence of such non-modular architectures in the human brain was predicted already by Fodor as architecture of higher-order isotropic systems [27] and by other authors [5, 28, 29]. Non-modularity seems to be a common case in experiments on semantics of language. In this, our findings were broadly consistent with those reported for the English language, which points to the universality of the factors governing brain’s lexical representations of narrated stories [6, 30].

5 Conclusion

This is the first study which demonstrated the existence of neurosemantic cluster “author”, which was predicted in the literary studies by Mikhail Bakhtin [9] as a necessary element in understanding novels. This authentic new result was only possible when we used in the current experiment meaningful stories written by the same author and not fragments of different texts or even narratives, which could not be attributed to a single author [6, 7]. In contrast to typical studies in cognitive neuroscience, we also selected a small number of engaged participants and presented these stories only once to prevent effects of semantic saturation and overall habituating.

On the whole, our results support the view of conceptual similarity as a defining factor in brain representation of lexical semantics. By taking into account the factor of conceptual similarity of a word to 12 reference clusters, we were able to predict localization of words not explicitly presented as stimuli [16]. Like in an analogous study of the English language [6], the findings point to a non-modular and widely distributed nature of semantic representations, which extended in our case beyond structures of neocortex and DMN. They also demonstrate that the right hemisphere can be substantially involved in representation of the “mentalist” component of conceptual structures including the newly discovered neurosemantic cluster related to identity of the author of narratives.

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References

1. Luria, A.R.: Basic problems in neurolinguistics. Mouton, The Hague (1976)
2. Warrington, E.K.: The selective impairment of semantic memory. Q. J. Exp. Psychol. **27**(4), 635–657 (1975)
3. Raichle, M.E., MacLeod, A.M., Snyder, A.Z., Powers, W.J., Gusnard, D.A., Shulman, G.L.: A default mode of brain function. Proc. Natl. Acad. Sci. **98**(2), 676–682 (2001)
4. Raichle, M.E.: The brain’s default mode network. Annu. Rev. Neurosci. **38**, 433–447 (2015)
5. Goldberg, E.: The rise and fall of modular orthodoxy. J. Clin. Exp. Neuropsychol. **17**(2), 93–208 (1995)

6. Huth, A.G., De Heer, W.A., Griffiths, T.L., Theunissen, F.E., Gallant, J.L.: Natural speech reveals the semantic maps that tile human cerebral cortex. Nature **532**(7600), 453–458 (2016). https://doi.org/10.1038/nature17637
7. Velichkovsky, B.M., Zabotkina, V.I., Nosovets, Z.A., Kotov, A.A., Zaidelman, L.Y., Kartashov, S.I., Korosteleva, A.N., Malakhov, D.G., Orlov, V.A., Zinina, A.A., Goldberg, E., Ushakov, V.L.: Towards semantic brain mapping methodology based on a multidimensional markup of continuous Russian-language texts. STM **12**(2), 14–25 (2020). https://doi.org/10.17691/stm2020.12.2.02
8. Propp, V.: Morphology of the Folktale. In: Laurence Scott (ed.). 2nd ed. University of Texas Press, Austin (1968/1927)
9. Bakhtin, M. M.: The Dialogic Imagination: Four Essays. In: Michael Holquist (ed.). University of Texas Press, Austin and London (1981/1957)
10. Lyashevskaya, O., Sharov, S.: Frequency Dictionary of the Modern Russian Language. Azbukovnik, Moscow (2009)
11. Rusvectores, webpage: https://rusvectores.org/
12. Zaidelman, L.Y., Nosovets, Z.A., Kotov, A.A., Ushakov, V.L., Zabotkina, V.I., Velichkovsky, B.M.: Russian-language neurosemantics: clustering of word meaning and sense from the oral narratives. Cogn. Syst. Res. **67**, 60–65 (2021). https://doi.org/10.1016/j.cogsys.2021.01.001
13. Bischof, N.: Das Kraftfeld der Mythen. Piper, München (1996)
14. Roediger, H.L.: Retrieval Experience: A New Arena of Psychological Study. In: Challis, B.H., Velichkovsky, B.M. (eds.) Stratification of consciousness and cognition, pp. 229–235. Amsterdam/Philadelphiam, John Benjamins (1999)
15. Roediger, H.L., Wertsch, J.: Past imperfect. New Sci. **228**(3043), 30–31 (2015)
16. Threat corpus, webpage: https://threatcorpus.org/brainmapping
17. Hoffman, P., Lambon, R.: From percept to concept in the ventral temporal lobes: graded hemispheric specialization based on stimulus and task. Cortex **101**, 107–118 (2018). https://doi.org/10.1016/j.cortex.2018.01.015
18. Patterson, K., Nestor, P.J., Rogers, T.T.: Where do you know what you know? The representation of semantic knowledge in the human brain. Nat. Rev. Neurosci. **8**(12), 976–987 (2007). https://doi.org/10.1038/nrn2277
19. Gainotti, G.: The contribution of language to the right-hemisphere conceptual representations: A selective survey. J. Clin. Exp. Neuropsychol. **35**(6), 563–572 (2013). https://doi.org/10.1080/13803395.2013.798399
20. Challis, B.H., Velichkovsky, B.M., Craik, F.I.M.: Levels-of-processing effects on a variety of memory tasks: new findings and theoretical implications. Conscious. Cogn. **5**(1/2), 142–164 (1996)
21. Craik, F.I.M., Moroz, T.M., Moscovitch, M., Stuss, D.T., Winocur, G., Tulving, E., Kapur, S.: In search of the Self: A Positron Emission Tomography study. Psychol. Sci. **10**(1), 26–34 (1999). https://doi.org/10.1111/1467-9280.00102
22. Velichkovsky, B.M., Krotkova, O.A., Kotov, A.A., Orlov, V.A., Verkhlyutov, V.M., Ushakov, V.L., Sharaev, M.G.: Consciousness in a multilevel architecture: Evidence from the right side of the brain. Conscious. Cogn. **64**, 227–239 (2018)
23. Abraham, A., von Cramon, D.Y., Schubotz, R.I.: Meeting George Bush versus meeting Cinderella: The neural response when telling apart what is real from what is fictional in the context of our reality. J. Cogn. Neurosci. **20**(6), 965–976 (2008)
24. Vyshedskiy, A.: Neuroscience of imagination and implications for human evolution. Curr. Neurobiol. **10**(2), 89–109 (2019)
25. Hrvoj-Mihic, B., Bienvenu, T., Stefanacci, L., Muotri, A.R., Semendeferi, K.: Evolution, development, and plasticity of the human brain: From molecules to bones. Front. Hum. Neurosci. **7**, 707 (2013). https://doi.org/10.3389/fnhum.2013.00707

26. Toga, A.W., Thompson, P.M.: Mapping brain asymmetry. Nat. Rev. Neurosci. **4**(1), 37–48 (2003). https://doi.org/10.1038/nrn1009
27. Fodor, J.A.: Modularity of mind. MIT Press, Cambridge (1983)
28. Goldberg, E.: Gradiental approach to neocortical functional organization. J. Clin. Exp. Neuropsychol. **11**(4), 517–589 (1989). https://doi.org/10.1080/01688638908400909
29. Velichkovsky, B.M.: Modularity of cognitive organization: why it is so appealing and why it is wrong. In: Callebaut, W., Rasskin-Gutman, D. (eds.) Modularity: Understanding the Development and Evolution of Natural Complex Systems, pp. 335–356. MIT Press, Cambridge (2005)
30. Dehghani, M., Boghrati, R., Man, K., Hoover, J., Gimbel, S.I., Vaswani, A., Kaplan, J.T.: Decoding the neural representation of story meanings across languages. Hum. Brain Mapp. **38**(12), 6096–6106 (2017). https://doi.org/10.1002/hbm.2381400:00-00

Reconstruction of Words, Syllables, and Phonemes of Internal Speech by EEG Activity

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Abstract. In this article, the process of internal pronunciation (covert speech) is associated with the internal speech through an intellectual process such as silent reading. The objective of the research is to compare the EP of visual and auditory perception and internal pronunciation of phonemes and syllables; to classify phonemes, words and syllables from covert speech, according to the EEG-data. Electrical activity was measured in tasks: for visual and auditory perception and pronunciation; for perception and pronunciation of conditioned stimuli. Electrophysiological experiment registrated using 19-channel EEG. Seven phonemes (A, B, F, G, M, R, U) and ten syllables composed of these phonemes (BA, FA, GA, MA, RA, BU, RU, MU, FU, GU) were selected for the experiment. Japanese words constructed using current phonemes were used as conditional stimuli (a trigger for the stimulus's pronunciation). The obtained data analysis was carried out using the statistical programming language R. Results, based on the ANOVA have significant differences for all experimental stages. Pronunciation as a reaction to a conditioned stimulus in the form of Japanese words were compared with two types of of covert speech initialization. The averaged reconstruction was between 63–67% (group averaging). In pairwise classifications of Japanese phonemes, stimuli reconstruction was between 76% and 83%. There is also a significant difference between the pronunciation and initialization type, regardless of the stimulus type ($p < 0.001$), but changes across channels are significant only for phonemes ($p = 0.03$). Main significant differences ($p < 0.05$) were found on C3 and F3 (for audio feed the differences are also seen on channel F7) in the early EP latencies (temporal zone).

Keywords: EEG · EP · Internal pronunciation · Covert speech · Syllables · Phonemes · Words · Conditioned stimuli · Non-existent words · Japanese · Neologisms · SVM

1 Introduction

According to Ch. Parnin, covert speech is a muted mental speech accompanied by a thought process [1]. In this article, the process of internal pronunciation (covert speech)

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is associated with the internal speech through an intellectual process such as silent reading. During this and similar processes, the movement of articulating organs is not visible to the unarmed eye. The movements made by the organs of the speech system are not necessary for the thinking process, but they are the final recipient of signals from the motor and premotor cortex. Dodge empirically proved this when there was no effect on covert speech in spite of medically achieved effects of numbness in his lips and tongue [2].

Other researchers in the late 19th and early 20th centuries have also analyzed the movement of the vocal apparatus during silent speech. These experiments used a rubber ball (or a ball made of glass) which was placed on the tongue to detect motion. Such studies of articulating organ movements proved to be unreliable, as too much interference was generated during breathing. Success in this area was only achieved with the invention and application of electromyographs to such studies.

1.1 State of the Art

The process of detecting ccovert speech (spoken words or phonemes) based on the electrical activity of the brain is relevant and significant for a number of practical applications. In particular, for improving the architecture of brain-computer interfaces (BCI-interfaces).

The findings of recent studies [3–5] have shown that the activity directly recorded from the brain by implanted electrodes (a system of local potentials based on the frequency of gamma-rhythm) can restore the signal related to speech and partially decipher the content of covert speech. However, the practical application of this invasive technology is very limited. In this context, the challenge is to develop a new method of internal speech content recognition based on non-invasive technology such as EEG.

The article “Reconstruction of Covert speech from Sound Centers of the Brain” [3] was of key importance for this paper. Pasley showed the possibility of reconstruction covertly pronounced syllables using a linear model based on an acoustic spectrogram using data on neural activity of the auditory cortex.

1.2 Objectives

Comparison of the EP in visual and auditory perception and internal pronunciation of phonemes, syllables and conditioned stimuli (Japanese words); to classify phonemes, used for the internal pronunciation, according to the EP data by various mathematical methods. Electrical activity was measured in tasks for visual and auditory perception and internal pronunciation, as well as for perception and internal pronunciation of conditioned stimuli (Japanese words).

2 Methods

2.1 Data Processing

The objective of the research is to compare the EP in visual and auditory perception and internal pronunciation of phonemes and syllables; to classify phonemes, used for the internal pronunciation, according to the EP data by various mathematical methods. Electrical activity was measured in tasks for visual and auditory perception and pronunciation as well as for perception and pronunciation of conditioned stimuli during electrophysiological experiment with registration of 19-channel EEG (according to the '10–20%' international system, using Neuro KM type electroencephalograph).

2.2 Procedure

Our experiments included four series:

1. Control series - the subject was shown words, phonemes and syllables in random visual and auditory order, task was to remember what participant was doing during the week (but not to pronounce himself).
2. Experiment with initialization of internal pronunciation on the basis of visual stimuli (phonemes and syllables). Is necessary to build a sound image (read a letter). This series is conducted with opened eyes.
3. Experiment with initialization of covert speech on the basis of auditory stimuli (words, phonemes and syllables). In these series, the sound image already exists, it is only need to be repeated). A participant speaks with his eyes closed.
4. Experiment with the initiation of internal pronunciation based on a conditional audio stimuli (Japanese words).

2.3 Participants and Stimuli

The study involved 25 subjects: fifteen females and ten males between the ages of 17 and 28. Participants learned pairs of association (Japanese word – Phoneme). It constituted a sound image in the face of interference with the the conditioned stimul (no one knew Japanese language). The participants were instructed to pronounce phonemes and syllables related to Japanese words covertly, with eyes closed. All stimuli were presented in a random order. The beginning of pronunciation was set by a special stimulus following the first one, which sets the phoneme or syllable to be pronounced.

Seven phonemes (A, B, F, G, M, R, U) and ten syllables composed of these Japanese phonemes (BA, FA, GA, MA, RA, BU, RU, MU, FU, GU) were selected for the experiment. A visual or audial stimulus continues on for 700 ms. Presentation of the stimulus was followed by a pause of 500 ms duration.

After a pause a fixation cross appears on the screen and participant hear a special signal. This is the start command for internal pronunciation, which must complete within 1500 ms.

To present the audible stimulus the participants were wearing headphones in which they were listening to pre-recorded phonemes and conditioned stimuli required for speaking.

The experiment was considered and approved by the Research Ethics Committee of the Faculty of Psychology, Lomonosov Moscow State University.

2.4 Method

The first method has the same interpretation and use as the "classic" dispersion analysis - its main difference is that it evaluates the difference in curves rather than averages. For this reason, the functional dispersion analysis is perfectly suited for evoked potentials and has been adapted to detect significant differences in the ERP package [6].

Although functional dispersion analysis can detect the existence of a significant difference, it cannot determine its exact location. This paper uses classical method of paired comparison for EPs to assess the significance of the differences between each matching point in the curves of EPs. Since this is irreversibly associated with an elevated risk of type I error due to multiple comparisons, the resulting p-values were corrected with the Benjamini-Hochberg correction used in the default EP package.

Fig. 1. Example of the stimulus used.

3 Results

As a result, EP were obtained for all stimuli in all experimental series for all subjects. The obtained data analysis was carried out using the statistical programming language R (version 3.6.3) (R Core Team, 2019) in the framework of the R studio integrated development environment. For this reason, functional analysis of variance (ANOVA) is excellent for evoked potentials (any EP is a curve) and has been adapted to detect significant differences in the EP package [6]. Finally, regardless of the type of stimulus, there is also a significant difference between the pronunciations depending on the type of initiation ($p < 0.001$), but the changes across the channels are significant only for phonemes ($p = 0.03$). This outcome is the opposite of what was observed before - with respect to the auditory supply, the visual one has firstly a negative and then a positive wave but on average, only a positive wave on C3 channel is significant (Fig. 1). In the case of comparing all pronunciations as associated with a conditioned stimuli in the form of Japanese words, significant differences were again found in all four cases ($p < 0.001$ for all auditory, $p = 0.01$ for visual phonemes, $p = 0.009$ for visual syllables), but significant interaction of the channel with stage was found only for auditory syllables ($p < 0.001$) (Fig. 2,3).

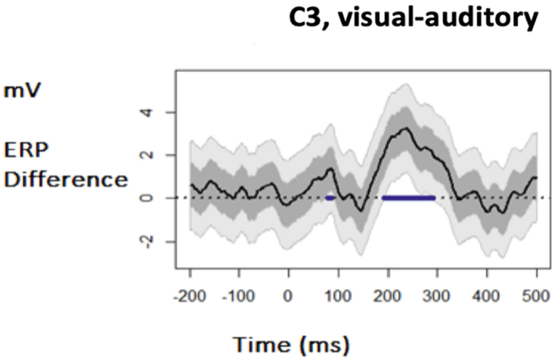

Fig. 2. Differences between evoked potentials (auditory syllables minus initiation of the conditional Japanese stimulus); regions of significant differences are marked in dark blue.

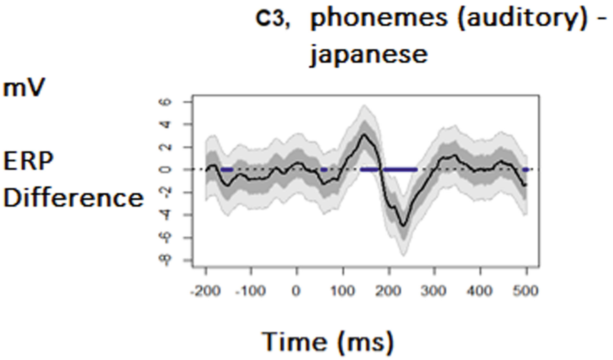

Fig. 3. Differences between evoked potentials (auditory phonemes minus the initiation of the conditioned Japanese stimulus); regions of significant differences are marked in dark blue.

The functional dispersion analysis showed significant differences in all cases which included comparisons of pronunciation with the first trial. (visually-auditory, phonemes-syllables), unexplained by variability within the subjects ($p < 0.001$). The effect check of channel variable and stage variable interaction showed significant differences at 0.05 only for auditory phonemes and syllables ($p = 0.02$ and $p = 0.005$, respectively). For visual presentation of phonemes and syllables the interaction is statistically insignificant ($p = 0.28$ and $p = 0.22$, respectively). It means that spatial distribution of EP through channels only changes with the first stage (in case of audial input). However, visual input remains relatively constant.

As for localization, the most significant differences (at the level of 0.05) are found on channels C3 and F3 (for audial initialization the differences were also observed on F7). These expressions y are marked by a positive wave in the region of 120–170 ms and a negative wave (on C3 and F3) at 200–280 ms. In this case, the positive wave at C3 and F3 is statistically significant regardless of the modality of the stimulus, and the negative wave is statistically significant only for auditory stimuli. An example of such difference can be seen in Fig. 4.

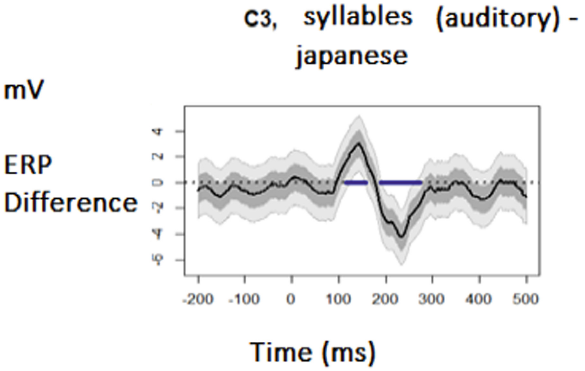

Fig. 4. Differences between evoked potentials (auditory syllables minus initiation of the conditional Japanese stimulus); regions of significant differences are marked in dark blue.

3.1 Machine Learning (Using SVM)

Experiments [5–7] have shown that signal directly recorded from the brain recorded by implanted electrodes (a system of local potentials at gamma rhythm frequency) allows us to restore speech signal and partially decipher the inner speech content.

The aim of our study was to use psychophysiological methods to register evoked potentials (EP) to identify specific characteristics of phonemes and syllables, taking into account their initiation, in order to build a classifier and compare its effectiveness.

We obtained the following statistics on reconstructability:

- the average value of the classifier for phonemes presented audibly is 62%;
- the average value of the classifier for visually presented phonemes - 62%;
- the average value of the classifier of syllables presented visually - 61%;
- average value of the classifier of syllables, submitted audiophile - 63%;
- the average classifier value of phonemes at initiation on conditional stimulus (Japanese words) - 64%.

The average degree of reconstruction is not depending on the initialization. However, from the data presented in Tables 1 and 2, we can conclude that each subject has its own optimal method of presentation in which classification is the best. While the average statistics are 61–65%, the individual reconstructivity of phonemes can exceed 68%.

Table 1. Example of pairwise classification of phonemes (audial, visual) with SVM, group average

Aud	B	F	G	M	R	U
A	0.63	0.62	0.63	0.59	0.56	0.62
B		0.63	0.58	0.60	0.60	0.62
F			0.66	0.58	0.63	0.65
G				0.61	0.67	0.64
M					0.65	0.60
R						0.63
Vis	B	F	G	M	R	U
A	0.63	0.65	0.65	0.64	0.66	0.63
B		0.64	0.57	0.57	0.62	0.63
F			0.66	0.58	0.65	0.69
G				0.65	0.70	0.62
M					0.57	0.57
R						0.60

Also, in paired classclassifications, some stimuli can be classified from 84 to 90% for individual subjects, indicating good prediction for individual stimuli in each subject, but the average of greater number of test subjects leads to the average of predictability value, so accuracy decreases. Comparing our study with last year's one, where the average predictor-to-test was between 63–67%, we can conclude that an increase in the sample leads to smoother results. However, there are subjects who have a higher accuracy of classification.

In pairwise classifications of Japanese phonemes (Table 2), some stimuli are classified between 76% and 83% on average. It indicates the higher quality of phoneme recognition for individual stimuli.

The results of our study can be compared with a number of Western works [8, 9]. A number of experiments with imaginary articulation have shown that representing facial movements during pronunciation activates neurons in the motor cortex which can be used to control the denture. This phenomenon often used in the architecture of the BCIs, and also suggests that imaginary articulation may help to improve the accuracy of classification.

Although functional variance analysis can detect the very fact of a significant difference, it cannot determine the exact location in the brain. Several signal recognition procedures are implemented in the EP package, but due to the relatively small sample size, many of them may be overly critical. in this work we use the classical method of EP pairwise comparisons. We evaluate the significance of differences between each matching point in the EP curves. Since this is irreversibly associated with a higher risk of type I error due to multiple comparisons, the resulting p-values were corrected using the Benjamini-Hochberg correction from the EP package.

Table 2. Example of pairwise classification of phonemes (Japanese words as a conditioned stimuli) with SVM, Participant №1

	B	F	G	M	R	U
A	0.56	0.56	0.55	0.54	0.74	0.58
B		0.62	0.60	0.67	0.70	0.83
F			0.69	0.59	0.59	0.60
G				0.67	0.60	0.59
M					0.72	0.61
R						0.68

4 Discussion

Based on the results, according to ANOVA method, all experimental stages have significant differences, but the spatial distribution of EPs shows significant differences for auditory stimuli only.

Also, all initialization options with muted pronunciation as a reaction to a conditioned stimulus in the form of Japanese words were compared to each other. Significant differences were found again in all four cases, but significant interaction of the channel with the stage was found only for auditory syllables and phonemes.

When perceiving and pronouncing stimuli, the channel effects depend on whether the subject perceives the stimulus or pronounces it. Whether the presentation of stimuli was visual or auditory did not alter the results. The experiment was designed in such a way that after the presentation of a stimulus command, there was a pause of 400 ms in order to compare perception of stimuli with internal speaking. Internal speaking and perception were different in each series of experiments.

Across the syllables pronunciation results expressed differences were observed in C3 and F3 channels (the left temporal zone) for all three cases,. These results are associated with the location of speech areas, which corresponds with previous experiments on the classification and study of the processes of internal pronunciation [3–7]. These differences depend on whether the stimulus was visual or auditory. When considering phonemes, a difference is also found depending on the method of stimulus presentation. There is also a significant difference between the pronunciations depending on the type of initiation, regardless of the type of stimulus ($p < 0.001$), but the changes in the channels are significant only for phonemes ($p = 0.03$). Overall, this data supports and expands on previous studies showing the effects of visual and auditory cues on processing different languages [10–13].

5 Conclusion

For syllables, differences in covert speech were observed at channels C3 and F3 (left temporal zone) [8, 13] which is related to the location of the zones that are responsible for speech (related to the reconstructon of the syllables). This data is compatible with the experimental studies of the processes of covert speech and its reconstruction. For syllables, it was also found a significant differences ($p < 0.001$) on the stimulus presentation (visually or audibly). The dependence on it b changes across channels and were only significant for phonemes ($p = 0.03$). There was also a significant difference of covert speech associated with the conditioned stimuli ($p < 0.001$). it changes across channels and were only significant for phonemes ($p = 0.03$) [3, 4].

A comparison of pronunciation to an auditory stimuli with pronunciation to a conditioned stimuli (Japanese words) showed significant differences in all series ($p < 0.001$) for all auditory, $p = 0.01$ for visual phonemes, $p = 0.009$ for visual syllables), however a significant channel-stage interaction was found only for auditory syllables ($p < 0.001$). The significant differences were observed in the early EP latencies, which was related to the perception of the conditioned stimuli.

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References

1. Parnin, C.: Subvocalization —Toward hearing the inner thoughts of developers. In: Conference: program comprehension (ICPC), 2011 IEEE 19th International Conference on (2011). https://doi.org/10.1109/icpc.2011.49
2. Dodge, R.: Die motorischenwortvorstellungen, in AbhandlungenzurPhilosophie und ihrer Geschichte (1896)
3. Pasley, B.N., David, S.V., Mesgarani, N., Flinker, A., Shamma, S.A., Crone, N.E., Knight, R.T., Chang, E.F.: Reconstructing speech from human auditory cortex. PLoS Biol. **10**(1), e1001251 (2012)
4. Martin, S., Brunner, P., Holdgraf, C., Heinz, H., Crone, N., Rieger, J.: Decoding spectrotemporal features of covert and ccovert speech from the human cortex. Front. Neuroengineering. **7**, 1–5 (2014). https://doi.org/10.3389/fneng.2014.00014
5. Mesgarani, N., David, V., Fritz, J.B., Shamma, S.A.: Influence of context and behavior on stimulus reconstruction from neural activity in primary auditory cortex. J. Neurophysiol. **102**(6), 3329–3339 (2009). https://doi.org/10.1152/jn.91128.2008
6. Causeur, D.: EP: Significance Analysis of Event-Related Potentials Data (2019)
7. Min, B., Kim, J., Park, H.J., Lee, B.: Vowel imagery decoding toward silent speech BCI using extreme learning machine with electroencephalogram. BioMed Res. Int. **2016**, 1–11 (2016). https://doi.org/10.1155/2016/2618265
8. Brumberg, J.S., Krusienski, D.J., Chakrabarti, S., Gunduz, A., Brunner, P., Ritaccio, A.L., Schalk, G.: Spatio-temporal progression of cortical activity related to continuous covert and covert speech production in a reading task. PLoS ONE **11**(11), e0166872 (2016)

9. Sarmiento, L., Lorenzana, P., Cortes, C., Arcos, W., Bacca, J., Tovar A.: Brain computer interface (bci) with eeg signals for automatic vowel recognition based on articulation mode. In: 5th ISSNIP-IEEE Biosignals and Biorobotics Conference: Biosignals and Robotics for Better and Safer Living (BRC). IEEE Press, New York (2014). https://doi.org/10.1109/brc.2014.6880997
10. Andrews, E.: Neuroscience and Multilingualism. Cambridge University Press, Cambridge (2014)
11. Wen, Y., Filik, R., van Heuven, W. J. B.: Electrophysiological dynamics of Chinese phonology during visual word recognition in Chinese-English bilinguals. Sci. Rep. **8**(1), (2007). https://doi.org/10.1038/s41598-018-25072-w
12. Guillaume, T., Yan, J.W.: Brain potentials reveal unconscious translation during foreign-language comprehension. PNAS **104**, 12530–12535 (2017)
13. Jack, B.N., Le Pelley, M.E., Han, N., Harris, A.F., Spencer, K.M., Whitford, T.J.: Inner speech is accompanied by a temporally-precise and content-specific corollary discharge. Neuroimage **198**, 170–180 (2019). https://doi.org/10.1016/j.neuroimage.2019.04.038

Phonological and Orthographic Representations in Visual Word Recognition: ERP Study of Russian Homophones

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Abstract. Our study focuses on the role of phonology in visual word processing recognition which is a crucial theoretical issue in the psycholinguistics research of reading. We use the ERP method in the homophone-error paradigm and show that both homophone errors and orthographic neighbours of the target word provoke N400 effect and homophony does not facilitate processing. It gives evidence for dual-route model of processing showing that meaning can be activated directly from visual (orthographic) representations and not via phonological codes. At the same time we report P600 effect for homophone errors which can be explained by further competition between phonological and visual representation of the word: it makes homophone errors more costly in the semantic integration of the phrase.

Keywords: Visual word recognition · Phonological representation · Orthographic representation · Homophones · ERP · N400 effect

1 Introduction

The role of phonology in visual word recognition is a crucial theoretical issue in the psycholinguistics research of reading. The question is what is stored in mental lexicon: phonological representations mapped onto semantics or both phonological and orthographic ones [1].

The dual-route theory [2] argues for two independent ways of printed words processing; one relies on the phonological representation and the other on the visual image of the word. For high-frequency words read by skilled readers the visual route to the meaning is accessed faster as due to frequent exposure meanings can be activated by orthographic representation before the phonological one is available [3].

The single-route theory [4] claims that phonological processing is a default procedure of cognitive system and meaning only can be accessed via phonological representation. Strong phonological models claim phonological processing to be mandatory and automatized.

Homophony turns out to be an ideal testing ground for these models: if a homophone is processed in the same way as any other orthographic neighbour, it gives evidence for

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the visual route to meaning. If homophony facilitates processing, it gives evidence for the phonological route. Thus, so called homophone-error paradigm [5] was used in a number of studies on visual word recognition. Experiments in priming paradigm, like [6] show that homophones can facilitate the processing of words semantically related to another member of homophone pair (*beach* facilitates lexical decision for *tree*, being a homophone for *beech*, while *bench* as a spelling control does not) which gave evidence for automatic activation of phonological code. Lukatela and Turvey [7] found that not only homophones (like *toad*) but also pseudohomophones, i.e. pseudowords which have the same phonological representations as real words (like *towed* and *tode*) facilitate lexical decision for *frog* (while orthographic neighbours like *told* or *tord* do not). However, lexical decision task reflects the process of visual word recognition but not actually the reading process. Feng and colleagues [8] in an eye-tracking study show that both homophone errors and orthographic neighbours provoke longer fixation duration times than correct homophones which gives evidence for the visual route of processing frequent words.

Forbs and Connoly [9] used ERP method to compare the processing of homophone errors and spelling controls and found that N400 component was higher for completely inappropriate words than for homophone errors, while for correct homophones and homophone errors this response was similar in amplitude. Newman and Connoly [10] used pseudohomophones like *phog* instead of *fog* and find no N400 effect for a pseudohomophone while ordinary pseudowords provoked it. Newman and colleagues [11] used ERP method to clarify the role of phonology in the activation of high frequency words during silent reading using target homophones (The students arranged to *meet* in the library), homophone errors (The students arranged to *meat* in the library) and spelling controls – orthographic neighbors (The students arranged to *mean* in the library) and found that N400 effect is more pronounced for spelling controls in comparison to homophone errors which is compatible with strong phonological model.

All these results were obtained on English material. However, it is an interesting issue in a cross-linguistic perspective, taking into account different degrees of orthographic transparency in different languages. Russian orthography is somewhere in between shallow and opaque orthographic systems being both sufficiently complex and quite consistent in its complexity at the same time. In particular, voiced consonants are pronounced as devoiced in the end of the word which causes regular homophony (e.g. kot /kot/ ‘cat’-kod /kot/ ‘code’).

2 Method

2.1 Materials

We selected 13 Russian homophones with either voiced or devoiced consonant in the end of the word (e.g. kot /kot/ ‘cat’-kod /kot/ ‘code’). For each word we selected 2 semantically congruent adjectives and constructed 52 semantically congruent noun phrases (e.g. *pushistyj kot* ‘fluffy cat, *seryj kot* ‘grey cat’, *sekretnyj kod* ‘secret code’, *programmnyj kod* ‘programming code’). In the homophone error condition we substituted the target nouns by their homophones (*pushistyj kod* ‘fluffy code’, *sekretnyj kot* ‘secret cat’) and in the spelling control condition we substituted the target noun by its orthographic neighbour which differed in one letter and was not homophonous (*pushistyj kol* ‘fluffy stake’). So we had 104 semantically incongruent phrases in homophone error ans spelling control conditions and also 262 semantically congruent fillers which were semantically congruent phrases, e.g. (*staryj drug* ‘old friend’, *belyj flag* ‘white flag’) so that anomalous phrases were not too frequent.

2.2 Subjects

19 native speakers of Russian, students of St.Petersburg State University, age 18–23, right-handed, with normal (or adjusted to normal) vision took part in the experiment on voluntary basis. All volunteers signed informed consents to participate in the experiment. The study was conducted in accordance with the Helsinki Declaration and approved by the Ethics Board of St. Petersburg University.

2.3 Procedure

Participants sat approximately 1,5 m from a 19-in. monitor in a sound attenuated room. The participants were presented with each word for 500 ms, the intertrial interval was 2000–3000 ms. The instruction was to read the phrases silently and to decide whether the noun is animate or inanimate to make sure that semantic processing takes place.

2.4 EEG Recording

Electroencephalogram (EEG) was recorded at 30 scalp sites (F3, Fz, F4, F7, F8, FC3, FCz, FC4, FT7, FT8, T3, T4, C3, Cz, C4, T7, T8, CP3, CPz, CP4, TP7, TP8, P3, Pz, P4, P7, P8) using Ag/AgCl electrodes embedded in a MCScap. Signals were recorded with respect to a linked-ear reference. The electrooculogram (EOG) was recorded with the two electrodes: one placed above the right eye (vertical), and another one - on the outer canthus of the right eye (horizontal). All EEG electrode impedances were maintained below 40 KΩ. The EEG was amplified by a Neurovizor BMM-52 amplifier and acquired and processed with Neocortex software (Neurobotics, Russia). Stimuli and trigger codes were delivered by Neostimul presentation program (Neurobotics, Russia). EEG was sampled continuously at 1000 Hz with a bandpass of $0.5-50$ Hz. Data were epoched off-line using EEGLAB from -200 to 800 ms post- stimulus onset, baseline correction was performed by averaging the pre-stimulus period (-200 to 0 ms). Trials contaminated with EOG activity and other artefacts (including alpha-waves) were excluded from the analysis.

2.5 Results

Separate ERP waveforms were calculated for each of the three experimental conditions (congruent phrases, homophone errors and spelling controls). We analyzed frontal, central and parietal sites (F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, P3, Pz, P4). To check the differences between the experimental conditions we used a MATLAB-based algorithm that allows comparing not averaged responses in different conditions in each time point of the epoch using Wilcoxon signed-rank test. Thus, we can find the exact time windows where the difference between the conditions is statistically significant. Of greatest interest was the N400 response, so we took into closer consideration nine electrodes where N400 was most pronounced (Fig. 1). Within 370–400 ms time window statistical analysis showed significant differences between conditions semantically congruent and spelling control condition in central and parietal sites Cz, Cp4 and Pz ($p < 0.05$). In addition, N400 amplitude (the same 370–400 ms time window) was significantly greater for phrases with homophone substitution in comparison to congruent phrases in C4, Cpz, Cp4, Pz and P4 ($p < 0.05$). There is no significant difference between the two incongruent conditions.

We also looked at the 560–600 ms time window where P600 component is usually observed in central and parietal sites. Within this time window, there was a significant difference between congruent phrases and phrases with homophone substitution ($p < 0.05$) in central and parietal sites (C3, Cz, C4, Cp3, Cpz, Cp4, P3, Pz, P4). For spelling control condition this effect was not pronounced.

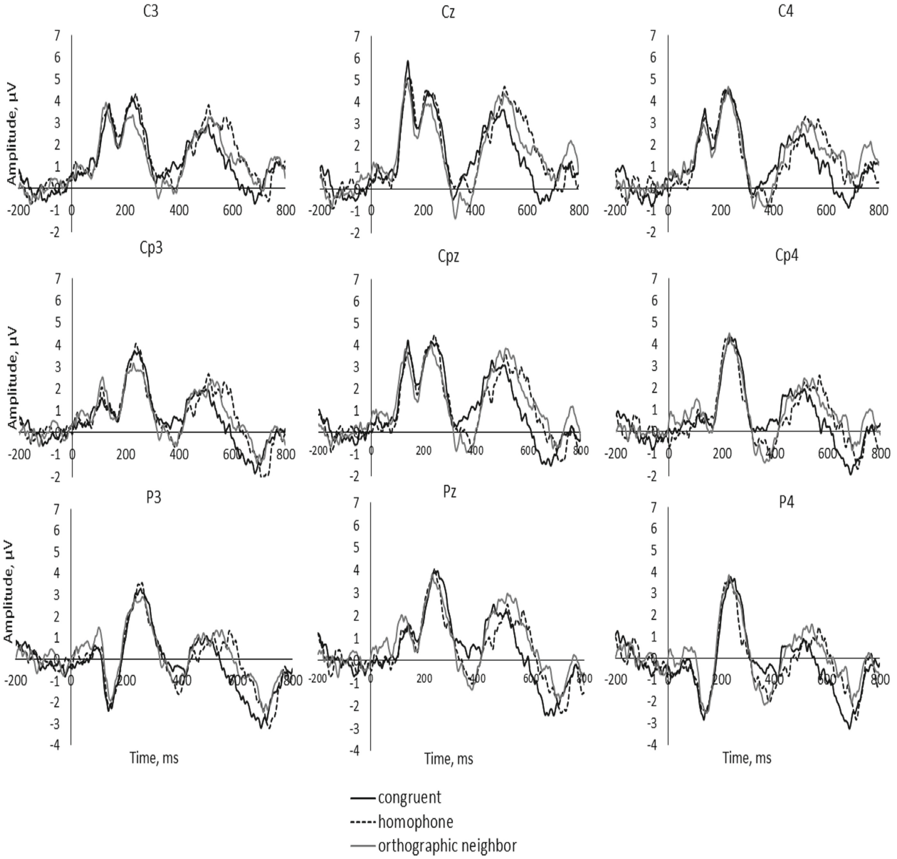

Fig. 1. ERP waveforms from nine electrode sites for congruent phrases, phrases with homophone substitution and phrases with orthographic neighbour substitution.

3 Discussion

The aim of our research was to determine whether phonology plays a noticeable role in lexical retrieval when skilled readers read silently. Our data indicate that phonological codes seem not to be involved in lexical access in Russian as homophone errors and spelling controls, both being semantically incongruent, produced an N400 response of similar magnitude, and both had a greater N400 than correct words. These findings are more compatible with a dual-route model which claims that word meanings seem to be activated directly from the visual representation of the word, as a result, a homophone error is processed in the same way as any other orthographic neighbor of the target word. At the same time, we find P600 effect for homophone errors and no P600 effect for spelling controls. While N400 is known to be a response for semantically anomalous words [12] or words or unpredictable from the preceding context [13], P600 effect is observed not only in response to syntactic violations [14], but also to semantic integration effects [15]. As for the homophone errors, they provoke the competition between phonological and visual representation of the word: phonological representation activates both the consistent and the inconsistent meaning while visual representation activates the inconsistent one. This competition between the meanings makes the homophone error more costly in the semantic integration of the phrase which may result in P600 response.

4 Conclusion

All in all, our ERP study in the homophone-error paradigm shows that both homophone errors and orthographic neighbours of the target word provoke N400 effect which means that homophony does not facilitate processing as strong phonological model would predict. Our data are compatible with dual-route model of processing which claims that meaning can be activated not only via phonological codes but also directly from orthographic representations. At the same time we report P600 effect for homophone errors which can be explained by further competition between phonological and visual representation of the word which makes homophone errors more costly in the semantic integration of the phrase.

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References

1. Clifton, C.: The roles of phonology in silent reading: a selective review. In: Frazier, L., Gibson, E. (eds.) Explicit and Implicit Prosody in Sentence Processing. Studies in Theoretical Psycholinguistics. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-12961-7_9
2. Coltheart, M.: Deep dyslexia: a review of the syndrome. In: Coltheart, M., Patterson, K., Marshall, J. (eds.) Deep Dyslexia. Routledge & Kegan Paul, London (1980)
3. Jared, D., Levy, B., Rayner, K.: The role of phonology in the activation of word meanings during reading: Evidence from proofreading and eye movements. J. Exp. Psychol. Gen. **128**, 219–264 (1999). https://doi.org/10.1037/0096-3445.128.3.219

4. Frost, R.: Toward a strong phonological theory of visual word recognition: True issues and false trails. Psychol. Bull. **123**, 71–99 (1998). https://doi.org/10.1037/0033-2909.123.1.71
5. Jared, D., O'Donnell, K.: Skilled adult readers activate the meanings of high-frequency words using phonology: evidence from eye tracking. Mem. Cognit. **45**, 334–346 (2016). https://doi.org/10.3758/s13421-016-0661-4
6. Lesch, M., Pollatsek, A.: Evidence for the use of assembled phonology in accessing the meaning of printed words. J. Exp. Psychol. Learn. Mem. Cogn. **24**, 573–592 (1998). https://doi.org/10.1037/0278-7393.24.3.573
7. Lukatela, G., Turvey, M.: Visual lexical access is initially phonological: 2. Evidence from phonological priming by homophones and pseudohomophones. J. Exp. Psychol. Gen. **123**, 331–353 (1994). https://doi.org/10.1037/0096-3445.123.4.331
8. Feng, G., Miller, K., Shu, H., Zhang, H.: Rowed to recovery: The use of phonological and orthographic information in reading Chinese and English. J. Exp. Psychol. Learn. Mem. Cogn. **27**, 1079–1100 (2001). https://doi.org/10.1037/0278-7393.27.4.1079
9. Forbs, K., Connoly, J.F.: An event-related brain potential (ERP) investigation of phonological recoding and orthographic influences during silent reading. Psychophysiology. **32** (Suppl.), 21 (1995)
10. Newman, R., Connolly, J.: Determining the role of phonology in silent reading using event-related brain potentials. Cogn. Brain Res. **21**, 94–105 (2004). https://doi.org/10.1016/j.cogbrainres.2004.05.006.105
11. Newman, R., Jared, D., Haigh, C.: Does phonology play a role when skilled readers read high-frequency words? evidence from ERPs. Lang. Cogn. Process. **27**, 1361–1384 (2012). https://doi.org/10.1080/01690965.2011.603932
12. Kutas, M., Hillyard, S.: Reading senseless sentences: Brain potentials reflect semantic incongruity. Science **207**, 203–205 (1980). https://doi.org/10.1126/science.7350657
13. Kutas, M., Federmeier, K.: Thirty Years and Counting: Finding Meaning in the N400 Component of the Event-Related Brain Potential (ERP). Annu. Rev. Psychol. **62**, 621–647 (2011). https://doi.org/10.1146/annurev.psych.093008.131123
14. Hagoort, P., Brown, C., Groothusen, J.: The syntactic positive shift (SPS) as an ERP measure of syntactic processing. Lang. Cogn. Process. **8**, 439–483 (1993). https://doi.org/10.1080/01690969308407585
15. Delogu, F., Brouwer, H., Crocker, M.: Event-related potentials index lexical retrieval (N400) and integration (P600) during language comprehension. Brain Cogn. **135**, 103569 (2019). https://doi.org/10.1016/j.bandc.2019.05.007

Foreign Language Proficiency, Typological Similarity to L1, and Cognitive Control

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Abstract. Cognitive control plays an important role in regulating attention and behavior. Research has shown a cognitive advantage in bilinguals, however whether these results apply to people learning a foreign language later in life using formal education is not entirely clear. Due to globalization processes more people tend to communicate in multiple languages. Learning foreign languages has become a part of the compulsory education curriculum worldwide. In this work we investigate the relation between foreign language proficiency and the efficacy of the cognitive control functions: inhibition and task switching. Computerized cognitive control tasks were completed by 63 participants (45 women, aged 19–33). The acquired data was factorized resulting in 3 measures of cognitive control efficacy: general efficacy, accuracy of inhibition, and accuracy of task switching. Using the Spearman's correlation analysis, we found that the accuracy of task switching is significantly linked with the level of language proficiency. These results are in line with the previous findings suggesting that code switching strongly involves the cognitive control functions in bilinguals.

Keyword: Cognitive control · Foreign languages · Foreign language proficiency · Task switching · Inhibition · Bilinguals

1 Introduction

A cognitive advantage in bilinguals has been a subject of unceasing debate for the last decade. Starting with a series of investigations by Bialystok conducted with bilingual children, advantages in the effectiveness of performing cognitive control tasks, especially on non-verbal material, have been identified [1–4]. When comparing the success of working memory, lexical reproduction and cognitive control tasks among adult bilinguals and monolinguals, the advantages of the bilingual sample in the field of cognitive control were also revealed, while the tasks for lexical reproduction were performed more successfully by monolinguals, and no significant differences were found in working memory tasks [5].

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The reasons for these differences in control success lie both in the bilingual advantage in the switching function, which provides coordinated activation of a number of interrelated language processes [6], and in the higher efficiency of inhibition, which is manifested in particular in resistance to proactive interference [7, 8]. The identified benefits were expressed in lower switching costs, faster task completion, greater success in trials with non-congruent stimuli, and greater sensitivity to warning signals [8]. Despite some differences in the results of various studies conducted on the materials of different tasks, the bilingual advantage in the effectiveness of cognitive control was recorded by most researchers in this field, which suggests the involvement of cognitive control functions in the process of bilingual communication and the possible transferability of the effect of cognitive training to other tasks, including those based on non-verbal material.

Obtaining stable results among natural bilinguals allows us to raise the question of the effect of acquired bilingualism (mastering a second language as a foreign language) on cognitive control. In natural bilingualism, language is acquired spontaneously, in the process of communication and interaction with others, while acquired bilingualism implies purposeful learning of a foreign language. Significant differences in the processes of assimilation of language material suggest differences in the nature and effectiveness of the functioning of cognitive control and its components. In a comparative study with Iranian speakers who speak English at a high level and Iranian speakers who speak English at an elementary level, significant differences were found in the efficiency of switching and updating working memory, but not in the effectiveness of the inhibition function [9].

When comparing the effectiveness of these functions in bilinguals and monolinguals, the advantage of native speakers of the two languages in switching and inhibition functions was revealed, but no significant differences were found in terms of updating working memory [1, 10]. When comparing English-Chinese bilinguals with monolinguals and native English speakers who studied Chinese as a foreign language, advantages in the effectiveness of cognitive control in both bilingual groups compared to monolinguals and qualitative differences in the nature of executive functions were also revealed [11]. The study used a lateralized LANT attention test [12] with congruent and non-congruent flanker tasks, expressing indicators of the effectiveness of monitoring and conflict resolution in response time and the number of errors. Natural bilinguals showed better results in overall reaction time, and respondents with acquired bilingualism made significantly fewer mistakes in tasks with non-congruent conditions. The authors interpreted these results to conclude that the effectiveness of cognitive control is highly sensitive to the age of second language acquisition, the degree of similarity of languages in a pair, and the symmetry of the use of these languages in everyday life [11].

However, this area of research remains controversial due to differences in experimental procedures and differences in understanding what constitutes bilingualism and which factors should be taken into account. A number of meta-analyses have shown the significance of age of acquisition, and socioeconomic status [13]. In the current study we are focusing on level of proficiency, the number of foreign languages, and linguistic similarity between the native and the strongest foreign languages. For the latter, the WALS database (The World Atlas of Language Structures) was used. It is a typological database developed on the basis of structural (phonological, grammatical and lexical) language properties.

2 Material and Methods

2.1 Participants

The study involved 49 participants, students and persons with higher education aged 19 to 33 years, belonging to nine language groups. When selecting respondents, the level of their proficiency in these languages was taken into account, one of which was a foreign language, that is, mastered using formal teaching methods at the age of seven. This excluded the representation of natural bilinguals in the study. Ethical approval for the study was provided by the local Ethics Committee of the Lomonossov Moscow State University.

2.2 Materials

Language Assessment. In order to assess the level of foreign language proficiency in participants, we asked them to complete a short questionnaire stating the age when they started learning the foreign language, the number of years and the way they learned it and the age when they could use the foreign language to produce oral or written speech. The participants were also asked to evaluate their speaking, reading, writing, and listening comprehension skills on the scale of one to ten where one signified “poorly”, and ten – “perfectly”. The results of standardized language tests were also given if such tests were previously taken. Due to the fact that the foreign languages varied from person to person, using a standardized language test as part of the experimental procedure was not possible. Lastly the participants commented on the frequency of the foreign language use and the most usual mode of use.

Cognitive Control Tasks. To evaluate the cognitive control functions, two tasks for evaluating inhibition functions and two tasks for evaluating switching functions were used. Two experimental tasks were used to evaluate the inhibition function: the Eriksen task and the Go-No-Go task. The tasks were presented on a personal computer in compliance with neutral light and noise conditions.

The Eriksen Task. The stimulus material is represented by five horizontally arranged black arrows and “–” signs on a white background and was presented in three conditions: congruent ($> > > > >$, $< < < < <$), non-congruent ($> > < > >$, $< < > < <$), or neutral (- - > - -, - - < - -). The task of the subject is to follow the middle target arrow and press the “z” key on the keyboard when the arrow is directed to the left and the “ / ” key when the arrow is directed to the right. The training series contains 36 presentations: each combination is presented six times. The main series contains four blocks, with 36 unique presentations each. The inter-stimulus interval is fixed and is 1000 ms. The maximum stimulus presentation time is 1500 ms and can be reduced with an earlier response from the respondent. If the allotted time was not enough for a response, it was counted as incorrect. The measurements were carried out on four scales: the average reaction time, the percentage of correct responses in each type of sample, the difference in reaction time and accuracy between congruent and non-congruent samples.

The Go-No-Go Task. The stimulus material is represented by the letters of the Russian alphabet, presented in black font in the center of the white screen. Target stimulus X is 80% of the presentation, non-target stimuli contain the letters A, G, E, I, K, L, M, N, P, T, O, E, Y. The distribution of stimuli is randomized. The task of the subject is to press the "space" button with the leading hand when presenting the target stimulus. The presentation time is 300 ms, the inter-stimulus interval is 700 ms. The subject can respond during the presentation of the stimulus or about the presentation of the next stimulus, so the maximum response time is 1000 ms. if the subject did not have time to answer in the allotted time, the answer in this sample was recorded as incorrect. The training series includes 20 presentations: 16 presentations of the target stimulus, and 4 presentations of the non-target stimulus. The main series contains 200 presentations: 160 presentations of the target stimulus and 40 presentations of non-target stimuli. The total task completion time is fixed and is 3.5 min. Measurements are made on four scales: the average reaction time for correct and incorrect answers, the percentage of correct answers for the entire task, the percentage of correct responses by pressing a key ("hits") and the percentage of false alarms.

The switching function was also evaluated using two tasks: with predictable and unpredictable task changes. Both tasks were presented on a personal computer in compliance with neutral light and noise conditions.

Switching Task 1 (predictable change of tasks). The stimulus material is represented by a square divided into four equal sections (two squares at the top and two squares at the bottom). in each of the squares, a pair of symbols is presented in turn: a number and a letter. Among the presented numbers are even (2, 4, 6, 8) and odd (3, 5, 7, 9); and among the letters are consonants (G, K, M, R) and vowels (A, I, E, And).

The task is to determine by pressing the button whether the number is even or odd if the characters are located in one of the upper squares, and whether the letter is a consonant or a vowel if a pair of characters is located in one of the lower squares. The answer is made using the "z" key for odd numbers and vowels and the " / " key for even numbers and consonants.

The training series consists of 24 presentations of the number-letter pair in all four sections of the screen clockwise - from the upper left to the lower right. In the first half of the training test, the respondent receives feedback: in case of an incorrect answer, the "number-letter" pair is colored red.

The Main series consists of 128 presentations. The stimuli are on the screen until the subject responds. The inter-stimulus interval between the subject's response and the next stimulus takes 500 ms. Measurements are carried out on six scales: reaction time and accuracy in samples with switching, reaction time and accuracy in samples with repetition, the difference in reaction time and accuracy in samples with switching and repetition ("switching cost").

Switching Task 2 (random task change). The stimulus material is also represented by even (2, 4, 6, 8) and odd (3, 5, 7, 9) numbers and consonants (G, K, M, R) and vowels (A, Z, E, And) letters in black, Courier font, 1.2 cm in height. The symbols were also presented in pairs: one digit and one letter. Each pair of stimuli was displayed in a 7.5-by-7.5-cm rectangle surrounded by a thin black line in the center of a light gray screen. The background color of the rectangle (blue and green) served as a signal for choosing a task (determining the parity-odd numbers, or consonance-vowel of letters). The interval between the presentation of the background signal and the stimulus is 600 ms, and the interval between the response and the stimulus is 500 ms. All stimuli are on the screen until the subject gives an answer.

The training series consists of 24 presentations, the main series is represented by 128 presentations. Half of the presentations are aimed at the switching task (the current task, expressed by the background color, does not match the previous one), and half – at the repetition task (the current task, expressed by the color of the rectangle-background, coincides with the previous one). Thus, each variant of consecutive presentation of background colors (blue-green, green-blue, blue-blue, green-green) is presented in a quarter of all stimuli.

The overall design of the task is as follows: 1) a rectangle colored blue or green appears; 2) after 600 ms, a stimulus pair appears: if the rectangle is colored blue, the respondent must evaluate the parity of numbers, and if it is colored green, the transparency of letters; 3) the stimulus pair is presented before the subject's answer; 4) after the subject's answer, the stimulus pair disappears and an empty rectangle is presented on the screen for 500 ms, then the algorithm repeats in the first paragraph. The answer is made using the "z" key for odd numbers and vowels and the " / " key for even numbers and consonants. Measurements are carried out on six scales: reaction time and accuracy in samples with switching, reaction time and accuracy in samples with repetition, the difference in reaction time and accuracy in samples with switching and repetition ("switching cost").

2.3 Procedures

The study was conducted individually with each subject on the experimenter's personal computer (laptop) in a well-lit, quiet room. Before conducting experimental tasks, respondents filled out a questionnaire in Russian or English at their choice, the experimenter was available to explain the questions of the questionnaire, if necessary, the data were supplemented with a short interview with the subject. The instruction was duplicated in English for respondents who were unsure of the material in Russian and was also accompanied by oral explanations for Russian-speaking respondents, if necessary, and to preserve the uniformity of the research procedure. The average execution time of the experimental task was 40 min, short breaks between tasks were allowed. The tasks were presented in a fixed order: Go-No-Go, the Erickson flank task, the switch task with a fixed presentation order, and the switch task with a randomized presentation order. After completing the tasks, the subjects were given explanations about the goals of the study.

3 Results

Based on the results of the experimental tasks, we obtained a number of performance indicators expressed in the time of task completion under different conditions and the number of errors. 32 indicators were selected. To simplify the processing and interpretation of the data, they were factorized to reduce the dimension of the data. For factor analysis of the data, exploratory factor analysis with the principal component method with Varimax rotation was used. The determination of the number of factors was based on the analysis of the “scree” plot and a meaningful analysis of the factor loads of indicators. The scree plot shows “break” points in the area of component 3 and 10. Eigenvalues greater than 1 (Kaiser’s rule) were observed up to component 10. Given the need for significant data reduction, it was decided to choose a factorial solution with three components.

A factorial solution with three components describes a total of 48% of the variance. The analysis of factor loadings allows us to give the following interpretations to the factors:

Factor 1 - General control factor. The factor combines most indicators of the effectiveness of cognitive control, both for switching tests and for inhibition tests. it includes mainly temporary indicators.

Factor 2 - Switching accuracy. The factor combines the total number of errors and the number of errors in the trials with repetition and switching for both switching tasks.

Factor 3 - Inhibition accuracy. The factor combines the accuracy indicators of both inhibition tasks (including the error monitoring indicator for the Erickson flank task).

In order to assess the impact of the number of foreign languages on the effectiveness of cognitive control, factor values were compared in groups of people who speak one ($n = 4$), two ($n = 25$) and three or more ($n = 20$) languages (nonparametric Kruskal-Wallis test). Significant differences were found for factor 1 ($\chi 2 = 6.6$, $p < 0.05$) and factor 2 ($\chi 2 = 6.8$, $p < 0.05$). In particular, an increase in the number of languages leads to a systematic decrease in the values of factor 2, that is, to a systematic increase in the accuracy of switching.

To assess the impact of the level of foreign language proficiency, an indicator of general language competence in the main foreign language was constructed. To do this, the self-assessment indicators of the effectiveness of reading, speaking, writing and listening comprehension were averaged for each subject. The Spearman correlation coefficient was calculated for the average indicator of language competencies and the values of cognitive control efficiency factors. The correlations were insignificant for the overall control efficiency factor ($r = 0.19$; $p = 0.17$) and for the inhibition accuracy ($r = 0.07$; $p = 0.64$). However, the correlation with the level of language competence was significant for factor 2 ($r = -0.31$; $p = 0.03$) (Fig. 5). Thus, the overall switching accuracy significantly increased with an increase in the level of foreign level proficiency.

To assess the effects of L1 to L2 typological similarity, we computed L1/L2 similarity scores using the World Atlas of Language Structures database. The World Atlas of Language Structures (WALS) is a large database of structural (phonological, grammatical, lexical) properties of languages. The first version was published in 2005 [14] and contained a description of 2560 languages on 140 features, and in 2011 an online version was launched, which contains a description of 2679 languages on 192 features [15]. This database is based on the representation of grammatical, lexical and phonological phenomena in languages, such as the presence of prefixes, grammatical tenses, and specific sounds, and evaluates the degree of similarity of languages by a broader set of criteria.

Using WALS, a L1/L2 similarity score was computed for all language pairs spoken by our participants. We fitted a linear and a quadratic regression using the least squares procedure of the cognitive control factors and the WALS typological similarity score. Linear regression models were all insignificant and explained less than 2% of the variance in cognitive control factors. Quadratic models were significant for Factor 1 (General control factor, $R^2 = 0.26$, $p < 0.01$) and Factor 2 (Switching accuracy factors, $R^2 = 0.13$, $p < 0.05$). Generally, cognitive control efficiency increased for low similarity and high similarity L1/L2 similarity scores.

4 Discussion

The results of the study address several relevant aspects of the structure, functions, and effectiveness factors of cognitive control. At the first stage, factorization of the respondents' data on 32 indicators allowed us to identify the factors of switching and inhibition efficiency as relatively independent, which is consistent with the data of previous studies on the structure of cognitive control functions. This gives reason to expect complex nonlinear relationships with various aspects of foreign language proficiency.

When comparing the indicators of the effectiveness of cognitive control in groups of people who speak and do not speak foreign languages, we found significant differences in the effectiveness of individual indicators and differences at the level of trends in the complex effectiveness of the inhibition and switching functions. A higher efficiency of interference inhibition in persons who speak a foreign language may indicate the training of the inhibition function when choosing the target language material in the process of communication in a particular language from the point of view of the model of activation of lexical material in all available languages in response to semantic activation [16–18]. The lower cost of switching in tasks with a change of tasks among people who speak foreign languages may indicate that the switching function is trained in the process of selecting a language code (code switching) when communicating in several languages. In addition to the concept of language code, which considers language as a system of connections, reflecting in particular the grammatical and syntactic structure of the language, the results obtained correlate with the model of selective activation [19].

The relationship between the number of languages spoken by the respondent and the effectiveness of cognitive control was also considered. A systematic increase in switching accuracy with an increase in the number of languages was found, which can be interpreted as a type of cognitive training and correlates with data on the relationship of foreign language proficiency with the time of onset of dementia [20]. Along with an increase in the accuracy of inhibition, an increase in the speed of task completion was observed in persons who speak three or more languages, that is, two or more foreign languages. The obtained data have an important practical application in the context of globalization processes and the expansion of international cooperation, which entails the need to learn foreign languages.

Another important aspect of the relationship between foreign language proficiency and the effectiveness of cognitive control functions is the level of foreign language proficiency. As a result of the correlation analysis, it was found that the accuracy of performing tasks in the language is significantly related to the level of proficiency of respondents in the main foreign language. It is important to note that the level of language proficiency is closely related to the time of the beginning of learning it, so the training itself for several years may not bring significant changes in the effectiveness of cognitive control, as was shown in studies of the impact of late learning a foreign language on the indicators of cognitive aging [21].

Finally, we considered the relationship of indicators of language proximity calculated from the WALS database which offers a comprehensive typological assessment of the similarity of languages, including grammatical features. As a result of the analysis, no linear relationships were found between the grammatical proximity of languages and indicators of the effectiveness of cognitive control, but when calculating quadratic functions, there were highly significant results showing an increase in the overall speed of performing tasks for cognitive control in groups that speak relatively close and relatively distant languages in their grammatical structure. At the same time, the overall speed of completing tasks was lower for those who speak languages with average grammatical similarity.

The obtained results allow us to make an assumption about the heterogeneity of the process of constructing speech activity in several languages. Probably, certain aspects of this process are more pronounced in the possession of grammatically close languages, while others are more pronounced in the possession of languages that are far away in terms of lexical and grammatical structure. Thus, the process that is of great importance in the possession of similar languages allows you to increase the overall speed of completing tasks for cognitive control in people who speak such languages, and the process that contributes to the construction of language structures in the possession of dissimilar languages affects similarly the speed of completing tasks in people who speak such languages, while in the possession of languages of medium similarity, both these processes do not receive enhanced development, or balance each other.

5 Conclusion

In this study, we assessed how foreign language knowledge and L1/L2 typological similarity affect cognitive control functions. It was found that the knowledge of a foreign language and the number of foreign languages known positively affect the effectiveness of cognitive control. Cognitive control was also positively related to the proficiency of foreign language use as measured by a number of language competencies indicators. Finally, we found that L1 to L2 typological similarity affects cognitive control in a parabolic fashion with cognitive control efficiency being highest for L2s with low of high similarity to L1. These results suggest an account of L2 knowledge as a type of cognitive training which affects the efficiency of cognitive control – most important, task switching – in a nonlinear way.

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References

1. Bialystok, E., Martin, M.M.: Attention and inhibition in bilingual children: evidence from the dimensional change card sort task. Dev Sci. **7**(3), 325–339 (2004). https://doi.org/10.1111/j.1467-7687.2004.00351.x
2. Bialystok, E., Shapero, D.: Ambiguous benefits: the effect of bilingualism on reversing ambiguous figures. Dev. Sci. **8**(6), 595–604 (2005). https://doi.org/10.1111/j.1467-7687.2005.00451.x
3. Carlson, S.M., Meltzoff, A.N.: Bilingual experience and executive functioning in young children. Dev Sci. **11**(2), 282–298 (2008). https://doi.org/10.1111/j.1467-7687.2008.00675.x
4. Martin-Rhee, M.M., Bialystok, E.: The development of two types of inhibitory control in monolingual and bilingual children. Bilingualism: Lang. Cogn. **11**(1), 81-93 (2008). doi:https://doi.org/10.1017/S1366728907003227
5. Bialystok, E., Craik, F.I.M., Luk, G.: Cognitive control and lexical access in younger and older bilinguals. J. Exp. Psychol. Learn. Mem. Cogn. **35**, 828 (2008). https://doi.org/10.1037/a0015638
6. MacWhinney, B.: The emergence of linguistic form in time. Connect. Sci. **17**, 191–211 (2005). https://doi.org/10.1080/09540090500177687
7. Bialystok, E., Craik, F.I.M., Ryan, J.: Executive control in a modified antisaccade task: effects of aging and bilingualism. J. Exp. Psychol. Learn. Mem. Cogn. **32**(6), 1341–1354 (2006). https://doi.org/10.1037/0278-7393.32.6.1341
8. Costa, A., Hernandez, M., Sebastian-Galles, N.: Bilingualism aids conflict resolution: evidence from the ANT task. Cognition **106**, 59–86 (2008). https://doi.org/10.1016/j.cognition.2006.12.013
9. Shoghi Javan, S., Ghonsooly, B.: Learning a foreign language: a new path to enhancement of cognitive functions. J Psycholinguist Res. **47**(1), 125–138 (2018). https://doi.org/10.1007/s10936-017-9518-7
10. Bialystok, E.: Acquisition of literacy in bilingual children: a framework for research. Lang. Learn. **57**, 45–77 (2007). https://doi.org/10.1111/j.1467-9922.2007.00412.x
11. Tao, L., Marzecová, A., Taft, M., Asanowicz, D., Wodniecka, Z.: The efficiency of attentional networks in early and late bilinguals: The role of age of acquisition. Front. Psychol. **2**, 123 (2011). https://doi.org/10.3389/fpsyg.2011.00123
12. Greene, J.D., Morelli, S.A., Lowenberg, K., Nystrom, L.E., Cohen, J.D.: Cognitive load selectively interferes with utilitarian moral judgment. Cognition **107**(3), 1144–1154 (2008). https://doi.org/10.1016/j.cognition.2007.11.004
13. von Bastian, C.C., Souza, A.S., Gade, M.: No evidence for bilingual cognitive advantages: a test of four hypotheses. J Exp Psychol Gen. **145**(2), 246–258 (2016). https://doi.org/10.1037/xge0000120
14. Haspelmath, M., Bibiko, H., Hagen, J., Schmidt, C.: The World Atlas of Language Structures. Oxford University Press, Oxford (2005)
15. Haspelmath, M., Dryer, M., Gil, D., Comrie, B.: The world atlas of language structures online (2013)
16. Green, D.W.: Control, activation, and resource: a framework and a model for the control of speech in bilinguals. Brain Lang. **27**(2), 210–223 (1986). https://doi.org/10.1016/0093-934x(86)90016-7
17. Green, D.W.: Mental control of the bilingual lexico-semantic system. Bilingualism: Lang. Cogn. **1**, 67–81 (1998). doi:https://doi.org/10.1017/S1366728998000133
18. Hermans, H.J.M., Kempen, H.J.G.: Moving cultures: the perilous problems of cultural dichotomies in a globalizing society. Am. Psychol. **53**(10), 1111–1120 (1998). https://doi.org/10.1037/0003-066X.53.10.1111

19. Pechmann, T., Zerbst, D.: The activation of word class information during speech production. J Exp Psychol Learn Mem Cogn. **28**(1), 233–243 (2002). https://doi.org/10.1037/0278-7393.28.1.233
20. Bialystok, E., Craik, F.I., Freedman, M.: Bilingualism as a protection against the onset of symptoms of dementia. Neuropsychologia. **45**(2), 459–464 (2007). doi: https://doi.org/10.1016/j.neuropsychologia.2006.10.009
21. Antón, E., García, Y., Carreiras, M., Duñabeitia, J.A.: Does bilingualism shape inhibitory control in the elderly? J. Mem. Lang. **90**, 147–160 (2016). https://doi.org/10.1016/j.jml.2016.04.007

Behavioral and Neurophysiological Correlates of Orthographic Learning in L1 and L2 Alphabets

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Abstract. The acquisition of new orthographic representations is a rapid and highly automatic process in monolingual readers. Our study extends existing research to biliterate populations, addressing the impact of phonological inconsistencies across native (L1) and second language (L2) alphabets during orthographic learning. Behavioral and EEG signals were collected from a group of 24 Russian-English biliterates via a reading-aloud task using familiar and novel words repeated across ten consecutive blocks in three Script conditions: (1) native Cyrillic, (2) non-native Roman, and (3) ambiguous (phonologically inconsistent graphemes shared by L1 and L2 alphabets). Linear mixed-effects modelling of both behavioral and ERP data revealed reliable Block x Lexicality x Script interactions, indicating that naming latencies and brain activity changed differently across training blocks for novel and familiar words and, importantly, depending on script presentation. Particularly, novel words presented in the ambiguous script showed longer naming latencies and slower reading automatization than those presented in L1 and L2 alphabets. Nonetheless, despite this interference, their naming latencies matched those of familiar words before the end of the training, suggesting the attribution of their representations in the reader's lexicon. The enhancement of early brain responses observed for these stimuli alongside their training confirmed the improvement in their orthographic analysis and lexical access. Critically, this pattern of results was not found for familiar, already represented words, which exhibited a suppression of their brain activity across repetitions. Overall, our results indicate that phonological inconsistency interferes with novel word encoding but it does not prevent efficient attribution of orthographic representations.

Keywords: ERPs · Rapid word learning · Orthographic learning · Biliteracy

1 Introduction

Extensive behavioral and neuroimaging research has demonstrated the impressive ability of the human brain to acquire novel vocabulary in a very rapid and accurate fashion, both in visual [1–4] and spoken [5–7] modalities. Hence, after just a handful of

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exposures to a novel lexical entry, a new word memory representation is formed, enabling its direct recognition in subsequent encounters. Such findings have been reported using either explicit training or incidental learning paradigms or even under non-attentive, passive exposure conditions, thus pointing to the existence of the general brain mechanisms for the fast and automatic formation of novel word-form representations (see [8] for a review).

In visual domain, this process is referred to as orthographic learning, and it has been shown as particularly important for the development of reading fluency; indeed, the incorporation and strengthening of new orthographic traces allow readers to transfer from a grapheme-to-phoneme, serial decoding of the novel word to a holistic, whole-word recognition strategy, thus ensuring sufficient cognitive resources for text comprehension [9, 10]. Such a fast automatization has been demonstrated after very short training periods (no more than ten exposures) by using different behavioral indices. In particular, the reduction of the length effect, i.e. the reduction in naming latency difference between short and long novel words [1–3, 11] and the reduction of the lexicality effect, i.e. the difference between naming latencies for novel and familiar words [12, 13], have been reported as indicative of fast representation acquisition of novel written word-forms.

Importantly, the ability to rapidly acquire new orthographic representations is not only critical for the acquisition of reading and general communicative skills in the native language, but is equally important in second language (L2) acquisition. The latter is especially relevant nowadays with the ever-growing number of bilingual people, many of them being biliterate bilinguals, i.e., fluent readers in a second language. Orthographic learning for bilinguals very often implies managing a typologically different script (e.g., compare Greek vs. French) or even a completely different writing system (e.g., Chinese vs. English). In this case, similarities and differences across L1 and L2 alphabets and writing systems could influence the reading performance and acquisition of new vocabulary in L2.

Indeed, several studies have reported systematic evidence for the transfer across L1-L2 alphabets during visual word recognition, showing that phonological representations are integrated across both languages and are simultaneously activated during reading [14–16]. Importantly, phonological inconsistencies across alphabets, supported by incongruent grapheme-to-phoneme mappings between L1 and L2, have been found to affect visual word recognition in biliterates [17–19]. In particular, L2 words that contain inconsistent or ambiguous graphemes (i.e., the same visual input is mapped into different phonemes across alphabets or scripts) are named significantly slower than those containing unambiguous, language-specific L2 graphemes, likely as a result of competing decoding rules in the two languages.

Despite the fact that such ambiguity across L1-L2 alphabets might likely affect the process of orthographic learning, the vast majority of studies have been carried out with monolingual populations, hence leaving this question largely unresolved. The present study is aimed at filling this gap by studying the acquisition of novel orthographic representations in a sample of Russian-English biliterates. These languages use alphabetic scripts showing a considerable degree of graphemic overlap, with several graphemes shared but inconsistently decoded across Cyrillic and Roman scripts, and hence particularly suitable to address the impact of phonological inconsistencies during the process of fast orthographic learning.

Moreover, taking into account the dynamic nature of human language, and rapid neural changes which are likely to unfold during the formation of new orthographic representations, high-temporal resolution techniques, such as electroencephalography (EEG), appear to be most optimal for addressing this question [8, 20]. Thus, in order to effectively capture this process and track the impact of phonological inconsistencies during orthographic learning, both naming latencies and brain electrical signals were recorded during a short training with novel written word-forms in L1 and L2 alphabets. We hypothesized that phonological inconsistencies across the two languages' scripts would interfere with the decoding and representation of novel L2 words, showing longer naming latencies and reduced match with other, already familiar words. Moreover, such inconsistencies could be expected to particularly affect the first 250 ms of novel written word-form processing, when orthographic analysis and lexical access take place, which could therefore be reflected in early brain responses known to index such processes, such as the N1/P1 and P200 ERP components [21–26].

2 Materials and Methods

2.1 Participants

24 participants (18 females, aged between 18 and 35 years old, M = 22.24, SD = 3.70) took part in the experiment. All participants were right-handed, native Russian (L1) speakers with normal or corrected-to-normal vision and no history of cognitive, neurological, or psychiatric disorders. All of them had English as their second language (L2), with different proficiency levels (the mean proficiency level obtained in Cambridge Test was 11.92, range = 4–23). The study was approved by the Ethics Committee of the Department of Psychology, National Research University Higher School of Economics.

2.2 Stimuli

Experimental stimuli consisted of 24 familiar and novel words, equally divided into L1 Cyrillic (4 familiar, i.e. "шаг"; 4 novel, i.e. "шаз"), L2 Roman (4 familiar, i.e. "vet"; 4 novel, i.e.: "vaz"), and an ambiguous script condition (4 familiar, i.e.: "cop"; 4 novel, i.e.: "pex"). All stimuli were matched in length and CVC structure; trigram frequency values for stimuli in L1 and L2 were obtained from Russian National corpus and British National Corpus online databases, respectively, and matched across each group of familiar and novel words. Importantly, unambiguous stimuli in Cyrillic and Roman scripts were designed by using graphemes specific to each alphabet (e.g., j, ш) and those common in both languages and mapped onto the same phonemes (e.g., a, м). In turn, ambiguous stimuli were created by combining common and consistent graphemes with common but inconsistent graphemes which are used in both Cyrillic and Roman alphabets but decoded into a different phoneme depending on the script (e.g., the grapheme p, decoded as /p/ in Roman but as /r/ in Cyrillic).

2.3 Procedure

After mounting the EEG cap on the participant's scalp, the task was explained to the participants as a novel word learning study, in which novel and also familiar words would be repeatedly presented across ten training blocks, either in L1 (Russian) or in L2 (English). Participants were asked to read the stimuli aloud as fast and accurately as possible, and they were informed about the assessment of their learning performance in a subsequent task. In total, 24 familiar and novel words were presented, one at a time, at the center of a computer screen in a handwriting black font over a grey background with the help of E-prime software [27], while EEG was recorded. The presentation of the stimuli was pseudorandomized within each block and participant in order to prevent the presentation of two consecutive stimuli in the same condition (see Fig. 1). Participants' articulation of each stimulus was recorded via a Microsoft LifeChat LX-3000 headset connected to the E-prime desktop computer. Immediately after completing the reading-aloud task, participants performed a recall task, in which they were asked to write down all stimuli they could remember from the previous training phase. The duration of the entire experiment was approximately one hour.

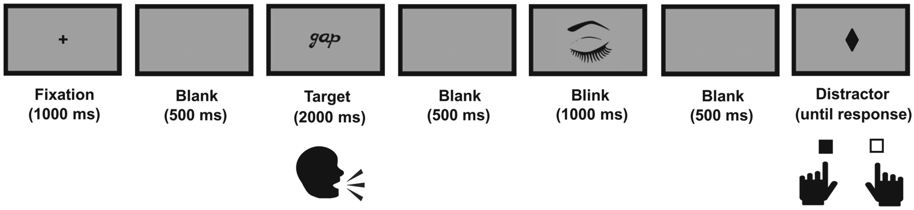

Fig. 1. Sequence of stimuli presentation during the training task. For each trial, target words were followed by a blink instruction and a distractor target, intended to prevent the bias in the pronunciation of ambiguous stimuli. Participants had to decide the colour of a geometrical figure by pressing the corresponding key on the keyboard. The colour of distractor stimuli was randomized across trials and responses were counterbalanced across participants.

2.4 EEG Recording and Preprocessing

EEG signals were recorded during the reading task by means of 64 Ag/Cl active electrodes, amplified and digitized with an ActiChAmp amplifier (Brain Products GmbH, Gilching, Germany) at 1000 Hz sampling rate. Two EOG electrodes, placed below and at the canthus of the left eye, were used to monitor vertical and horizontal ocular movements. An additional analog channel was used to feed the amplifier with input signals recorded by a sound sensor, thus allowing us to detect the onset of participant's utterances during EEG recording. The EEG signal was referenced to the vertex electrode (Cz) during recordings, and high and low pass filters at 0.1 and 100 Hz were applied online. Preprocessing of the EEG data was carried out using Brainstorm software [28]. A 45-Hz low-pass filter was applied offline and channels showing bad signal were eliminated across trials. An Independent Component Analysis (ICA) was implemented to remove ocular artifacts. Data was re-referenced to averaged mastoid activity and epoched between −200 to 2000 ms post stimulus onset; 200-ms pre-stimulus onset was used for baseline correction. An additional artifact rejection procedure (using exclusion criteria at ± 100 μV) was applied to remove any epoch containing artifacts or naming responses earlier than 400 ms stimulus onset. Finally, EEG epochs were averaged per subject and per condition and ERPs were computed (the average number of trials per condition was four).

2.5 Statistical Analyses

Naming latencies were extracted manually for each trial and participant using Praat software [29]. Utterances containing errors or latencies 2 SD above or below the mean were excluded from further analyses (representing 3.38% of data). Remaining data was analyzed by means of mixed-effects models [30] using lmer function and lmerTest packages [31], implemented in R software [32]; Block (from 1 to 10), Lexicality (familiar vs. Novel words), and Script (Cyrillic, Roman and Ambiguous) were entered as predictor variables (fixed effects), participants and items were used as random effects, and the RTs – as the dependent variable. Step function was used to determine the best model (showing the lowest AIC —Akaike's Information Criterion). Similar analysis was carried out for the percentage of correctly recalled stimuli, including script (Russian, English, Ambiguous) and lexicality (familiar and novel words) as predictors (fixed effects) and participants as a random effect.

Regarding the EEG data, a visual inspection of the grand-averaged ERP waveforms was carried out in order to detect time windows of differences across conditions. Accordingly, ERP activity was averaged across conditions at three different latencies: 30–60 ms, 90–120 ms and 150–250 ms. For each latency, 44 channels broadly distributed over frontal, central and posterior scalp sites were selected and divided into sixteen different topographical regions (8 vertical lines, divided in 2 anterior-posterior horizontal lines and in 2 left-right hemisphere vertical lines), with an average of two to three channels computed per region (see Fig. 3). This data was analyzed using mixed-effects models with Block (1 and 10), Lexicality (familiar and novel words), Script (Cyrillic, Roman and Ambiguous), Hemisphere (left and right), Anterior-Posterior (anterior and posterior sensor location) and Laterality (including four vertical lines, from left to right) and as predictors (fixed effects) and participants as a random effect.

3 Results

3.1 Behavioral Data

Mixed-effects modelling conducted on naming latencies showed the best model as RT ~ Block x Script x Lexicality + (1|Participant) + (1|Item). A general ANOVA conducted on this model confirmed the significance of the three-way interaction (F (18,5270) = 1.63, p = .044), revealing that repeated exposures across the ten training blocks caused a decrease in the differences between familiar and novel words, although differently depending on the script of presentation. Follow-up analyses were carried out in order to further explore this interactive effect. These post hoc comparisons indicated that the script of presentation had an impact on naming latencies for both novel (F (2,2662) = 31.52, p < .001) and familiar words (F (2,2662) = 44.76, p < .001), and the direction of this effect was different for both types of stimuli. Namely, in Block 1, novel words were named similarly slower in both L2 and Ambiguous scripts than in L1, although pair-wise comparisons did not reach significance (L2 vs. L1, Estimate = 143.6, p > 0.05; Ambiguous vs. L1, Estimate = 144.06, p > 0.05); however, familiar words were much more affected by their presentation in L2 (Estimate = 130.88, p > 0.05) than by the ambiguity of the script (Ambiguous vs. L1: Estimate = 36.49, p > 0.05). Nonetheless, at the end of the training (Block 10), the impact of the script was similarly reduced for both novel and familiar words (Novel words: L2 vs. L1: Estimate = 7.49, p = 1; Ambiguous vs. L1: Estimate = 48.49, p > .05; Familiar words: L2 vs. L1: Estimate = 48.43, p > .05; Ambiguous vs. Cyrillic, Estimate = 39.17, p > .05).

Regarding the effect of training, this was found stronger for novel words (F (9,2655) = 19.44, p < .001) than for familiar words (F(9,2655) = 6.76, p < .001). In particular, the largest decrease of naming latencies was found for novel words presented in L2 (Estimate = 206.05, p < .001) and in Ambiguous script (Estimate = 163.08, p < .001), followed by those presented in L1 (Estimate = 72.92, p < .05), whereas for familiar words, only those presented in L2 showed a significant decrease in their naming latencies across repetitions (L2: Estimate = 140.39, p < .001; Ambiguous: Estimate = 46.08, p > .05; L1: Estimate = 46.29, p > .05). As a consequence, differences between novel and familiar words decreased differently depending on the script. The general effect of lexicality was found significant both at Block 1 (F (1,532) = 38.29, p < .001) to Block 10 (F(1,531) = 7.30, p < .05); nonetheless, the pattern of results found in pair-wise comparisons, as well as pointed by the three-way interaction, likely indicate that lexical differences decreased across the training, and faster in L1 and L2 than in the Ambiguous script, although these pair-wise comparisons did not reach significance. Thus, initial differences observed in Block 1 between familiar and novel words in L1 and L2 scripts (L1: Estimate = 73.80, p > .05; L2: Estimate = 74.74, p > .05) were decreased already at the third presentation (L1: Estimate = 26.0, p > .05, L2: Estimate = 28.0, p = 1). However, novel and familiar words presented in Ambiguous script only showed a similar decrease after the sixth presentation (first block: Estimate = 175.23, p > 0.05; sixth block: Estimate: 34.76, p > .05) (see Fig. 2).

Results for the recall task revealed the best model as Accuracy $\sim$ Script + (1| Participant). An ANOVA carried out for this model confirmed the main effect of script (F(2,159) = 10.85, p < .001). Pair-wise comparisons revealed that stimuli presented in the ambiguous script exhibited the best recall rates (41.2%), significantly higher than those presented in L1 (19.45%, p < 0.001) and higher, albeit insignificantly, than those recalled in L2 (33.33%, p = 0.18). Notably, the stimuli presented in the native alphabet showed the lowest recall rates, significantly lower than those presented in L2 (19.45 vs. 33.33%, p = .005).

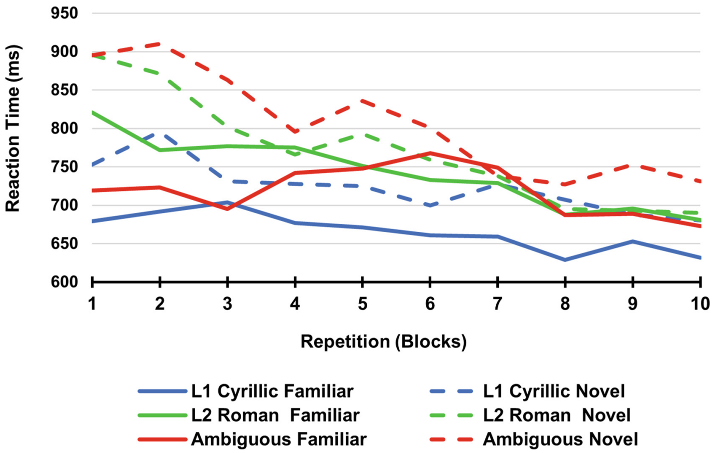

Fig. 2. Mean naming latencies (RTs) obtained across training blocks for each experimental condition (familiar and novel words in L1, L2 or ambiguous script).

3.2 Electrophysiological Data

30–60 ms. Mixed-effects modelling conducted on this time window showed the best model as Signal ~ Script:Block:Hemisphere. An ANOVA carried out on this model confirmed the significance of the three-way interaction Script x Block x Hemisphere (F (2, 12625) = 3.917, p = .019). To follow this up, the interaction Script x Block interaction was explored across the two hemispheres. The interaction was found significant over both hemispheres, although stronger for the right (F(2, 6307) = 19.84, p < .001) than the left hemisphere (F(2, 6307) = 3.28, p = 0.037). Thus, across the training blocks, the stimuli showed (regardless of their lexical status) an enhancement of early brain responses in the left hemisphere, particularly stronger for those presented in L2 (Estimate = −1.17, t = −7.26, p < .0001) in comparison to that exhibited by those in L1 (Estimate = −0.63, t = −3.90, p = .0013) or Ambiguous script (Estimate = −0.70, t = −4.400, p = .0002). This modulation caused the increase of differences across training blocks between L2 stimuli and those presented in L1 (Block 1: Estimate = 0.2, t = 1.25, p = 0.81; Block 10: Estimate = 0.74, t = 4.60, p = 0.0001) and in ambiguous script (Block 1: Estimate = −0.35, t = −2.21, p = 0.23; Block 10: Estimate = −0.81, t = −5.08, p < .0001). Importantly, stimuli presented in L1 and ambiguous script showed no differences, neither in the first (Estimate = 0.15, t = −0.964, p = 0.92) nor in the last block of training (Estimate = −0.07, t = −0.47, p = 0.99). The pattern found in the right hemisphere was very similar except for stimuli presented in L1 script, which showed no modulation across training blocks (Estimate = 0.05, t = 0.33, p = 0.99) (see Fig. 3).

90–120 ms. Results on this time window revealed the best model as Signal ~ Script:Lexicality:Block. An ANOVA conducted on this model confirmed a significant Script x Lexicality x Block interaction (F(2, 12625) = 13.35, p <.001) implying that, at this latency, brain responses for novel and familiar words showed a different change across their training depending on the script of presentation. Post hoc comparisons

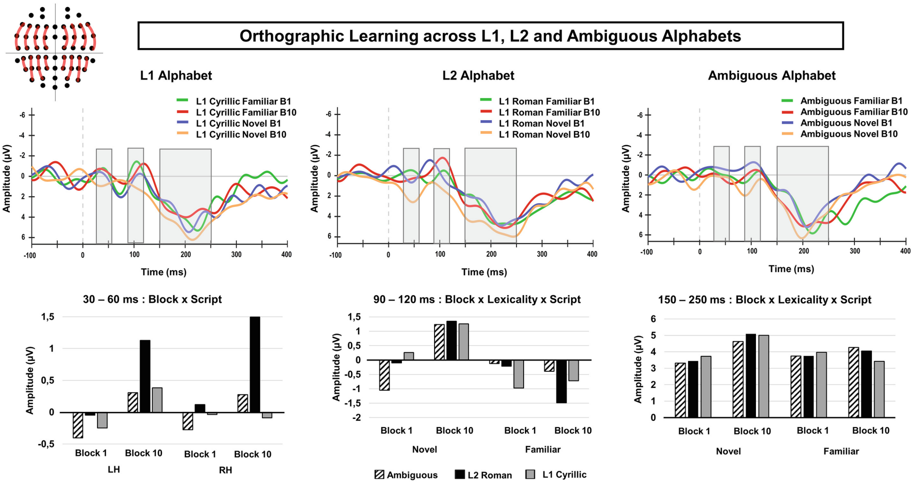

Fig. 3. Effect of orthographic learning across the three script conditions. Upper part. Averaged ERP waveforms for novel and familiar words in the first and tenth block of training across the three different script conditions (the average was computed at all the scalp positions included in the analysis, displayed in the map on the left upper part, where interactions resulted broadly significant). Grey shaded areas indicate the time windows for significant interactions between Block and Script (30–60 ms) and Block x Lexicality x Script (90–120 and 150–250 ms).

conducted by collapsing the rest of topographic factors showed that novel words exhibit a significant increase of their activity across blocks, including those presented in ambiguous (Estimate = –2.285, t= –13.27, p < .0001), L2 (Estimate = −1.45, t = –7.63, p < .0001) and L1 (Estimate = −0.9995 t = –3.869, p = 0.0006) scripts, whereas familiar words showed the opposite pattern, with no change or suppression of their activity across blocks (only significant for those presented in L2, Estimate = 1.273, t = 6.706, p < .0001, but not in L1 or ambiguous scripts, p > .05), thus suggesting lower engagement of low-level extraction of visual features during a sublexical stage of visual recognition. As a result, initial differences between familiar and novel words, particularly higher in L1 (Estimate = 1.230, t = 4.78, p < .0001) and ambiguous scripts (Estimate = −0.927, t = −5.38, p < .0001) as compared to L2 (Estimate = 0.11, t = 0.592, p = 0.93) were found increased after the training (L1: Estimate = 1.97, t = 7.68, p < .0001; Ambiguous: Estimate = 1.62, t = 9.44, p < .0001; L2: Estimate = 2.83, t = 14.93, p < .0001) (see Fig. 3).

150–150 ms. Mixed-effects modelling conducted on the averaged time window showed the best model as Signal ~ Script:Lexicality:Block. An ANOVA carried out in this model confirmed the significance of the three-way interaction Script x Lexicality x Block (F(2, 12619) = 3.46, p = 0.031). Follow-up analyses collapsing topographic factors were carried out in order to explore this interactive effect. Novel words showed a significant increase in their activation across blocks of training, similarly for those presented in L1 (Estimate = −1.27, t = −6.58, p < .0001), L2 (Estimate = −1.65, t = -8.19, p < .0001) or ambiguous script (Estimate = −1.31, t = −6.81, p < .0001), indicating the increase in the access to the newly word-form representations achieved throughout the training; however, familiar words showed a different pattern of activation, with no modulation (L2: Estimate = −0.301, t = −1.49, p = 0.43) or with a suppression of their activity across repetitions, as shown by those presented in native alphabet (Estimate = 0.54, t = 2.79, p = 0.027); only those familiar words presented in ambiguous script showed an enhancement of their neural responses at this latency (Estimate = -0.528, t = -2.73, p = 0.031) (see Fig. 3). As a consequence of the higher modulation elicited by novel words across the training, the differences between these and familiar words were found to be increased at the end of the training, particularly for those in L1 (Block 1: Estimate = −0.239, t = −1.23, p > .05; Block 10: Estimate = 1.58, t = 8.14, p < .0001) and L2 (Block 1: Estimate = -0.306, t = −1.52, p = 0.42; Block 10: Estimate = 1.042, t = 5.17, p < .0001), but not for Ambiguous script, in which familiar words showed no enhancement through repetitions (Block 1: Estimate = -0.43, t = −2.23, p > .05; Block 10: Estimate = 0.35, t = 1.84, p > .05).

4 Discussion

The present study investigated the process of orthographic learning using both native and non-native alphabets. In particular, we aimed to determine the impact of phonological (in)consistencies across L1 and L2 scripts on the decoding and representation of novel words. To this end, behavioral and neurophysiological responses were obtained from a group of Russian-English biliterates during a short training with familiar and novel written word-forms, presented either in their L1, L2 or in an ambiguous script condition in which stimuli's graphemes were inconsistently decoded across alphabets. In general, our results demonstrate that phonological inconsistency across alphabets influenced the decoding and reading automatization for novel words. Despite this interference, all learned words were represented and accessible in the reader's lexicon, as indicated by various behavioral and neural indices. These results are discussed in more detail as follows.

Behavioral data obtained during the training with novel written words confirmed the impact of phonological inconsistency on the reading latencies of these stimuli, which were significantly higher than for those presented in L1 and L2 scripts in which novel word's graphemes were unambiguous. Nonetheless, this ambiguity effect was mainly detected at the beginning of the reading task, when stimuli were unfamiliar. Indeed, the impact of the inconsistency was stronger for novel and unfamiliar words than for the familiar words, in agreement with previous findings [17–19]. Critically, the impact of the phonological ambiguity decreased later during the training and, by the end of the task, was similar to that exhibited by familiar words. These findings suggest that, along their repeated exposure, new memory traces were formed for these stimuli, assisting their reading through a direct, whole-word recognition rather than a serial grapheme-to-phoneme decoding strategy. Importantly, the attribution of such mental representations was confirmed by the reduction of the differences in naming latencies between novel and familiar ambiguous words along the training. Such change in the lexicality effect, known to reflect differences in the processing of familiar and non-lexical entries [33], speaks in favor of the representation of novel ambiguous words in reader's lexicon, despite their inconsistent grapheme-to-phoneme mapping. Furthermore, results obtained in the recall task also confirmed the successful formation and access to newly-acquired mental representations for novel ambiguous words, which exhibited equal performance to familiar words. Nonetheless, a more careful block-by-block analysis of the lexicality effect indicated that, in fact, phonological inconsistency does impact the speed at which novel orthographic representations are built up in the reader's lexicon. Thus, whereas novel and familiar words presented either in L1 or L2 conditions matched in their naming latencies already at the third training block, the similar effect was observed in the ambiguous condition only at the sixth presentation. Taken together, these results demonstrate that, although phonological inconsistency interferes with and slows down the representation of novel word-forms in the reader's lexicon, this effect does not prevent a successful development and access of these orthographic traces after a relatively short training. Therefore, these findings indicate the presence of a rapid orthographic learning for novel word forms even in conditions of phonological inconsistency, thus extending previous behavioral results obtained in uniliterate populations [1–3, 11, 34].

Furthermore, successful formation of the corresponding representations for novel ambiguous words was also reflected in participant's electrophysiological responses obtained during training. Our comparison of the brain signals elicited by novel ambiguous words at the beginning and the end of their training revealed an enhancement of very early brain responses to these stimuli, indicating an improvement in their visual processing at both sublexical and lexical stages. Indeed, orthographic training of novel stimuli was found to modulate brain responses starting from $\sim$ 30 ms to $\sim$ 250 ms post stimulus onset, likely reflecting recruitment and enhancement of early attentional mechanisms engaged in subsequent extraction of visual features and word-form access, respectively [24, 25, 35, 36]. Importantly, such a pattern of brain responses was found differently modulated through the training, depending on the alphabet of presentation. Early brain responses as the one obtained in the first time window (30–60 ms) have been found during repetition of relevant stimuli; although such early repetition effects remain unclear, and thus might be consider cautiously, they have been propose to be related to attentional mechanisms, oriented towards low-level, physical properties of the salient stimuli during visual processing [37, 38]. This modulation was similar for novel and familiar words, thus indicating similar engagement of attentional mechanisms the stimuli regardless of their lexical status and general familiarity. Nonetheless, this early brain response was sensitive to the script in which stimuli, either novel or familiar, were presented, particularly to that containing non-native, L2-specific graphemes. Indeed, stimuli presented in L2 elicited a significantly stronger modulation of this early ERP through their training, likely indicating the higher saliency and strong demand for attentional resources during the repeated exposure to stimuli in non-native alphabet, a result that could be influenced by the comparatively low level of L2 proficiency in our sample. In contrast, the stimuli containing native or shared L1-L2 graphemes (namely those in L1 and ambiguous scripts) showed similar enhancement of this early response across the exposures, which also suggests that ambiguous stimuli engaged similar attentional resources those in L1, despite the graphemic inconsistency. Importantly, this early modulation suggests that the language script is detected in a very fast and automatic fashion, as early as 30 ms after word processing onset.

Subsequent brain activity modulations observed during the training (90–120, 150–250 ms) are closely related to the orthographic processing carried out at sublexical and lexical stages of visual word recognition, rather than to general visual attention mechanisms. In particular, responses starting from ∼100 ms post word onset are considered to index the extraction of low-level visual features of words (i.e., letters), followed by lexical word-form access from ∼200 ms after presentation [24, 25, 35, 36, 39]. Accordingly, an increased response elicited by novel words at these latencies suggests an enhancement in the orthographic analysis and representation of these stimuli as a consequence of their training, in agreement with previous M/EEG studies carried out in monolingual and monoliterate populations [6, 40]. Importantly, such an enhancement was only exhibited by novel, to-be-lexicalized words but not by those already having strong lexical representations, which, in contrast, showed an activity suppression through repetitions. Thus, at the 90–120 ms time window, novel words showed a significant enhancement of their activity across the training, particularly those in ambiguous or non-native alphabet, for which the underlying extraction of visual features during orthographic analysis is likely more effortful; however, familiar words (either in L1 or in ambiguous script) did not show such enhancement but an activity suppression. Only L2 words, consisting on non-native graphemes, showed an ERP enhancement at this latency, likely driven by the low L2 proficiency level of participants. A similar pattern of enhancement vs. Suppression of activity was found for novel and familiar words in the late time window (150–250 ms); such enhancement elicited by novel words likely reflects the progressive formation and increasingly improved access of newly built up representations for these stimuli across their training, which, importantly, was observed regardless of their script. L1 familiar words, on the contrary, did not show an enhancement at this latency but instead exhibited a suppression of their activity. This indicates that, for already lexicalized stimuli, word access is achieved irrespectively of their repetitions, with some repetition-related habituation. Importantly, such differential pattern of enhancement vs. Suppression of activity is consistent with previous findings for repetition of novel vs. Familiar stimuli, reflecting the extraction and incorporation of new information in order to further represent a novel stimulus vs. Adaptation of the neural response to a familiar one, which already has a robust representation [41, 42].

It is important to note that, at this late time window, not only novel but also familiar words in ambiguous script exhibited an enhancement of their activity, suggesting a facilitation of their access across repetitions. Although ambiguous familiar words might possess representations in both L1 and L2 lexicons, these are likely much weaker in L2 than in L1, especially taking into account the level of L2 proficiency of these participants (as also reflected in the earlier brain responses as well as in naming latencies, particularly slow in this condition in comparison to words presented in L1 or ambiguous scripts). Thus, for familiar words, such activity enhancement might reflect the formation (or update) and access of representations for these stimuli in L2 mental lexicon through repetitions. Importantly, future studies might also analyze participant’s articulation of ambiguous stimuli, thus clarifying whether these stimuli were actually read and hence represented in L2 rather in L1.

5 Conclusion

Overall, our findings indicate a rapid (after just 10 exposures) learning of novel written word-forms even in conditions of phonological inconsistency. Although inconsistent decoding rules across L1 and L2 alphabets does impact the naming latencies and the speed in which ambiguous novel words are represented in the mental lexicon, these stimuli show markers at both behavioral (reduction of the lexicality effect) and neurophysiological (enhancement of ERP activity at sublexical and lexical stages of their processing) levels indicative of fast orthographic learning. Importantly, EEG and other similarly temporary-precise tools (e.g., MEG) demonstrate their value in revealing the temporal dynamics underlying this process. In this regard, future ERP studies might scrutinize more elaborately the changes occurring both at behavioral and neural level with each new exposure to novel written-word forms.

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References

1. Kwok, R.K.W., Ellis, A.W.: Visual word learning in skilled readers of English. Q. J. Exp. Psychol. **68**(2), 326–349 (2015)
2. Kwok, R.K.W., Cuetos, F., Avdyli, R., Ellis, A.W.: Reading and lexicalization in opaque and transparent orthographies: word naming and word learning in English and Spanish. Q. J. Exp. Psychol. **70**(10), 2105–2129 (2017)
3. Maloney, E., Risko, E.F., O'Malley, S., Besner, D.: Short article: tracking the transition from sublexical to lexical processing: on the creation of orthographic and phonological lexical representations. Q. J. Exp. Psychol. **62**(5), 858–867 (2009)
4. Bermúdez-Margaretto, B., Beltrán, D., Cuetos, F., Domínguez, A.: Brain signatures of new (Pseudo-) words: visual repetition in associative and non-associative contexts. Front. Hum. Neurosci. **12**, 354 (2018)
5. François, C., Cunillera, T., Garcia, E., Laine, M., Rodriguez-Fornells, A.: Neurophysiological evidence for the interplay of speech segmentation and word-referent mapping during novel word learning. Neuropsychologia **98**, 56–67 (2017)
6. Kimppa, L., Kujala, T., Leminen, A., Vainio, M., Shtyrov, Y.: Rapid and automatic speech-specific learning mechanism in human neocortex. Neuroimage **118**, 282–291 (2015)
7. Yue, J., Bastiaanse, R., Alter, K.: Cortical plasticity induced by rapid Hebbian learning of novel tonal word-forms: evidence from mismatch negativity. Brain Lang. **139**, 10–22 (2014)
8. Shtyrov, Y.: Neural bases of rapid word learning. Neuroscientist **18**(4), 312–319 (2012)
9. Share, D.L.: Phonological recoding and self-teaching: sine qua non of reading acquisition. Cognition **55**(2), 151–218 (1995)
10. Share, D.L.: On the anglocentricities of current reading research and practice: the perils of overreliance on an "outlier" orthography. Psychol. Bull. **134**(4), 584 (2008)
11. Álvarez-Cañizo, M., Suárez-Coalla, P., Cuetos, F.: Orthographic learning in Spanish children: influence of previous semantic and phonological knowledge. J. Res. Reading **42**(1), 137–149 (2019)

12. Bermúdez-Margaretto, B., Beltrán, D., Domínguez, A., Cuetos, F.: Repeated exposure to "meaningless" pseudowords modulates LPC, but not N (FN) 400. Brain Topogr. **28**(6), 838–851 (2015)
13. Salasoo, A., Shiffrin, R.M., Feustel, T.C.: Building permanent memory codes: codification and repetition effects in word identification. J. Exp. Psychol. Gen. **114**(1), 50 (1985)
14. Jared, D., Szucs, C.: Phonological activation in bilinguals: evidence from interlingual homograph naming. Bilingualism **5**(3), 225 (2002)
15. Jouravlev, O., Lupker, S.J., Jared, D.: Cross-language phonological activation: evidence from masked onset priming and ERPs. Brain Lang. **134**, 11–22 (2014)
16. Jared, D., Kroll, J.F.: Do bilinguals activate phonological representations in one or both of their languages when naming words? J. Mem. Lang. **44**(1), 2–31 (2001)
17. Havelka, J., Rastle, K.: The assembly of phonology from print is serial and subject to strategic control: evidence from serbian. J. Exp. Psychol. Learn. Mem. Cogn. **31**(1), 148 (2005)
18. Rastle, K., Havelka, J., Wydell, T.N., Coltheart, M., Besner, D.: The cross-script length effect: further evidence challenging PDP models of reading aloud. J. Exp. Psychol. Learn. Mem. Cogn. **35**(1), 238 (2009)
19. Lukatela, G.: Effects of frequency and phonological ambiguity on naming Serbo-Croatian words. Eur. J. Cogn. Psychol. **11**(1), 1–16 (1999)
20. Shtyrov, Y., Stroganova, T.: When ultrarapid is ultrarapid: on importance of temporal precision in neuroscience of language. Front. Hum. Neurosci. **9**, 576 (2015)
21. Barnea, A., Breznitz, Z.: Phonological and orthographic processing of Hebrew words: electrophysiological aspects. J. Genet. Psychol. **159**(4), 492–504 (1998)
22. Proverbio, A.M., Vecchi, L., Zani, A.: From orthography to phonetics: ERP measures of grapheme-to-phoneme conversion mechanisms in reading. J. Cogn. Neurosci. **16**(2), 301–317 (2004)
23. Wu, Y., Mo, D., Tsang, Y.K., Chen, H.C.: ERPs reveal sub-lexical processing in Chinese character recognition. Neurosci. Lett. **514**(2), 164–168 (2012)
24. Assadollahi, R., Pulvermüller, F.: Early influences of word length and frequency: a group study using MEG. NeuroReport **14**(8), 1183–1187 (2003)
25. Assadollahi, R., Pulvermüller, F.: Neuromagnetic evidence for early access to cognitive representations. NeuroReport **12**(2), 207–213 (2001)
26. Hauk, O., Pulvermüller, F., Ford, M., Marslen-Wilson, W.D., Davis, M.H.: Can I have a quick word? Early electrophysiological manifestations of psycholinguistic processes revealed by event-related regression analysis of the EEG. Biol. Psychol. **80**(1), 64–74 (2009)
27. Schneider, W., Eschman, A., Zuccolotto, A.: E-prime: user's guide. Psychology Software Incorporated (2002)
28. Tadel, F., Baillet, S., Mosher, J.C., Pantazis, D., Leahy, R.M.: Brainstorm: a user-friendly application for MEG/EEG analysis. Comput. Intell. Neurosci. **2011**, 1–13 (2011). https://doi.org/10.1155/2011/879716s
29. Boersma, P.: Praat: doing phonetics by computer (2006). https://www.praat.org/
30. Baayen, R.H., Davidson, D.J., Bates, D.M.: Mixed-effects modeling with crossed random effects for subjects and items. J. Mem. Lang. **59**(4), 390–412 (2008)
31. Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.: lmerTest package: tests in linear mixed effects models. J. Stat. Softw. **82**(13), 1–26 (2017)
32. Team, R.C.: R: a language and environment for statistical computing (2013)
33. Chambers, S., Foster, K.I.: Lexical access and naming time'. J. Verbal Learn. Verbal Behav. **12**, 627635 (1973)
34. Suárez-Coalla, P., Álvarez-Cañizo, M., Cuetos, F.: Orthographic learning in Spanish children. J. Res. Reading **39**(3), 292–311 (2016)

35. Bentin, S., Mouchetant-Rostaing, Y., Giard, M.H., Echallier, J.F., Pernier, J.: ERP manifestations of processing printed words at different psycholinguistic levels: time course and scalp distribution. J. Cogn. Neurosci. **11**(3), 235–260 (1999)
36. Coulson, S.: Electrifying results: ERP data and cognitive linguistics, pp. 400–423. Methods in Cognitive Linguistics. Amsterdam, John Benjamins (2007)
37. Braeutigam, S., Bailey, A.J., Swithenby, S.J.: Task-dependent early latency (30–60 ms) visual processing of human faces and other objects. NeuroReport **12**(7), 1531–1536 (2001)
38. Poghosyan, V., Shibata, T., Ioannides, A.A.: Effects of attention and arousal on early responses in striate cortex. Eur. J. Neurosci. **22**(1), 225–234 (2005)
39. Kutas, M., Van Petten, C., Kluender, R., Traxler, M., Gernsbacher, M.A.: Handbook of Psycholinguistics. Traxler, M., Gernsbacher, M. (Eds.), pp. 659–724 (2006)
40. Partanen, E.J., Leminen, A., Cook, C., Shtyrov, Y.: Formation of neocortical memory circuits for unattended written word forms: neuromagnetic evidence. Sci. Reports **8**(1), 1–10 (2018)
41. Henson, R., Shallice, T., Dolan, R.: Neuroimaging evidence for dissociable forms of repetition priming. Science **287**(5456), 1269–1272 (2000)
42. Grill-Spector, K., Henson, R., Martin, A.: Repetition and the brain: neural models of stimulus-specific effects. Trends Cogn. Sci. **10**(1), 14–23 (2006)

Bilingualism as an Unstable State

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Abstract. Mathematical modeling of some processes underlying the phenomena of the individual and collective natural bilingualism confirmed the hypothesis of the instability of these states. It is shown that natural bilingualism, providing "double" communication can, at the same time, be a phase of the transition to monolingualism. This tendency of natural bilingualism towards a monolingual program can manifest itself at different levels of social organization. The disappearance of the languages of small ethnic groups is the most extensive manifestation and implementation of this tendency. The use of mathematical modeling methods allows understanding the degree of the influence of key parameters on the process of the disappearance of the ethnic language. The formation of natural bilingualism in children differs from the development of a language in a monolingual environment by possibility stops in the development of language (fossilization) and erasure of the language (language attrition). Practice shows that the negative impact of bilingual education on the intellectual and linguistic development of a child is possible, although it does not always manifest itself. Mathematical modeling of this process aims at finding an answer to the question of specific conditions leading to negative consequences. It confirmed the possibility of blocking spontaneous acquisition of one as well as of two languages simultaneously and showed which specific variables should be measured by instrumental methods for a more detailed description of the mechanisms of language acquisition. The developed models may be modified for better matching of the available solutions to experimental data.

Keywords: Language acquisition · Bilingualism · Phenomenological model · Analysis of dynamic modes · Language attrition · Disappearance of languages

1 Introduction

This work is devoted to the mathematical modeling of some processes underlying the phenomena of individual and collective bilingualism. In particular, we will speak about the spontaneous formation of bilingualism and about its disappearance. It seems obvious that natural bilingualism, that is involuntarily acquired in a linguistic environment, both at the level of an individual native speaker and in linguistic communities, expands

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the possibilities of communication. But there is another, less apparent side of this phenomenon. Natural bilingualism providing “double” communication is, at the same time, a phase of the transition to monolingualism [1].

It is known that bilingualism occurs as a result of social factors. Such factors are either the need to communicate in two languages in a bilingual environment (natural bilingualism) or motivated learning (artificial bilingualism). One might get the impression that social factors completely determine the success of the development of bilingualism. However, very little is known about the biological basis of bilingualism. What biophysical mechanisms can provide the functional operations necessary for children to communicate in two languages? What are the limitations that inevitably accompany any process?

To answer these questions the physical approach makes use of mathematical models based on the experimental experience of specialists in this field. The importance of the modeling method in studies of language development, bilingualism and multi-lingualism is noted in the works [2, 3]. On the basis of biophysical concepts of processing information signals in living systems, balance equations are formed (see, for example, [4–8, 16, 17]). The analysis of the solutions of such models and their comparison with the dynamic modes recorded by specialists allows forming an idea of the adequacy of the formalized description language being developed. Well-known theoretical points formed on the basis of the experience of specialists were taken into account for constructing models of individual and collective bilingualism:

Bivalence (dichotomy) “species specificity—plasticity” of the behavior of higher living beings [9]. The formation of a language in a monolingual environment is a species-specific process for Homo sapiens. For a healthy representative of the species, clear terms of the formation of speech in ontogenesis are mandatory, which occurs as self-development and can only be disturbed as a result of a disease. Bilingualism, both natural and artificial, is not a species-specific characteristic of a person. It is acquired through brain plasticity.

The concept of procedural—declarative memory [10]. These memory systems are provided by various neurofunctional and neuroanatomical structures. Two cognitive processes coexist, are switched on depending on the conditions of presentation of language material, complement each other and thereby make it possible to master new languages in different conditions and at different ages. The parallel in time, but oppositely directed influence of implicit linguistic competence and explicit metalinguistic knowledge creates the effect of the continuum.

The idea of bilingualism as a manifestation of brain plasticity, which manifests itself as the ability to acquire knowledge and skills, adaptation and restoration of impaired functions. Natural bilingualism is caused by a social phenomenon – the need to communicate in two languages. Under the influence of this need (implicit motivation), biological adaptation occurs. Like other natural adaptations, it has a return mechanism – language attrition. This involuntary (implicit) level of functioning of the language system, when more than one languages are acquired and lost due to fluctuations in the need to communicate. Most often, full or partial replacement of the first language with the second can be observed in younger children [11, 12]. Artificial bilingualism is formed as a result of motivated learning, when language knowledge and skills are acquired through formal (explicit) instructions and an appeal to declarative memory.

Hypothesis: The evolutionary mission of brain ***plasticity*** is, first of all, to maintain species-specific forms of behavior [13]. If we accept this hypothesis, the emergence of natural bilingualism becomes clear: in an unfamiliar linguistic environment, species-specific behavior (verbal communication) is not provided, so brain plasticity tools come into action. It is likely that the demand of the social environment – the need to understand several languages – formed this adaptation in phylogenesis and leads to its formation in ontogenesis.

The tendency to monolingualism in individual and collective bilingualism. With natural individual bilingualism, at the speech level this tendency is manifested in the form of linguistic interference, and at the behavioral level as a mixture of languages, ignoring one of the languages, language attritions. These phenomena are well observed during the change of generations in a family under conditions of migration [1].

2 Basic Elements of the Phenomenological Model Description

The dynamic models of natural bilingualism in a bilingual social environment were considered for both, individual bilingualism (language attritions) and collective bilingualism at the population level (disappearance of ethnic languages). Each of these model descriptions is based on the idea that words of any language are acoustic or symbolic (written) nomination[1] of concepts and images mastered and/or lost by an individual. Mathematical models allow considering various hypotheses and can be used, in particular, to overcome the myth about the undoubted usefulness of early bilingualism. Many researchers, as well as speech therapists and children's teachers (see for example, [14, 15]) note the possibility of negative manifestations in the process of the formation of bilingualism. At the same time, there is still no formalized description of possible reasons hindering the speech and general intellectual development of specific children. A version of such a model is shown in Sect. 2.2.

The interest in mathematical modeling of complex social processes, processes of inheritance and preservation of non-innate, "cultural information" at the population level is more widespread [5–8, 18, 20]. In particular, dynamic models of bi- and multilingualism in society are constructed [3, 16, 17]. The processes of dynamics of specific parts of the population corresponding to the frequencies of the use of one of two languages or simultaneous use of both (bilingualism) were considered [16, 17]. However, in these models, the main attention was, as rule, paid to the process of refusal from the active use of one of possible languages by an adult and the role of mastering two languages by a child was not taken into account. The global dynamics of the competitive interaction of languages was considered in [19].

The mathematical model of population (collective) bilingualism constructed in Sect. 2.3 is based on a general approach to modeling inheritance processes proposed in [6] and developed in [7]. This approach works effectively, including description of the processes of "cultural" inheritance, which implies the development and preservation of one

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[1] Of course, in principle, tactile, gustatory and olfactory languages are also possible. However, they are unlikely to be developed to the level of acoustic and written speech.

or more languages [8]. It is important that the specific features of language acquisition, typical for younger children are taken into consideration in this case [1, 12, 14, 15].

2.1 Image and Categories of Objects

The images of specific objects in human thinking in all modalities of perception – visual, auditory, tactile, olfactory and gustatory – can be very complex and detailed. However, during verbal communication of one person with others, these images can be displayed/transmitted only as the intersection of generalized categories. Meanwhile, not a single utterance ever reaches the accuracy and individuality of representing an object, like in thinking and perception of a person who is trying to convey the image of this object. If one looks into any dictionary of any language, then with some degree of surprise it will be found that all the words available in it, without exception, designate categories of objects, actions, or signs. Even technical terms, the use of which is based on an agreement (convention) between professionals, never designate a unique object, although they narrow the class of designated objects. For a more or less accurate verbal statement, one has to characterize an object by listing the categories to which it belongs. For example, “big green crocodile”. Verbal enumeration, in contrast to the demonstration of paintings and the performance of symphonies, is always sequential rather than parallel. Therefore, the formed verbal image of an object is always the intersection of categories to which it can belong.

Not only humans, but also animals are capable of categorical generalization [21]. If we do not recognize their ability for logical thinking, then we have to admit that the spontaneous generalization of their life practice is the mechanism for the formation of categories. Moreover, technogenic systems, the substratum of the functioning of which are electronic elements rather than neurons, are also capable of generalizing images to the level of categories. Thus, in the well-known work [22] it is shown that a network of processors receiving at the input a flow of images (actually image codes) from the Internet, spontaneously, without training and encouragement formed generalized images of cats, human faces and bodies.

Therefore, we took as the basis for describing bilingualism modeling of the process of spontaneously occurring acquisition of images of the environment by a child. The main quantitative characteristic of such a model is the number of generalized images of environmental objects acquired by a human. The competition of languages is considered as a competition for nominating these acquired images with the words of one or another language. In fact, in the nominal representation the formed generalized image can have one, another, or two language markers at once. The above description refers to changes in time in the number of active algorithms for operations on images of the environment, as well as algorithms that a living system has learned to form (master) to isolate elements important for it from the “noise” component of the sensory flow.

2.2 A Variety of Modes for Individual Bilingualism

These phenomena were reproduced on the mathematical model of the formation of individual bilingualism in a bilingual environment. The model is a system of two balance equations describing the change in the number of active instrumental algorithms and “cognitive filters” for mastering the first and second languages. Such a reduced model of a broader formalized description of the processes of mastering fundamental concepts by a child and their nomination in the social environment:

$$\tau_{1V_1}\frac{dV_1}{dt} = -\frac{\tau_{1V_1}}{\tau_{2V_1}}\cdot V_1 + F_0\left[-T_1 + \gamma_{11}\cdot V_1 - \gamma_{12}\cdot V_2\right]$$

$$\tau_{2V_2}\frac{dV_2}{dt} = -\frac{\tau_{1V_2}}{\tau_{2V_2}}\cdot V_2 + F_0\left[-T_2 - \gamma_{21}\cdot V_1 + \gamma_{22}\cdot V_2\right]$$

where: τ_{1V_1} and τ_{1V_2} are the characteristic times of spontaneous learning of new elements of the first (V_1) and second (V_2) languages (usually, days - weeks); τ_{2V_1} and τ_{2V_2} are the characteristic times of destruction of the proportion of elements of the languages V_1 and V_2 or their transfer from active working memory to passive “storage” (usually months - years);F_0 are the stepwise nonlinear functions are stepwise with thresholds T_1 and T_2 for languages V_1 and V_2, respectively; γ_{ij} - the coefficients of the influence of the language V_j on the activation of acquiring language V_i. To simplify the analysis, the unit Heaviside function is used as F_0.

A qualitative study of possible solutions to these equations was done on the phase plane (V_1, V_2). Solutions - the trajectories of the image point on the phase plane are determined by the type of stable and unstable zero - isoclines. Different types of solutions are highly dependent on the thresholds T_1 and T_2, as well as on the γ_{ij} - coefficients of the mutual influence of languages on each other. The considered phenomenological model allowed identifying regions of parameters when the model modes of spontaneous learning corresponded to the modes of behavior of children recorded experimentally and in the process of observation during language acquisition [1, 11–15].

2.2.1. It was shown that at high thresholds of switching on of the mechanisms for the formation of new categorization algorithms and conscious perception of the flow of external sensory signals, it is possible to block spontaneous language acquisition. These thresholds are known to increase at unfavorable emotional states, as well as in case of insufficient energy supply to the subject.

2.2.2. It was shown that spontaneous, natural mastering of several (two) languages leads to a decrease in the volume of each language in comparison with the case of mastering only one language. The reason for this is the waste of the time resource allocated for training in several languages, instead of using this resource to master one language, preferably the native one.

2.2.3. The conditions of switching over from mastering two languages to mastering only one language and inhibiting the other, or inhibiting the development of both languages were considered.

Thus, the formalized description confirms the possibility of blocking spontaneous mastering of both, one language and two languages at once and demonstrates which variables should be measured by instrumental methods for a more adequate description of the mechanisms of language acquisition.

2.3 A Tendency to Monolingualism in Collective Bilingualism

For collective (population) bilingualism, there is a tendency to switch to a more common language. At the same time, the less common language weakens and further disappears. Almost any phenomena observed in individual bilingualism can be observed in collective bilingualism. Two languages occupy different niches both in the life of an individual bilingual and in the life of a bilingual society. Strengthening of the position of one of the languages inevitably leads to weakening of the other, both in the formation of natural bilingualism in children and in collective bilingualism. If one of the languages loses social relevance, then it weakens and **may** disappear in both, the bilingual and the society. The disappearance or death of a language is the major manifestation of the tendency to a monolingual state. Natural bilingualism on any scale is an unstable phenomenon, which is often characterized by the tendency to stable monolingualism [1].

To study the features of the phenomenon of collective bilingualism on the basis of a general approach to modeling the processes of transmission of non-innate (acquired) information [8], a dynamic model of a bilingual community was constructed under the following assumptions:

a) the size of the community is constant in time, which entails the equality of the number of births per capita per unit time (birth rate a) to the corresponding number of deaths;
b) proficiency in a particular language does not affect fertility/mortality;
c) community members can speak one of two languages, conventionally called “first” and “second”, or both languages simultaneously; $z_1$is the proportion of community members who speak only the first language; z_2 is the proportion of community members who speak only the second language; z_{12} is the proportion of community members who speak both languages;
d) the proportion of individuals who do not speak any language (children under two years of age) is negligibly small;
e) the likelihood of simultaneous (spontaneous) mastering of two languages by an individual is negligible; an individual first learns one language (the most optimal language acquisition process in early childhood) and only after that he\she can master another one (become bilingual);
f) children of the individuals who speak one language, speak the language of their parents;
g) children of bilinguals initially master the first or the second language with probabilities c_1 and c_2 accordingly, which reflects the social attractiveness (social preferences) of knowing a particular language; $c_1 + c_2 = 1$; without loss of generality, it is assumed that $c_1 > c_2$.
h) the average speed of spontaneous acquisition of a new language in a community when one language has been mastered (the speed of the process of the emergence of bilingualism) is proportional to the product of native speakers of this language and individuals who do not speak it; the proportionality coefficient b does not depend on the type of language.

The latter assumption actually means that the probability of mastering a new language by an individual who speaks one language is proportional to the amount of communication between him\her and the native speakers of the other language (the hypothesis of effective encounters).

These assumptions lead to the following model:

$$\frac{dz_1}{dt} = c_1 \cdot a \cdot z_{12} - b \cdot z_1 \cdot z_2 - b \cdot z_1 \cdot z_{12}$$

$$\frac{dz_2}{dt} = c_2 \cdot a \cdot z_{12} - b \cdot z_1 \cdot z_2 - b \cdot z_2 \cdot z_{12}$$

$$\frac{dz_{12}}{dt} = 2b \cdot z_1 \cdot z_2 + b \cdot z_1 \cdot z_{12} + b \cdot z_2 \cdot z_{12} - a \cdot z_{12}$$

where $z_1 + z_2 + z_{12} = 1$. Taking into account the last identity, one variable can be expressed through the other two and we can pass to a system of two equations only.

A qualitative analysis of possible solutions to the constructed model was carried out. It was found that, depending on the values of the parameters, this system has two or three equilibrium states. Two equilibrium states (1, 0, 0) and (0, 1, 0) correspond to the preservation of only one language in the community, with the second state being always unstable. The third state corresponds to the indefinitely long preservation of both languages in stable proportion.

It is shown that the third state exists if the relation $(c_1 - c_2) \cdot a < b$ holds. In this case, it will be globally asymptotically stable, and the first equilibrium state (1, 0, 0) will be unstable. This means that both languages remain in the community indefinitely long, with the number of their speakers approaching with time a stable proportion determined by the values of the model parameters.

If the opposite inequality $(c_1 - c_2) \cdot a \geq b$ is satisfied, the model has only two equilibrium states, and the first state (1, 0, 0) being asymptotically globally stable. This corresponds to the process of gradual replacement of the second language by the first one. Since this $c_1 \cdot a$ is the specific rate of appearance of native speakers only of the first language, $c_2 \cdot a$ is the rate of appearance of native speakers only of the second language, and b characterizes the rate of the appearance of natural bilinguals, the result obtained means that the second language is displaced by the first if the process of appearance of bilinguals does not compensate for the excess of the rate of appearance of speakers of the first language over the rate of appearance of native speakers of a second language.

Thus, to ensure the preservation of two languages in the community, all other things being equal (stable fertility/mortality and the likelihood of the appearance of natural bilinguals), efforts should be made to increasing the parameter c_2, that is, the likelihood of the initial acquisition of a second language by bilingual children, and this, as already noted above, is determined by special measures to change the social attractiveness of the language.

3 Conclusion and Outlook

Mathematical modeling of the processes underlying the phenomena of individual and collective natural bilingualism confirms the hypothesis of the instability of these states.

These models also show which specific variables should be measured by instrumental methods for conducting a more detailed description of the mechanisms of mastering languages of communication between people. At the same time, there are options to modify the models for better matching the available solutions to experimental data. Understanding of both social and biophysical mechanisms of the weakening and disappearance of one of the languages under collective bilingualism is necessary for the development of measures to preserve linguistic diversity.

The formation of a linguistic function in a bilingual environment proceeds in different ways, even in children from the same family, and is rarely completely smooth. One of the deepest understandings of this phenomenon belongs to L.S. Vygotsky, who noted the dynamism of the phenomenon, its unpredictability, irreducibility to particular cases and warned about the potential vulnerability of the child's psyche in a multilingual environment: "… Bilingualism, under certain conditions, can become a factor that hinders both the development of the child's native language and its general intellectual development …" [14]. The task of researchers of the present days is to find an answer to the question: under what specific conditions this is possible.

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References

1. Alexandrova, N.S.: The disappearance of languages, natural bilingualism and nonlinear dynamics. In: 8th International Conference on Cognitive Science, pp. 35–37, Svetlogorsk, Russia (2018). Abstracts. (in Russian)
2. Freeman, D.L., Cameron, L.: Research methodology on language development from a complex systems perspective. Mod. Lang. J. **92**(2), 200–213 (2008). https://doi.org/10.1111/j.1540-4781.2008.00714.x
3. Herdina, P., Jessner, U.: A Dynamic Model of Multilingualism: Perspectives of Change in Psycholinguistic. Multilingual Matters, Bristol (2002)
4. Yakhno, V.G., Makarenko, N.G.: Will the creation of the "digital human twin" help us better understand each other? In: Redko, V.G. (ed.) Approaches to the Modeling of Thinking, pp. 169–202. LENAND, Moscow (2014). (in Russian)
5. Whitehouse, H., Jong, J., Buhrmester, M.D., Gómez, Á., Bastian, B.: The evolution of extreme cooperation via shared dysphoric experiences. Sci. Rep. **7**, 44292 (2017). https://doi.org/10.1038/srep44292
6. Gorban, A.N.: Selection Theorem for Systems with Inheritance. Math. Model. Nat. Phenom. **2**(4), 1–45 (2007). https://doi.org/10.1051/mmnp:2008024
7. Kuzenkov, O., Morozov, A.: Towards the construction of a mathematically rigorous framework for the modelling of evolutionary fitness. Bull. Math. Biol. **81**, 4675–4700 (2019). https://doi.org/10.1007/s11538-019-00602-3
8. Kuzenkov, O., Ryabova, E.: Mathematical modeling of selection processes. Lobachevsky State University, Nizhnii Novgorod (2007). (in Russian)
9. Lenneberg, E.: Biologische Grundlagen der Sprache. Suhrkamp, Frankfurt (1972)
10. Paradis, M.A.: Neurolinguistic Theory of Bilingualism. John Benjamins Publishing Company, Amsterdam (2004)

11. Alexandrova, N.S.: Native language, foreign language and linguistic phenomena that have no name. Questions Linguist. **3**, 88–100 (2006). (in Russian)
12. Köpke, B.: Language attrition at the crossroads of brain, mind, and society. In: Language Attrition: Theoretical Perspectives, pp. 9–37. John Benjamins Publishing Company (2007). https://doi.org/10.1075/sibil.33.03kop
13. Alexandrova, N.Sh.: Providing species–specific forms of behavior – the primary goal of brain plasticity? Article in collection of articles. In: Proceedings of the Conference on Cognitive research at the present stage, Arkhangelsk, pp. 14–17 (2018). (in Russian)
14. Vygotsky, L.S.: To the question of multilingualism in childhood. In: Vygotsky, L.S. (eds.) Mental Development of children in the Learning Process: Collection of Articles, pp. 53–72. State Educational and Pedagogical Publishing House (1935). (in Russian)
15. Alexandrova, N.: Can natural bilingualism be harmful? Polylinguality Transcult. Pract. **14**(2), 211–216 (2017). https://doi.org/10.22363/2312-8011-2017-14-2-211-216. (in Russian)
16. Fernando, C., Valijдrvi, R.-L., Goldstein, R.A.: A model of the mechanisms of language extinction and revitalization strategies to save endangered languages. Hum. Biol. **82**(1), 47–75 (2010). https://doi.org/10.3378/027.082.0104
17. Tchendjeu, A.E.T., Bowong, S., Tchitnga, R., et al.: Dynamics of the competition between two languages. SeMA **77**, 351–373 (2020). https://doi.org/10.1007/s40324-020-00219-w
18. Perry, L., Shrestha, M.D., Vose, M.D., et al.: Collective action problem in heterogeneous groups with punishment and foresight. J. Stat. Phys. **172**, 293–312 (2018). https://doi.org/10.1007/s10955-018-2012-2
19. Gaspard, M.: An integro-differential model of language competition. SIAM Undergraduate Res. Online **12** (2019). https://doi.org/10.1137/18S017363
20. Kuijper, B., Leimar, O., Hammerstein, P., McNamara, J.M., Dall, S.R.X.: The evolution of social learning as phenotypic cue integration. bioRxiv (2020). https://doi.org/10.1101/2020.10.30.358028
21. Zorina, Z.A., Smirnova, A.A.: What the “Talking” Monkeys Told About: Are Higher Animals Capable of Operating with Symbols? Languages of Slavic Cultures, Moscow (2006). (in Russian)
22. Le, Q.V., et al.: Building High-level Features Using Large Scale Unsupervised Learning (2012). https://arxiv.org/abs/1112.6209

Cognitive Processing of Emotional Words by Russian Native Speakers and Heritage Turkic-Speaking Bilinguals

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Abstract. The article describes an experimental study aimed at identifying the peculiarities of cognitive processing of Russian emotional words – diminutives as well as the influence of the bilingualism factor on this process. The purpose was solved in two stages: a survey and an RT-experiment. Each of the stages was carried out sequentially first in a group of native Russian speakers, then in Turkic-Russian bilinguals. Based on the data obtained during the first stage, we found that emotionality interacts with the psycholinguistic parameters (age of acquisition, type of evaluation, contextual implementation, subjective frequency) in the perception of words by native speakers and bilinguals. It was demonstrated by the presence of correlations between the parameters. The results of the RT-experiment showed that both groups of participants had significant differences in the cognitive processing of neutral and emotional words. Summing up the results, it can be concluded that the bilingualism type – unbalanced with the dominance of the L2 has influence on the perception and cognitive processing of emotional words.

Keywords: Emotionality · Diminutive · Turkic-Russian bilingualism

1 Introduction

A growing body of literature investigating the cognitive processing of emotional words has emerged in recent years. Positive results have been obtained in a significant number of diverse works devoted to this issue, but a number of unresolved and controversial problems remain, including the question of the presence and nature of differences in the perception of emotionally colored and neutral vocabulary.

Currently, experimental studies have obtained data on 1) processing advantages for positive over neutral words [1–3]; 2) a greater processing speed of negative words over neutral ones [4, 5]; 3) a greater processing speed of positive words over negative ones [6]. The obtained ambiguous results encourage scientists to generate numerous explanatory hypotheses and theories (for instance, the hypothesis of automatic vigilance, the theory of semantic richness, etc. See more details in the paper by O. V. Nagel [7]). In our opinion, there are several reasons that to some extent explain the disunity of the results.

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Firstly, the class of emotional vocabulary is characterized by significant heterogeneity and the conclusions obtained in the research are based on the analysis of various empirical material. As linguistic research suggests, emotion vocabularies are often associated with words that cause negative or positive emotions in the speaker (*gun, win, echo*) [8], or evoke positive or negative qualities of objects, but do not express the speaker's attitude to these objects and qualities (*optimistisch – optimistic; grausam – cruel*) [9]. Also, as reported by Scott [10], until recently, most studies did not compare positive, negative and neutral words, but instead considered only two of these three categories or sometimes words that name certain emotional states, which makes it difficult to draw direct conclusions and generalize the results.

Secondly, it seems that the inconsistent results are also influenced by insufficient differentiation between the impact of the emotionality factor and other psycholinguistic factors that affect the cognitive processing. As such, valence (perception of a stimulus as positive or negative), and arousal (the degree to which a stimulus is «calm» or «exciting») should be considered.

In addition, we'd like to emphasize a certain lack of involved empirical material that can reveal new aspects of the complex phenomenon of emotional processing (insufficient involvement of the different-type language material and different types of native speakers).

The problem of perception and processing of emotional units by bilinguals is also ambiguously solved and is related to a more general research question about the nature of the relationship between emotionality and a second language. A number of studies claim that the first language (L1) is more emotional than the second one (L2) or subsequent languages [11–13]. As Ponari points out [14], studies using objective measures (such as reaction time) in some cases show advantages in processing of emotional words in L1, in other cases advantages in L2, or no difference between languages [15]. EEG research using lexical decision task demonstrate weaker or delayed automatic affective processing of L2 [16, 17].

A detailed examination of this problem reveals the presence of some factors that cause differences in the perception and use of L2 emotional units by bilinguals. In particular, for example, a series of studies by Dewaele [18–20] revealed the influence of such factors as age and context of L2 acquisition: bilinguals who learned a second language at an early age consider L2 words to be more emotionally loaded compared to those who learned it later. The same is true for respondents who studied L2 in a natural environment as opposed to emergent bilinguals.

Thus, we believe that while studying cognitive processing, it is necessary to strictly determine the limitation of conclusions by the types of attracted subclasses of emotional units, their place in the system of expressing emotionality in a particular language or interacting languages in the mental lexicon of a bilingual, in the latter case – taking into account the type of bilingualism.

This paper examines the specifics of cognitive processing of diminutives, a class of Russian language system vocabulary. Emotionality of this word class is marked by derivational affixes in comparison with other classes of emotional and neutral vocabulary. The cognitive processing of these emotional words is analyzed in two groups: native speakers of Russian and Turkic-Russian bilinguals, early natural unbalanced, whose mother language has the status of a heritage language, the language of family communication, which gets replaced in other social communications by Russian.

The experimental study was carried out in two stages, each of them was conducted sequentially first in a group of native Russian speakers, then in a group of bilinguals. At the first stage, a survey was conducted to identify the ratio features between the emotionality and related categories. At the second stage, an RT-experiment was performed.

2 Method

2.1 Survey

Participants. Russian native speakers (56 respondents covering the age range from 18 to 71; average age – 30.8) and Turkic-Russian bilinguals who indicated Tatar, Khakass, or Shor as their first language (60 people – from 16 to 73; average age – 32, 7).

Material. The surveys (as well as RT-experiments) involved 371 words used as stimuli which included 3 groups of words. The first one is a group of 163 non – emotional non-derivative words that can form diminutives and relate to a person and his environment: the name of family ties (Russian: *papa – father, tyotya – aunt, babushka – grandmother*), body parts (Russian: *ruka – hand, zhivot – stomach, glaz – eye*), clothing items (Russian: *bluza – blouse, dzhinsy – jeans, kostyum – suit*), household items and furniture items (Russian: *vilka – fork, stul – chair, kovyor – carpe*t). The second group consists of 166 emotional words with diminutive suffixes formed from non – derivative words (Russian: *stul'chik – chair, kostyumchik – suit, dochen'ka – daughter, kovrik – carpet*). The third group was made up of 42 words with a positive and negative evaluation (Russian: *velikolepie – splendor, triumph – triumph, merzost' – abomination, bezobrazie – ugliness*).

Procedure. The survey was carried out using the Likert scaling. Participants in the experimental sessions were asked to rate the proposed words on a scale from 1 to 7 according to the following parameters: type of evaluation, contextual implementation – in conversations with whom the word is used (child or adult), in conversations about whom the word is used (child or adult), subjective frequency, age of acquisition.

Results. As a result of two stages of the survey 74,287 observations were received: 53,634 observations from Russian native speakers, 21,959 observations from Turkic-Russian bilinguals.

Correlation analysis has shown that emotionality interacts with the studied psycholinguistic parameters in the perception of words by both groups of participants (native Russian speakers and Turkic-Russian bilinguals). It is demonstrated by the presence of correlational relations between the parameters. The most significant correlations were attributed to the following parameters: «use in conversations with a child/adult» and «use in conversations about a child/adult» ($r = 0.874$; $r = 0.870$); «type of evaluation» and «use in conversations with a child/adult» ($r = 0.442$; $r = 0.509$); «age of acquisition» and «use in conversations with a child/adult» ($r = 0.450$; $r = 0.449$); «emotionality degree» and «use in conversations with a child/adult» ($r = -0.467$; $r = -0.303$); «emotionality degree» and «type of evaluation» (r = −0.375; r = −0.562). In the following values of the correlation relations in each option the first value relates to a group of native speakers of Russian, the second – group of Turkic-Russian bilinguals.

As can be seen from the numerical values, the correlations found in bilingual respondents and native speakers of Russian are similar. In this case, we can conclude that early natural bilinguals, native speakers of heritage Turkic languages do not differ from Russian native speakers in the systems of evaluating the ratio of words emotionality with other significant psycholinguistic parameters.

2.2 RT-Experiment

At the second stage, we designed an RT-experiment to test the hypothesis that cognitive processing of the diminutives and neutral words is different in groups of Russian native speakers and in Turkic-Russian bilinguals. It can be expressed in reaction time to the stimuli as well as in the differences in related psycholinguistic characteristics effects.

Participants. Russian native speakers: 23 people (9 male, 14 female; age 18–53, average age–27 years). Bilinguals: 23 people (10 male, 13 female; age 16–52, average age–28.3 years).

Procedure. The stimuli were introduced to the categorization task, and subjects were asked to assign the word to a group «part of a person/part of a person's body» or to «an object». Experiment procedure consisted of a training session and the main experiment. Stimuli were presented pseudorandomized. The time for presenting stimuli was

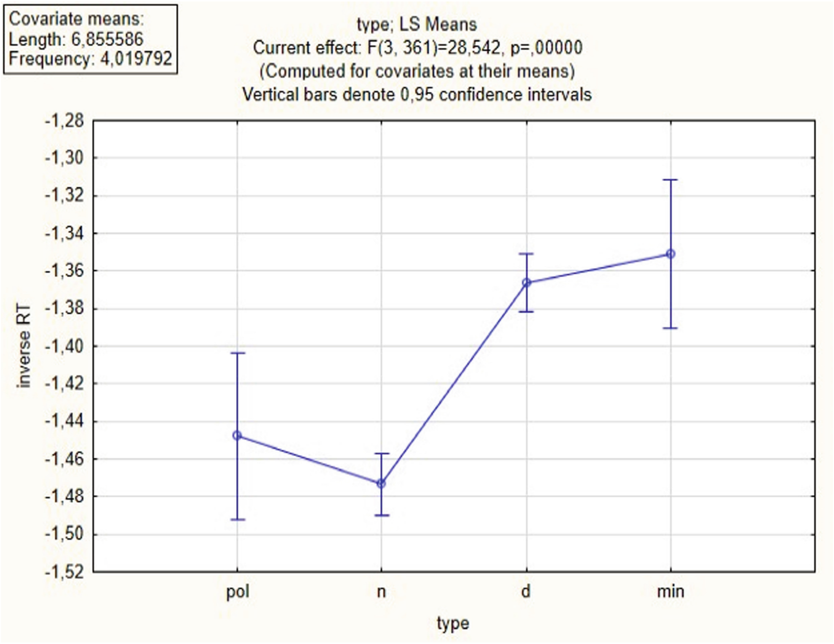

Fig. 1. The dependence of RT from a type of stimulus (Russian native speakers)

3000 MS, before starting a new trail, a blank screen appeared (ITI - intertrial interval) – 250 MS, the time for presenting the fixation cross – 250 MS.

Results and Discussion. In total, 8163 observations of Russian-speaking respondents and 8419 observations of heritage Turkic-Russian bilinguals were received. The obtained data were analyzed using the method of covariance analysis (ANCOVA).

The results showed that the cognitive processing of diminutives differs from the cognitive processing of neutral words both in Russian-speaking participants and in Turkic-Russian bilinguals: in native speakers of Russian this difference is manifested regardless of the frequency factor influence, and in Turkic – Russian bilinguals regardless of the frequency and length. Besides, Russian speakers' RT and the RT of Turkic-Russian bilinguals significantly differ both for all units as a whole and for each type separately. Native Russian speakers process units faster than bilingual participants ($p < 0.001$) (see Fig. 1 and Fig. 2).

In addition, a correlation analysis was carried out to identify the peculiarities of RT interaction with the psycholinguistic parameters (subjective frequency, emotionality degree, type of evaluation and contextual implementation). The following correlations were distinguished: «RT» and «emotionality degree» (0.390 –native speakers of Russian, 0.322 - Turkic-Russian bilinguals); «RT» and «subjective frequency» (0.313–native speakers of Russian, 0.329 - Turkic-Russian bilinguals); «RT» and «contextual implementation» (−0.302405 – native Russian speakers).

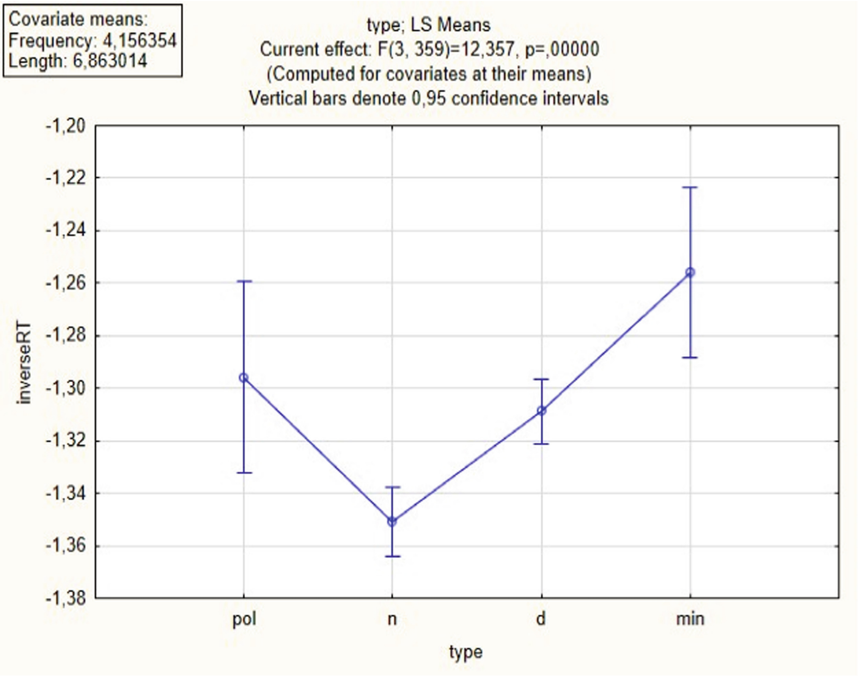

Fig. 2. The dependence of RT from a type of stimulus (Turkic-Russian bilinguals)

3 Conclusion

In our opinion, the obtained differences are explained by the type of the studied lexical units and their special position in the Russian and Turkic languages: in both language systems diminutives are a broad class of units that have a significant number of meanings, but the implementation of these meanings depends on many factors, in particular, for instance, on differences in the ways of expressing diminutivity. However, on the other hand, similar sensitivity to emotional units, as well as the same principles of processing emotional and neutral units, suggest that the conceptual presence of diminutively, as well as the type of bilingualism – early unbalanced with the dominance of the second language still affects their perception and cognitive processing, which correlates with the data obtained earlier.

The obtained results are consistent with the information in the literature on: 1) interaction of emotionality and related categories, 2) influence of the bilingualism type on the perception of emotional words, 3) influence of a number of psycholinguistic factors on the cognitive processing of emotional units. In addition, our research proves that the choice of stimuli, as well as the involvement of a certain type of respondents, largely determine the obtained results, which explains the heterogeneity of the data available in the previous research.

However, it should be noted that the specific type of the investigated lexical units – diminutives and their derivative nature raise the question of whether the observed differences in processing of emotional and neutral words are explained by a type of semantics, or derivation also has the impact. This question is related to the evidence available in the literature on the possible influence of word morphological complexity on its cognitive processing. In our opinion, these conclusions determine the visible prospects for research using different types of emotional vocabulary as well as with varying groups of participants.

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References

1. Kanske, P., Kotz, S.A.: Concreteness in emotional words: ERP evidence from a hemifield study. Brain Res. **1148**, 138–148 (2007). https://doi.org/10.1016/j.brainres.2007.02.044
2. Kuchinke, L., Võ, M.L.-H., Hofmann, M., Jacobs, A.M.: Pupillary responses during lexical decisions vary with word frequency but not emotional valence. Int. J. Psychophysiol. **65**, 132–140 (2007). https://doi.org/10.1016/j.ijpsycho.2007.04.004
3. Sheikh, N.A., Titone, D.A.: Sensorimotor and linguistic information attenuate emotional word processing benefits: an eye-movement study. Emotion **13**, 1107–1121 (2013). https://doi.org/10.1037/a0032417
4. Knickerbocker, H., Johnson, R.L., Altarriba, J.: Emotion effects during reading: influence of an emotion target word on eye movements and processing. Cogn. Emot. **29**(5), 784–806 (2015). https://doi.org/10.1080/02699931.2014.938023
5. Tabert, M.H., et al.: Differential amygdala activation during emotional decision and recognition memory tasks using unpleasant words: an fMRI study. Neuropsychologia **39**(6), 556–573 (2001). https://doi.org/10.1016/s0028-3932(00)00157-3

6. Dahl, M.: Asymmetries in the processing of emotionally valenced words. Scand. J. Psychol. **42**, 97–104 (2001). https://doi.org/10.1111/1467-9450.00218
7. Nagel', O.V.: Slovoobrazovatel'nye mekhanizmy v protsessakh vospriyatiya, identifikatsii i ispol'zovaniya yazyka [Word-Formation Mechanisms in the Processes of Perception, Identification and Use of the Language]. Abstract of Philology Dr. Diss. Tomsk (2017)
8. Kousta, S.-T., Vinson, D.P., Vigliocco, G.: Emotion words, regardless of polarity, have a processing advantage over neutral words. Cognition **112**, 473–481 (2009). https://doi.org/10.1016/j.cognition.2009.06.007
9. Wentura, D., Rothermund, K., Bak, P.: Automatic vigilance: the attention-grabbing power of approach-and avoidance-related social information. J. Pers. Soc. Psychol. **78**(6), 1024–1037 (2000). https://doi.org/10.1037/0022-3514.78.6.1024
10. Scott, G.G., O'Donnell, P.J., Leuthold, H., Sereno, S.C.: Early emotion word processing: evidence from event-related potentials. Biol Psychol. **80**(1), 95–104 (2009). https://doi.org/10.1016/j.biopsycho.2008.03.010
11. Dewaele J. M.: Perceived language dominance and language preference for emotional speech. First Lang. Attrition: Interdisc. Perspectives Methodol. Issues, **28**, 81 (2004). https://doi.org/10.1075/sibil.28.06dew
12. Altarriba, J.: Expressions of emotion as mediated by context. Bilingualism: Lang. Cogn. **11(02),** 165–167 (2008). https://doi.org/10.1017/S1366728908003295
13. Pavlenko, A.: Emotion and emotion-laden words in the bilingual lexicon. Bilingualism: Lang. Cogn. **11(02)**, 147–164 (2008). https://doi.org/10.1017/S1366728908003283
14. Ponari, M., et al.: Processing advantage for emotional words in bilingual speakers. Emotion **15**(5), 644–652 (2015). https://doi.org/10.1037/emo0000061
15. Ayçiçegi, A., Harris, C.L.: Bilinguals' recall and recognition of emotion words. Cogn. Emot. **18**, 977–987 (2004). https://doi.org/10.1080/02699930341000301
16. Opitz, B., Degner, J.: Emotionality in a second language: it's a matter of time. Neuropsychlogia. **50**(8), 1961–1967 (2012). https://doi.org/10.1016/j.neuropsychologia.2012.04.021
17. Conrad, M., Recio, G., Jacobs, A.M.: The time course of emotion effects in first and second language processing: a cross cultural ERP study with german-Spanish bilinguals. Front. Psychol. **2**, 351 (2011). https://doi.org/10.3389/fpsyg.2011.00351
18. Dewaele, J.-M.: The emotional force of swearwords and taboo words in the speech of multilinguals. J. Multilingual Multicultural Dev. **25**, 204–222 (2004). https://doi.org/10.1080/01434630408666529
19. Dewaele, J.-M.: Blistering barnacles! What language do multilinguals swear in? Estudios de Sociolingüística. **5**, 83–105 (2004)
20. Dewaele, J.-M.: Expressing anger in multiple languages. In: Pavlenko, A. (ed.) Bilingual minds: Emotional experience, expression and representation, pp. 118–151. Clevedon, UK, Multilingual Matters Ltd (2006)
21. Dewaele, J.-M.: The emotional weight of I love you in multilinguals' languages. Journal of Pragmatics. **40**, 1753–1780 (2008)

Emotions and Monoamines: New Approach to the Emotional Text Classification in Sentiment Analysis

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Abstract. The paper presents the classification of Internet-texts in Russian according to their monoamine status. We consider the levels of serotonin, noradrenaline and dopamine supposedly present in the blood of the text producer. The procedure of the non-discrete annotation of emotional tonality was used for the corpora data to identify the verbal markers for low-serotonergic, high-serotonergic, low-noradrenergic, high-noradrenergic, low-dopaminergic and high-dopaminergic texts. It is based on the Lövheim Cube model which includes eight emotional classes. The assessment results were mapped to a particular point in the Cube's 3D-space. We identified six subcorpora from the assessed data according to their monoamine status. The parameters of verbal structures proper to the corpora-antipodes provided by Sketch Engine gave us potential serotonergic features such as absolutist words, adjective-noun combinations, numerals, noradrenergic features – indefinite and demonstrative pronouns, quantifier words – and dopaminergic features – combinatorics of *как*, etc. The obtained results give a perspective for the sentiment analysis which relates not only the linguistic representation with its corresponding emotional status but an individual's biochemical response as well, thereby representing the wider mechanism of emotion generation.

Keywords: Emotion · Sentiment analysis · Lövheim Cube · Monoamines

1 Introduction

The paper focuses on the problem of sentiment analysis of texts in Russian. During the two years of working on this project we have had a number of problems to solve. One of them is to design a relevant procedure of assessment to provide us with a reliable data to train a supervised machine learning algorithm. The latter is expected to classify texts in multiple emotional categories. Using a neurobiologically based model of emotions, we made an attempt to implement it in the research of elaborating an interface for non-discrete emotions assessment. In process we have realized that conceptualizing emotions according to the monoamines which trigger them offers an interesting perspective to feature the texts not only from the point of emotions verbalized in them, but considering their monoamine status too.

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2 The Problem Statement

The sentiment analysis technologies have changed drastically over the last few years. If the first models and algorithms were designed to make a binary (positive tonality/negative tonality) or ternary (positive/negative/ neutral) classification of texts [1, 2], nowadays, the researchers are mostly interested in technologies able to assign to a text not an opinion but an emotion [3].

There are many psychological conceptions which give a definitive list of emotions. However, “until the present, scholars have not been able to specify the differences among a wide range of emotion categories in any systematic way” [4]. In fact, well known conceptions such as Darwin’s theory of universal emotions [5] or Izard’s model of basic emotions [6] developed later in Ekman’s approach to emotions as affect programs [7], do not give a definitive answer about the mechanism enabling humans to experience a particular psychical state referred to as an emotion.

Despite being based on the rather well-known typology of Tomkins’ affects [8], a recent study of Swedish neuroscientist H. Lövheim [9] proposes a new vision of emotions conceptualization. He suggests that the quality of emotional state experienced by an individual depends on the level of three monoamines. They are all derived from one amino acid (hence the name monoamines) and are produced by relatively few neurons in small areas in the upper part of the brainstem. According to Lövheim, a limited number of possible combinations of three monoamines narrows the number of emotions available to the detection – there are eight of them. To make the model more explicit, H. Lövheim visualized it in the form of cube, known as Lövheim Cube. Each emotion is placed in one of the cube vertices in accordance with the combination of different levels of three monoamines.

In our experimental assessment we asked our informants to use a specially designed interface. As a result of assessment, each text was localized in the 3D-space of Lövheim Cube in relation with 3 monoamines axes: x-axis is for serotonin, y-axis is for noradrenaline and z – for dopamine. By regrouping texts in accordance with the level of three monoamines, we identified six subcorpora: low-noradrenergic, high-noradrenergic, low-serotonergic, high-serotonergic, low-dopaminergic and high-dopaminergic texts.

3 The Research Question

The research question of our interest: if the “classical” sentiment analysis presumes that there is a number of features proper to the texts of an emotional tonality and if each emotion, according to Lövheim, is predetermined by a combination of different levels of three monoamines, is there any detectable correlation between text features and low or high level of monoamines? In other words, is it possible to identify any verbal markers for low-noradrenergic, high-noradrenergic, low-serotonergic, high- serotonergic, low-dopaminergic and high-dopaminergic texts?

It should be noted that in psychiatric linguistics [10] it is a regularly arising question provoking discussions, particularly in the context of research on altered states of consciousness [11, 12]. On the other hand, the research of artificial intelligence, exploring human cognition and its covert mechanisms in order to implement their findings in robotics, manifest an increasing interest towards the verbal and nonverbal outcomes of changes in monoamines levels in human organisms [13]. Our work aims to answer the research question combining the achievements of computer technologies and the logic of linguistics methodology.

4 The Purpose of the Paper

The paper describes the results obtained in our attempt to classify Internet-texts in Russian in accordance with their monoamines status, presumed by Lövheim Cube model.

5 Research Methods

We used the method of scaling to organize an experimental assessment backed by Lövheim model. The linguistic analysis of texts from groups with different monoamine status was conducted using the corpus linguistics methodology along with the tools provided by Sketch Engine platform. The statistical processing of the obtained results was supported by Python programming language.

6 Theoretical Background: The Model of Lövheim Cube

The name of the emotion model applied in our research comes from the geometric figure of cube used by Swedish neurobiologist Hugo Lövheim to visualize his conception of emotion activators. The scientists stated that the different levels of the three monoamines – dopamine, noradrenaline and serotonin – are linked with the emotional states experienced by an individual. He represented the correlations existing between emotions and monoamines by orthogonal monoamines axes. Altogether the axes form a cube. He placed eight emotions as eight vertices of the cube.

Thus, on the first vertical axis, depending on the level of noradrenaline, he puts the emotions of Shame/Humiliation, Fear/Terror, Enjoyment/Joy, Contempt/Disgust (each emotion has a double name because the first nomination indicates the weakest degree of its manifestation, while the second – the strongest) on the axis bottom (minimal level of the noradrenaline) and the emotion of Distress/Anguish, Anger/Rage, Interest/Excitement and Surprise – on the axis top. According to the level of serotonin, the same emotions were placed differently on another “left to right” axis: Shame/Humiliation, Fear/Terror, Distress/Anguish, Anger/Rage – at the beginning because of the minimal monoamine’s level, and Contempt/Disgust, Enjoyment/Joy, Surprise and Interest/Excitement on the end of the axis.

Finally, the third “front to back” axis showing the level of the dopamine starts from the low-dopaminergic emotions of Shame/Humiliation, Distress/Anguish, Contempt/Disgust, Surprise and goes to the high-dopaminergic emotions of Fear/Terror, Anger/Rage, Enjoyment/Joy and Interest/Excitement.

Localized in this way, the emotions form four oppositions, which correspond with the supporting diagonals inside the cube:

1) Distress – Enjoyment (“–” serotonin; “+” noradrenaline; “–” dopamine / “+” serotonin; “–” noradrenaline; “ +” dopamine);
2) Rage – Disgust (“–” serotonin; “+” noradrenaline; “ +” dopamine / “ +” serotonin; “–” noradrenaline; “–” dopamine);
3) Shame – Excitement (“–” serotonin; “–” noradrenaline; “–” dopamine / “+” serotonin; “ +” noradrenaline; “ +” dopamine);
4) Fear – Surprise (“–” serotonin; “–” noradrenaline; “+” dopamine / “ +” serotonin; “ +” noradrenaline; “–” dopamine).

Thus, such dichotomies allow us to conceptualize paired emotions as antipodes: from the point of the combination of three monoamines and their level, for example, fear, is a negative form of surprise; rage is aggressive antonym of disgust, etc. We used these four dichotomies to design the interface for the emotion assessment.

7 Preliminary Details of Collecting Data

To collect the dataset, we used several public groups in Russian social network “VKontakte” as text sources. Using developer API, we obtained about 15000 text fragments (80–100 words each) with different emotional hashtags (for example, the hashtag #Overhead_ stydno perfectly maps to the emotion of shame). From this dataset we sampled 3920 posts which were submitted to the procedure of human assessment. Samples were equally distributed according to the eight base emotional classes in Lövheim model.

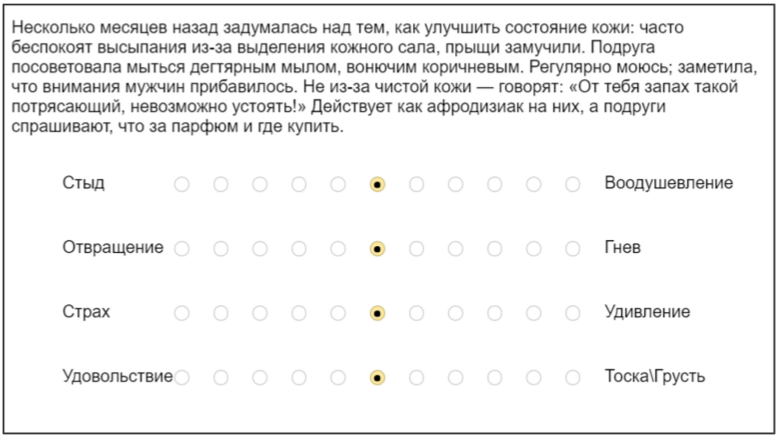
A special interface was developed to run the assessment procedure. It includes four sliders which coincide with four supporting diagonals of Lövheim Cube: ’shame_excitement’, ’disgust_rage’, ’fear_surprise’, ’enjoyment_distress’. The ends of the scales mean the strongest expression of the named emotions; the middle point correlates with zero emotion assessment – the less emotion a person feels, the nearer to the scrollbar middle they put the slider from -5 to 5. The slider step is 1 (as shown on the Fig. 1).

Two thousand informants registered on a crowdsourcing platform were provided with a following instruction:

Please, read the text carefully, two times if necessary. What are the emotions that the author expresses in it? Put each slider close to the emotion, which is the strongest in the text. You can graduate the strength of the emotion expression by using the step markers: 1 step from the center – you can feel the emotion, but it is weak, step 3 – the emotion is evident, step 5 – the emotion dominates the text. If there is no emotion, put the slider in the middle of the scale, on the zero point.

In order to get the resulting emotion’s point in Cube’s space we need transformation and pooling strategy. The data collected was scalars, but the needed data we could process must be of spatial 3D nature. Thus, the general task is to convert labeled scalars into spatial coordinates.

Our approach for converting raw survey results is described in the previous work [14]: each scrollbar from survey is treated as vector along the cube diagonal; we measure magnitude of the vector and pool all four vectors into resulting one by summing them. In this way, we take final “coordinates” of an assessed text in 3D-space of the Cube. We



Несколько месяцев назад задумалась над тем, как улучшить состояние кожи: часто беспокоят высыпания из-за выделения кожного сала, прыщи замучили. Подруга посоветовала мыться дегтярным мылом, вонючим коричневым. Регулярно моюсь; заметила, что внимания мужчин прибавилось. Не из-за чистой кожи — говорят: «От тебя запах такой потрясающий, невозможно устоять!» Действует как афродизиак на них, а подруги спрашивают, что за парфюм и где купить.

Стыд ○ ○ ○ ○ ○ ● ○ ○ ○ ○ ○ Воодушевление

Отвращение ○ ○ ○ ○ ○ ● ○ ○ ○ ○ ○ Гнев

Страх ○ ○ ○ ○ ○ ● ○ ○ ○ ○ ○ Удивление

Удовольствие ○ ○ ○ ○ ○ ● ○ ○ ○ ○ ○ Тоска\Грусть

Fig. 1. Screen for task assessment in Toloka crowdsourcing platform

also do a scaling in period of [0, 1] for each monoamine axis and take point [0.5, 0.5, 0.5] as neutral (or initial) coordinates of a text.

Such 3D model provides us with a tool for non-discrete, continuous way of representing sentiment because we model each text in terms of coordinates in 3D-space, which is mapped to given three monoamine axes.

On each axis – dopamine, serotonin and noradrenaline – we calculated 0.1 and 0.9 percentiles. Then we assumed texts below 0.1 percentile according to certain axis to be low-monoaminic (i.e. low-noradrenergic, etc.), and texts with values above 0.9 percentile to be high-monoaminic (i.e. high-serotonergic, etc.). On the Fig. 2 there is a visualization of splitting used to extract high-dopaminergic subcorpora.

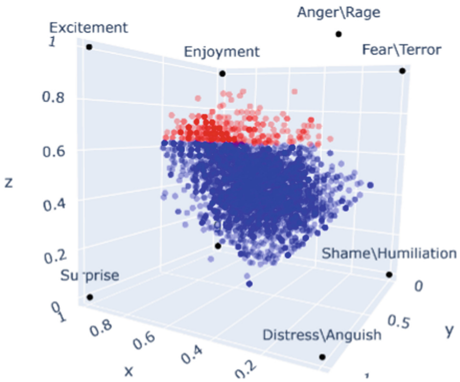


Fig. 2. Visualization high-dopaminergic subcorpora (red) and other texts (blue)[1]

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[1] Access to the full transformation pipeline and raw data access using Colab notebook – https://colab.research.google.com/drive/1ASaVNleaHrYxwsr8XK37hPqygoNkawLi?usp=sharing.

As result we obtained 6 subcorpora with their volumes below (see Table 1). In our further work we used the tools provided by Sketch Engine corpus manager to study verbal structures corresponding to each text subcorpus.

Table 1. Six subcorpora volumes

№	Subcorpus name	Subcorpus volume
1	Low-noradrenergic texts	170347 tokens
2	High-noradrenergic texts	323895 tokens
3	Low-serotonergic texts	254098 tokens
4	High-serotonergic texts	263044 tokens
5	Low-dopaminergic texts	304527 tokens
6	High-dopaminergic texts	204074 tokens

8 Featuring the Text Classes with Different Monoamine

8.1 Low- and High-Serotonergic Texts Features

Serotonin is a neuromodulator that plays a critical role in developing of psychiatric conditions. Researchers emphasize its impact on such states as depression, anxiety disorder, fears [15, 16]. In some works, serotonin is presented as a neuromodulator influencing the way that one thought leads to another, specifically by inhibiting chains of thoughts which then lead to negative affective states (“let’s not go there”) [17].

Accepting the last assumption, the first thing we focused on when searching for any features of low- and high-serotonergic texts, was the frequency of so-called “absolutist words” [18]. As such, we used Russian lexemes *не, нет, никогда, ничто, никто, ничего*. Using the request on CQL language [lemma = “не|нет|никогда|ничто|никто|ничего”], we received the frequency values for two compared subcorpora (see Table 2, line 3).

Two-tailed P value is less than 0.0001, i.e. the difference between the frequency of absolutist words in low- and high-serotonergic texts is statistically significant.

Among less significant, but rather interesting findings worth mentioning, are the frequencies of adjective-noun combinations, and numerals frequency (see Table 2, lines 1–2).

As the Table 2 shows, the high-serotonergic texts contain more adjective-noun combinations than low-serotonergic. Using the function of “key-terms”, we compared the

Table 2. The frequency values of adjective-noun combinations and numerals in low- and high-serotonergic texts

№	Feature	Low-serotonergic texts	High-serotonergic texts
Absolute frequency/Relative frequency			
1	Adjective-noun combinations	8482/26462 ipm	10902/32879 ipm
2	Numerals	6555/20450 ipm	8848/26685 ipm
3	Absolutist words	7709/24050 ipm	961/2898 ipm

two subcorpora and identified two lists of the most specific adjective-noun combinations for each subcorpus in relation to another. As the analysis has shown, the list of nine most specific terms in low-serotonergic texts contain two adjectives of negative appreciation (*худшая компания*, *чертов нож*) and one of positive (*ценная вещь*) while in the list of the most specific terms (which is, by the way, longer than such of its reference corpus) in high serotonergic texts we found no negatively connotated adjectives, but on the contrary, seven adjectives expressing positive connotation: *милейший человек, счастливый родитель, офигенная семья, счастливый человек, любимый человек, лучший парень, любимый мужчина.*

8.2 Low- and High-Noradrenergic Texts Features

According to the researchers, depletion of noradrenaline (norepinephrine) in the brain causes a decrease in sexual drive and motivation, being a part of the 'fight or flight' response, which increases heart rate, etc. [19]. It is also called the stress hormone, which impacts both – the individual attention (making it more selective) and the level of concentration (redundant) [20, 21]. Taking into account this assumption, we suggested that the categories of demonstrative pronouns, quantifier words and indefinite pronouns are mostly affected by the changes in noradrenaline level. The comparative analysis of mentioned above frequencies supported by statistical tools of Sketch Engine has confirmed the hypothesis: in high-noradrenergic texts, the relative frequency of demonstrative pronouns and quantifier words [22] is considerably higher than in low-noradrenergic texts (see Table 3). While the relative frequency of indefinite pronouns (*как-то, когда-то, что-то,* etc.) is more important in low-noradrenergic texts.

As for syntactical specificity, it is to note that completive clauses are more frequent in high-noradrenergic texts (6032/14700 ipm) than in low-noradrenergic texts (1937/9000 ipm).

8.3 Low- and High-Dopaminergic Texts Features

Dopamine provides a dynamic estimate of whether to spend a limited internal resource, such as energy, attention, or time [23], it is also involved in motor control. Searching for featuring low- and high-dopaminergic texts we were primary focused on the frequency

Table 3. The frequency values of demonstrative pronouns, quantifier words and indefinite pronouns in low- and high-noradrenergic texts

№	Feature	Low-noradrenergic texts	High-noradrenergic texts
Absolute frequency/Relative frequency			
1	Demonstrative pronouns *тот*, *этот*, *это*, *те*	2790/12965 ipm	6302/15497 ipm
2	Quantifier words *весь*, *вся*, *все*, *всё*	1663/7616 ipm	4010/10420 ipm
3	Indefinite pronouns	800/3713 ipm	1077/2635 ipm

of verbs in general and on the verbs of movement in particular. However, the difference in the use of the verbs appears insignificant.

On the contrary, the main unexpected feature distinguishing two subcorpora is the frequency of the comparison conjunction *как*: in low-dopaminergic texts the relative frequency of the conjunction is almost two times less than in high-dopaminergic texts (see Table 4).

Table 4. The frequency of conjunctive element *как* in low- and high-dopaminergic texts

Low-dopaminergic texts	High-dopaminergic texts
Absolute frequency/Relative frequency	
1578/3976 ipm	1530/5949 ipm

Using different association scores (T-score, MI, LogDice) we identified good collocations with the conjunction *как* in low- and high-dopaminergic texts. They are different. The main discrepancy worth mentioning is that in high-dopaminergic texts the collocations implicating the idea of eventuality or of so called "possible worlds" is on the list of ten collocations with the highest statistical score: *как будто* (8 rank), *как бы* (10 rank). In fact, in low-dopaminergic texts such collocations don't show any relevance – they have minimal statistical score.

9 Conclusion

The analysis of the linguistic data from the six subcorpora provided us with a number of features. The significance of these features isn't equal. However, despite heterogeneity of verbal markers retrieved for each text category, the research validates our main assumption that there are distinctions between texts of different monoamine status. They can be detected and predicted after some preliminary work.

Furthermore, the idea gives a rather amazing perspective for sentiment analysis paradigm to change the view on the classification. To search not only for different emotions in texts, but, moreover, to try to recognize the biochemical status of an individual by analyzing their speech.

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References

1. Hogenboom, A., Frasincar, F., Jong, F., Kaymak, U.: Polarity classification using structure-based vector representations of text. Decis. Support Syst. **74**, 46–56 (2015). https://doi.org/10.1016/j.dss.2015.04.002
2. Liu, Y., Huang, X., An, A., Yu, X.: ARSA: a sentiment-aware model for predicting sales performance using blogs. In: Kraaij, W., de Vries, A.P. (eds.) Proceedings of the 30th Annual International ACM SIGIR Conference on Research and Development in Information Retrieval, session 25, pp. 607–614. ACM, New York (2007). https://doi.org/10.1145/1277741.1277845
3. Staiano, J., Guerini, M.: DepecheMood: A lexicon for emotion analysis from crowd-annotated news. In: Toutanova, K., Wu, H. (eds.) Proceedings of the 52nd Annual Meeting of the Association for Computational Linguistics (ACL), pp. 427–433. Association for Computational Linguistics, Baltimore (2014). https://doi.org/10.3115/v1/P14-2070
4. Thamm, R.A.: The Classification of Emotions. In: Stets, J.E., Turner, J.H. (eds.) Handbook of the Sociology of Emotions. Handbooks of Sociology and Social Research, pp. 11–37. Springer, Boston (2006). https://doi.org/10.1007/978-0-387-30715-2_2
5. Darwin, C.: The Expression of the Emotions in Man and Animals, 3rd edn. Oxford University Press, London (1872)
6. Izard, C.E.: Basic emotions, relations among the emotions and emotion-cognition relation. Psychol. Rev. **99**(3), 561–565 (1992). https://doi.org/10.1037/0033-295x.99.3.561
7. Ekman, P.: Are there basic emotions. Psychol. Rev. **99**(3), 550–553 (1992). https://doi.org/10.1037/0033-295X.99.3.550
8. Tomkins, S.S.: Affect theory. In: Ekman, P. (ed.) Emotions in the Human Face, pp. 353–395. Cambridge University Press, Cambridge (1982)
9. Lövheim, H.: A new three-dimensional model for emotions and monoamine neurotransmitters. Med. Hypotheses **78**, 341–348 (2012). https://doi.org/10.1016/j.mehy.2011.11.016
10. Pashkovskiy, V.E., Piotrovskaya, V.R., Piotrovsky, R.G.: Psychiatric Linguistics. URSS, Moscow (2009) (in Russian)
11. Spivak, D.L.: Altered states of consciousness. Psychology and linguistics. Juventa, Saint-Petersburg (2000) (in Russian)
12. Sukhikh, S.A.: Altered states of consciousness represented verbally. Language, Communication and Social Environment **3**, 78–93 (2006). (in Russian)
13. Talanov, M., Leukhin, A., Lövheim, H., Viverdú, J., Toschev, A., Gafarov, F.: Modeling psycho-emotional states via neurosimilation of monoamine neurotransmitters. In: Viverdú, J., Müller, V. (eds.) Blended cognition. Springer Series in Cognitive and Neural Systems, vol. 12, pp. 127–157. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-03104-6_6

14. Kalinin, A., Kolmogorova, A., Nikolaeva, G., Malikova, A.: Mapping texts to multidimensional emotional space: challenges for dataset acquisition in sentiment analysis. In: Alexandrov, D., Boukhanovsky, A., Chugunov, A., Kabanov, Y., Koltsova, O. (eds.) Digital Transformation and Global Society. DTGS 2018. Communications in Computer and Information Science, vol. 859, pp. 361–367. Springer, Cham (2018). https://doi.org/10.1007/978-3-030-02846-6_29
15. Bauer, E.P.: Serotonin in fear conditioning processes. Behav. Brain Res. **277**, 68–77 (2015). https://doi.org/10.1016/j.bbr.2014.07.028
16. Cowen, P.J., Browning, M.: What has serotonin to do with depression? World Psychiatry Official J. World Psychiatric Assoc. (WPA) **14**(2), 158–160 (2015). https://doi.org/10.1002/wps.20229
17. Dayan, P., Huys, Q.J.: Serotonin, inhibition, and negative mood. PLOS Comput. Biol. **4**(2), e4, 0001–0011 (2008). https://doi.org/10.1371/journal.pcbi.0040004
18. Al-Mosaiwi, M., Johnstone, T.: Linguistic markers of moderate and absolute natural language. Personality Individ. Differ. **134**, 119–124 (2018). https://doi.org/10.1016/j.paid.2018.06.004
19. Aldred, E.M., Buck, C., Vall, K.: Chapter 31 – The nervous system. In: Aldred, E.M., Buck, Ch., Vall, K. (eds.) Pharmacology: A Handbook for Complementary Healthcare Professionals, pp. 235–246. Churchill Livingstone, London (2009). https://doi.org/10.1016/B978-0-443-06898-0.00031-1
20. Gaillard, A.W.K.: Concentration, stress and performance. In: Hancock, P.A., Slazma, J.L. (eds.) Performance Under Stress, pp. 59–75. Ashgate Publishing, Hampshire (2008)
21. Ellenbogen, M.A., Schwartzman, A.E., Stewart, J., Walker, C.-D.: Stress and selective attention: the interplay of mood, cortisol levels, and emotional information processing. Psychophysiology **39**(6), 723–732 (2002). https://doi.org/10.1111/1469-8986.3960723
22. Boguslavskiy, I.M.: The whole – part – sign. In: Apresyan, Y.D. (ed.) Sacred Meanings: Word. Text. Culture: Collected papers in honor of N.D. Arutyunova, pp. 44–53. Languages of Slavic Culture, Moscow (2004) (in Russian)
23. Berke, J.D.: What does dopamine mean? Nat. Neurosci. **21**, 787–793 (2018). https://doi.org/10.1038/s41593-018-0152-y

RUPEX Search: Online Tool for Analyzing Multichannel Discourse

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Abstract. The paper presents an online search system built for the "Russian Pear Chats & Stories" corpus (RUPEX). RUPEX is a collection of communication sessions used for studying multichannel discourse. It aims at discovering how interlocutors use verbal, prosodic, oculomotor, manual gesticulation and other channels as they take part in natural monologic and dialogic communication. The sessions were recorded with microphones, video cameras, and eye trackers, and an integrated multichannel annotation scheme was implemented to them. The search system operates on these data and provides an intuitive graphic user interface that offers the following options: creating simple and complex queries, viewing search results in a multi-layered annotation format associated with video fragments, specifying search domain. To illustrate this functionality, we discuss search queries relevant to a specific multichannel research, that of dialogic elicitations.

Keywords: Multimodality · Natural discourse · Multichannel communication · Linguistic corpora · Web development

1 Introduction

When linguists want to study how the language is used in real life, they often recur to linguistic corpora, i.e., structured collections of annotated texts. Corpora are virtually always equipped with searching functionalities that allow to extract annotated data basing on users' requests. Large corpora (e.g., [1–3]) and online corpus managers [4] offer powerful tools for linguistic analysis. However, most corpora pay little to no attention to non-verbal components of natural communication. In fact, during face-to-face interactions, not only do we use words, or syntactic constructions, or other "purely linguistic" devices, but we also rely on a wide range of other resources—such as prosody, gesticulation, gaze direction, body postures, etc. So, our language is a multimodal [5, 6], or a multichannel [7], phenomenon, and to study the natural discourse in its entirety we need multimodal, or multichannel, corpora [8]. While such corpora are obviously much harder to build and to annotate than the "usual" ones, there are several multichannel projects, e.g. [9–11]. As far as we know, few of them have both (i) free access, and (ii) an online search system taking advantage of a genuinely multichannel annotation. In this paper, we present such a system, which is being developed for RUPEX—the "Russian

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Pear Chats & Stories” corpus [12]. The search operates online, has an intuitive graphic user interface, and displays requested data in a multi-layered format associated with related video fragments.

The paper is organized as follows. In Sect. 2, we describe RUPEX and outline the basic principles of multichannel annotation implemented in this corpus. Section 3 gives an overview of technical solutions employed in our search system and enumerates the main features of its graphic user interface. In Sect. 4, we provide a brief illustration of how these features can be used in a specific multichannel research. Section 5 contains concluding remarks.

2 Corpus and Annotation

“Russian Pear Chats & Stories” (RUPEX) is a multichannel corpus that consists of 40 communication sessions recorded in Moscow in 2015 and 2017. This is a part of the Multichannel Discourse Initiative [13]. A model subcorpus of three annotated sessions is available on the initiative website; https://multidiscourse.ru/.

All sessions had the same recoding set-up. In each session, there were three main participants who discussed and related the contents of the “Pear Film” created by Wallace Chafe and his group [14]. Prior to the recording, two participants (further referred to as the Narrator and the Commentator) were shown the film, and immediately after that the third participant (hereafter, the Reteller) was introduced. The sessions were divided into four stages. During the First Telling stage, the Narrator told the Reteller the content of the film while the Commentator and the Reteller were asked to keep silent. During the Conversation stage, all the three participants were engaged in a dialogic communication, where the Commentator presented their interpretation of the story and the Reteller requested additional clarification form both the Narrator and the Commentator. After that, the fourth participant (the Listener) joined in and the Retelling stage began, where the Reteller conveyed the content of the film to the Listener and the other participants were not allowed to speak. The Changeover stage occurred between the Conversation and the Retelling (while the Listener was being introduced) and had no communication limitations. The sessions were audio and video recorded; Narrators and Retellers also had eye-tracking devices on that registered their oculomotor activity. All participants were native Russian speakers previously unfamiliar of the “Pear Film”, they gave a signed consent agreeing that the sessions may be used for scientific research. For more detail on the recording set-up and equipment, see [15].

The basic goal of RUPEX is to provide a resource for analyzing the interaction of different communication channels. Hence, the annotation is carried out independently for:

- the vocal modality (verbal and prosodic channels);
- the oculomotor channel (gaze direction);
- the channel of manual gesticulation;
- the channel of cephalic (head) gesticulation; and
- some other communication channels.

The data are annotated using several software solutions, the results are stored in eaf format used in ELAN—a widespread software for annotating video files [16]. While annotating different channels may require different techniques and specific procedures, there are basic principles implemented in the integrated multichannel annotation [17]. For every channel/modality, each participant's behavior is segmented into units of various levels. This segmentation is performed on formal grounds, and precise time boundaries are identified for each unit. Also, identified units are annotated for additional formal and functional properties. For example, elementary discourse units (EDUs) are basic steps in speech production, they are delimited using a set of prosodic criteria, such as tempo, intensity and pitch patterns; and they exhibit various discourse properties, such as illocutionary/phase values (statements, questions, incompleteness, and so on) [18]. Table 1 provides a partial list of vocal, oculomotor, and manual gesticulation units and their selected properties. Overall, there are more than 200 annotation tiers available for each session. For a detailed discussion of the annotation procedure, refer to [13].

Table 1. Units of segmentation and properties thereof, grouped by communication channels

Communication channel	Units	Selected properties
Verbal and prosodic (=vocal modality)	Elementary discourse units	Illocutionary/phase value
	Words and pauses	Pitch accent; tempo; type of fillers
Oculomotor (eye gaze)	Fixations	Recipient and concrete localization of the gaze
Manual gesticulation	Manual movements	Movement type (preparation, stroke, etc.)
	Manual gestures	Handedness; functional type

3 Search Engine and User Interface

There are two ways to search through annotated data in RUPEX. The first one is to download the annotations in eaf format and the corresponding media files, and to analyze them in ELAN. ELAN offers an in-built search functionality that allows users to create simple and complex requests and to view the returned hits outright in the annotation editor window. However, this solution has several drawbacks. ELAN search is not too easy to learn, as even relatively simple queries may require sophisticated request techniques. Also, to use ELAN search with RUPEX data, one needs to acquire a detailed understanding of the implemented annotation scheme that contains dozens of tiers for every participant. Moreover, some request types are not supported in ELAN, e.g., search units cannot be restricted by duration; there is no handy way to specify whether two units in a sequence should or should not be produced by one and the same participant; and so on.

The alternative way is to use the web service specifically designed for RUPEX. As of October 2020, its beta version 0.12.14 is available at https://multidiscourse.ru/search/?locale=en. In what follows, we present its basic features and provide necessary technical details.

On the server side, queries are executed on an SQL database that has an entity-attribute-value structure. The data are converted from the resulting eaf annotations mentioned in Sect. 2. The server is built on Java; it also handles a set of video files that can be played upon user request. For each session, six video files are stored—a cover shot video of the whole scene, individual (frontal shot) video files of the three main participants, and the files recorded by the eye trackers of the Narrator and the Reteller.

On the client side, a single-page JavaScript application is built using the Model-view-viewmodel pattern. We use the JSON data exchange format for client-server interaction. The graphic user interface consists of several tabs that provide users with the following options:[1]

- Creating simple and complex queries. Queries are composed of search units that correspond to segmentation units discussed in Sect. 2 above. Adding a search unit to the query is made in two steps. First, the user chooses the unit type under the colored button corresponding to the selected channel/modality; e.g., elementary discourse units, words, and silent pauses can be selected under the “voc”(al) button. Then, the unit’s properties can be specified in a separate window. Some properties—such as duration and producing participants—are shared by all unit types, others are type-specific, see Table 1.
- In complex queries, two or more search units are connected by distance relations. Users can also optionally indicate whether units should or should not be produced by one and the same participant. Queries are dynamically displayed as they are edited by users; an example can be seen in Fig. 4, Sect. 4. Also, unlike in many search systems, each unit in a complex query can be related to any number of other units, so that a query structure is not necessarily a tree, but rather a network.
- Query results are displayed upon clicking the “Search button”. Viewing results is available in two modes. The simple list mode provides a list of returned hits, where each hit is represented in a simplified text format; see Fig. 3 in Sect. 4. Clicking a hit in the list rearranges the window to an extended view. In this view, users can navigate across multi-layered annotations (similar to those used in ELAN) and watch video fragments synchronized with them. An example is given in Fig. 5, Sect. 4.
- Obviously, only a part of over 200 annotation tiers are displayed in the extended view mode. Some of them are shown by default, others can be switched on and off by the user in the “Result settings” tab. Also, users can specify the search domain, e.g., restrict the search to concrete sessions and/or stages thereof (see Sect. 2). These settings are available both before and after composing a query and viewing its results.

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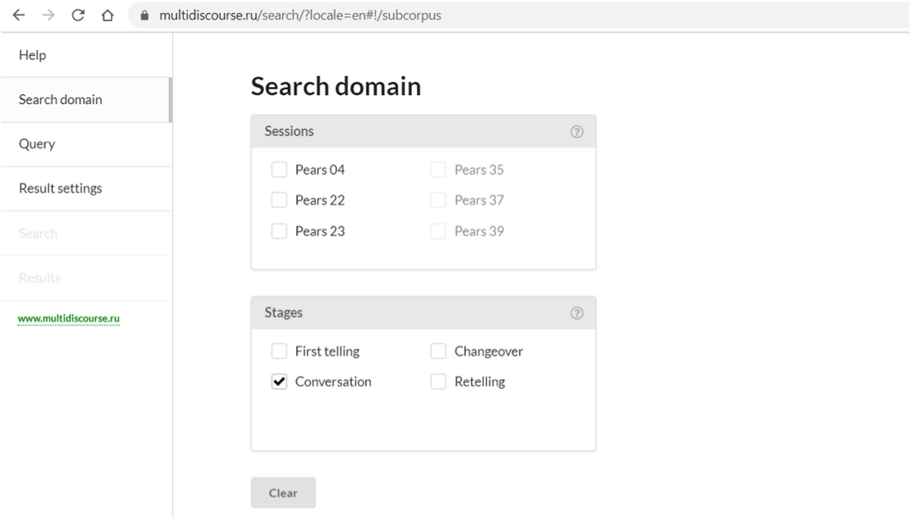
[1] Some functions described in Sects. 3 and 4 may not work properly under Safari and Internet Explorer, though they work fine under Chrome, Firefox, Chromium, Opera, and Microsoft Edge.

4 Searching in RUPEX: A Case-Study

This section provides a brief illustration of how the RUPEX search engine can be used when conducting a specific research on natural communication. The study we refer to focuses on contexts of elicitation, i.e., communication exchanges initiated by one participant who requests information possessed by other participants [19]. In RUPEX, elicitation is frequently initiated by Retellers, who were prompted by design to seek for a detailed understanding of the story they had not watched. Note that here we do not discuss the results of this research (preliminary findings were reported in [20]), but rather demonstrate how it can be facilitated by using our search system.

The first step would be to specify the search domain. Since elicitation happens in dialogues, search could be restricted to Conversation stages, see Fig. 1.



Search domain

Sessions

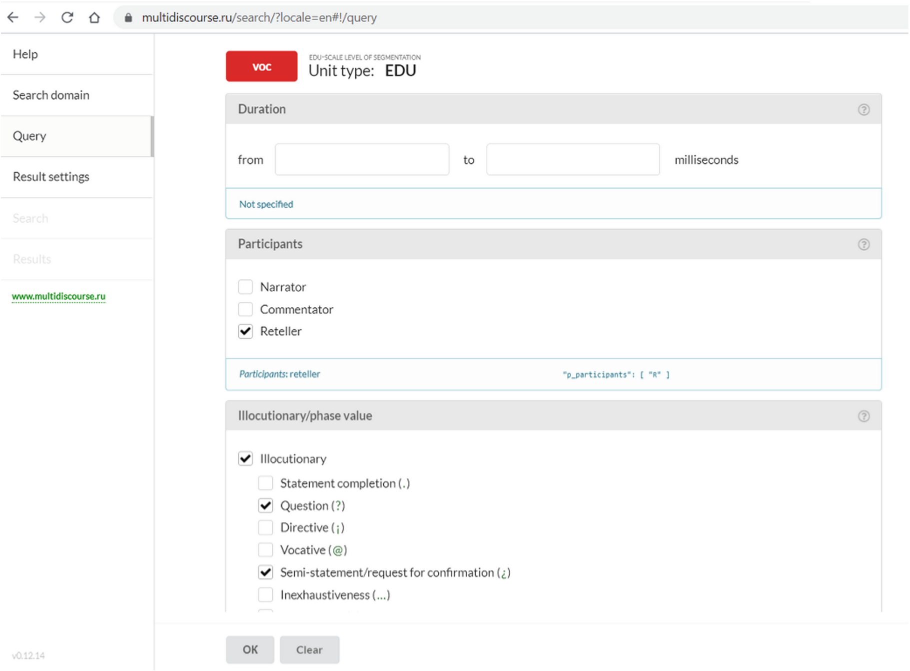
☐ Pears 04 ☐ Pears 35
☐ Pears 22 ☐ Pears 37
☐ Pears 23 ☐ Pears 39

Stages

☐ First telling ☐ Changeover
☑ Conversation ☐ Retelling

Fig. 1. Specifying search domain. Only data from the Conversation stages will be searched for

Next, one could identify initiating turns that launch elicitation exchanges. They can be found using a simple query consisting of one elementary discourse unit (EDU). This EDU should express an illocutionary value of question or semi-statement. In Russian, specific questions have *wh*-phrases and may exhibit various intonation patterns, while general questions are almost never marked syntactically but are predominantly pronounced with a distinctive rising pitch accent. Semi-statements, on the other hand, usually bear falling pitch accents, which makes them formally similar to (if not identical with) statements. However, they are functionally much closer to questions, as speakers produce them as tentative assumptions they want their interlocutors to confirm or reject. Moreover, as our preliminary results show, when speakers do not get a response from other participants, they tend to reiterate their request more often if it was initially formulated as a semi-statement rather than as a question [20]. Figure 2 demonstrates how these two illocutionary values can be specified in the unit's properties window.



Unit type: EDU

Duration

from ____ to ____ milliseconds

Not specified

Participants

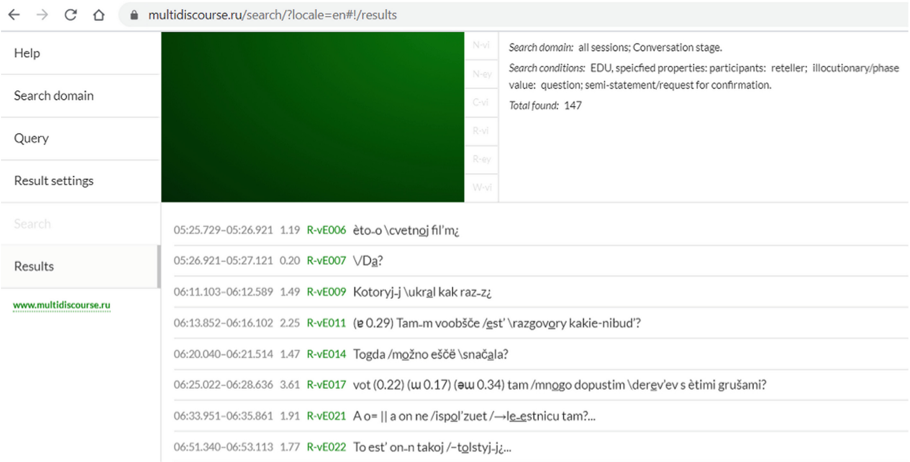
☐ Narrator
☐ Commentator
☑ Reteller

Participants: reteller "p_participants": ["R"]

Illocutionary/phase value

☑ Illocutionary
  ☐ Statement completion (.)
  ☑ Question (?)
  ☐ Directive (¡)
  ☐ Vocative (@)
  ☑ Semi-statement/request for confirmation (¿)
  ☐ Inexhaustiveness (...)

Fig. 2. Specifying properties of a search unit. Elementary discourse units (EDUs) are set to be uttered by the Retellers and have an illocutionary value of question or semi-statement.



Search domain: all sessions; Conversation stage.

Search conditions: EDU, speicfied properties: participants: reteller; illocutionary/phase value: question; semi-statement/request for confirmation.

Total found: 147

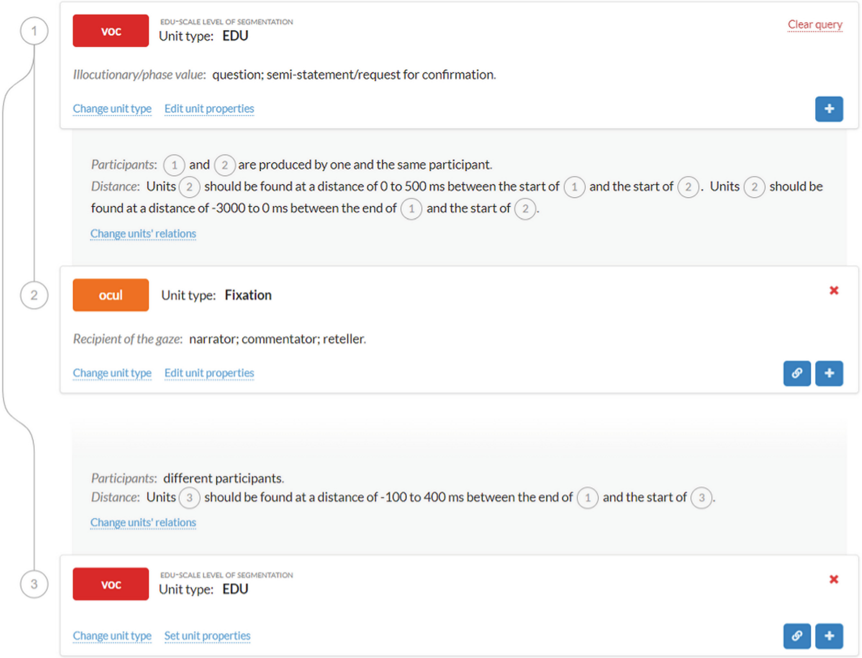
05:25.729–05:26.921 1.19 R-vE006 èto-o \cvetnoj fil'm¿
05:26.921–05:27.121 0.20 R-vE007 \/Da?
06:11.103–06:12.589 1.49 R-vE009 Kotoryj-j \ukral kak raz-z¿
06:13.852–06:16.102 2.25 R-vE011 (ɐ 0.29) Tam-m voobšče /est' \razgovory kakie-nibud'?
06:20.040–06:21.514 1.47 R-vE014 Togda /možno eščë \snačala?
06:25.022–06:28.636 3.61 R-vE017 vot (0.22) (ɯ 0.17) (əɯ 0.34) tam /mnogo dopustim \derev'ev s ètimi grušami?
06:33.951–06:35.861 1.91 R-vE021 A o= || a on ne /ispol'zuet /→le-estnicu tam?...
06:51.340–06:53.113 1.77 R-vE022 To est' on-n takoj /–tolstyj-j¿...

Fig. 3. Viewing query results in a simple list format

Consecutively clicking OK and Search buttons will return result for this preliminary query, as shown in Fig. 3. This is a simple view, where each hit is represented as a text transcript. In transcripts, questions are denoted by question marks, semi-statements by inverted question marks. Clicking a hit will rearrange the window, display this hit in a multi-layered format and play the corresponding video fragment. However, before analyzing multichannel annotations and viewing video files, it would be reasonable to make a more complex query, so that it would account for the multichannel nature of the elicitation contexts.

Here is one way to do that. In addition to uttering a question or a semi-statement, the participants who initiate elicitation most often direct their gaze towards the interlocutor who they think should provide the requested information. This phenomenon has often been discussed in studies on turn-taking, beginning from [21]. Taken together, vocal and oculomotor actions strongly projects that a reaction will follow. The pattern can be summed up in a complex query presented in Fig. 4. It consists of three search units:

1. an EDU constituting a question or a semi-statement;
2. a gaze fixation directed at one of the three main participants; and
3. another EDU.



Unit type: EDU

Illocutionary/phase value: question; semi-statement/request for confirmation.

Participants: ① and ② are produced by one and the same participant.
Distance: Units ② should be found at a distance of 0 to 500 ms between the start of ① and the start of ②. Units ② should be found at a distance of -3000 to 0 ms between the end of ① and the start of ②.

Unit type: Fixation

Recipient of the gaze: narrator; commentator; reteller.

Participants: different participants.
Distance: Units ③ should be found at a distance of -100 to 400 ms between the end of ① and the start of ③.

Unit type: EDU

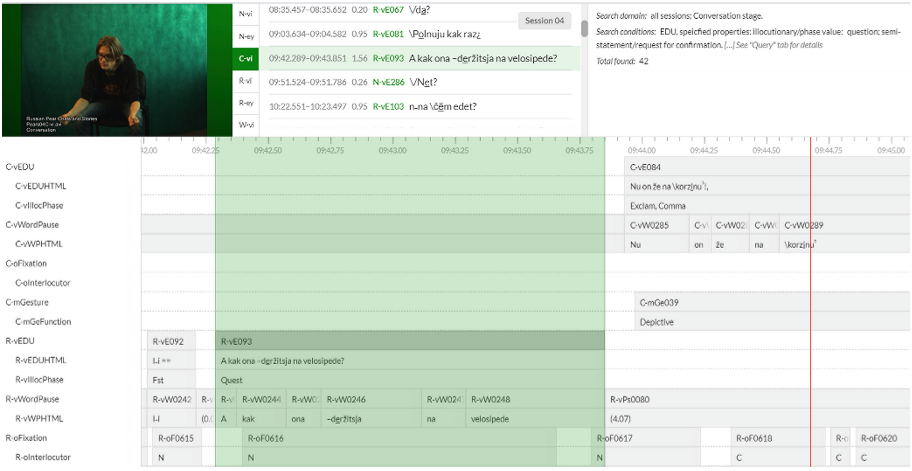
Fig. 4. A complex tree-like query consisting of three units

Relations between these three units are specified as follows:

- The fixation 2 should be produced by the same participant as the EDU 1 and is set to start within a 500 ms interval after the start of that EDU, but not before its end.

- The EDU 3 should be produced by another participant and is set to start no earlier than 100 ms before and no later than 400 ms after the end of the EDU 1. (Thus, a short overlap of vocal turns is allowed.)

Figure 5 shows an extended view of one hit returned for this query. This example has a somewhat unusual structure. The Reteller initiates the sequence as she makes a question and directs her gaze at the Narrator. However, this is not the Narrator but the Commentator who provides an answer and thus violates the Reteller's initial expectations on the turn-taking structure of the oncoming exchange. The video player shows the Commentator producing a depictive manual gesture that corresponds to an object he describes verbally. Overall, studying the hits returned for such a complex query offers a finer-grained understanding of how the participants co-operate as they seek to achieve a shared task while using various communication channels.



N-vi 08:35.457–08:35.652 0.20 R-vE067 \/da̲?

N-ey 09:03.634–09:04.582 0.95 R-vE081 \Po̲lnuju kak raz¿

C-vi 09:42.289–09:43.851 1.56 R-vE093 A kak ona –de̲ržitsja na velosipede?

R-vi 09:51.524–09:51.786 0.26 N-vE286 \/Ne̲t?

R-ey 10:22.551–10:23.497 0.95 R-vE103 n–na \čë̲m edet?

Search domain: all sessions; Conversation stage.

Search conditions: EDU, speicfied properties: illocutionary/phase value: question; semi-statement/request for confirmation. *[...] See "Query" tab for details*

Total found: 42

Fig. 5. Viewing search results in an extended multi-layered format

5 Conclusion

Natural discourse is performed via multiple communication channels. Analyzing this complex phenomenon requires a lot of preparatory work. First, a reliable annotation scheme should be developed and implemented to multichannel data. Second, a convenientsearch system needs to be put into practice. In this paper, we presented a beta version of the search system built for the RUPEX—"Russian Pear Chats & Stories" corpus. It operates online and does not require any specific software other than a web browser. We discussed its basic features using an on-going research on elicitation contexts. Of course, this is just an example. There are numerous subjects that could be studied with the help of RUPEX search, such as the temporal coordination of speech and co-speech gestures [22] or the gesticulation patterns that accompany speech disfluencies [23], to name but a few. We hopefully expect that RUPEX and its search engine will be used in actual research on multichannel communication.

References

1. British National Corpus. https://www.natcorp.ox.ac.uk/, Accessed 01 Nov 2020
2. Český národní korpus. https://www.korpus.cz/, Accessed 01 Nov 2020
3. Russian National Corpus, Национальный корпус русского языка. https://ruscorpora.ru/new/, Accessed 01 Nov 2020
4. Sketch Engine, https://www.sketchengine.eu/, Accessed 01 Nov 2020
5. Müller, C., Cienki, A., Fricke, E., Ladewig, S., McNeill, D., Tessendorf, S. (eds.): Body – Language – Communication: An international handbook on multimodality in human interaction. De Gruyter Mouton, Berlin (2013). https://doi.org/10.1515/9783110261318
6. Vigliocco, G., Perniss, P., Vinson, D.: Language as a multimodal phenomenon: implications for language learning, processing and evolution. Phil. Trans. Roy. Soc. B. Biol. Sci. **369**(1651), 20130292 (2014). https://doi.org/10.1098/rstb.2013.0292
7. Kibrik, A.A.: Russian multichannel discourse. Part I. Setting up the problem, Русскиймультиканальный дискурс. Часть I. Постановка проблемы. Psychol. J. **39**, 70–80 (2018). https://doi.org/10.7868/S0205959218010075
8. Adolphs, S., Carter, R.: Spoken Corpus Linguistics : From Monomodal to Multimodal. Routledge, Abingdon (2013). https://doi.org/10.4324/9780203526149
9. Carletta, J.: Announcing the AMI meeting corpus. ELRA Newsl. **11**(1), 3–5 (2006). https://groups.inf.ed.ac.uk/ami/corpus/overview.shtml
10. Kotov, A.A., Budyanskaya, E.M.: The Russian emotional corpus: communication in natural emotional situations. In: Computational Linguistics and Intellectual Technologies: Proceedings of the International Conference “Dialogue 2012”, vol. 11, pp. 296–306 (2012)
11. Joo, J., Steen, F.F., Turner, M.: Red hen lab: dataset and tools for multimodal human communication research. Künstl Intell. **31**, 357–361 (2017). https://doi.org/10.1007/s13218-017-0505-9
12. Russian Multichannel Discourse, Русский мультиканальный дискурс, https://multidiscourse.ru/main/, Accessed 01 Nov 2020
13. Fedorova, O.V., Kibrik, A.A.: The MCD handbook: A practical guide to annotating multichannel discourse. Institute of Linguistics RAS (to appear)
14. Chafe, W. (ed.): The Pear Stories: COGNITIVE, Cultural, and Linguistic Aspects of Narrative Production. Ablex, Norwood (1980)
15. Kibrik, A.A., Fedorova, O.V.: An empirical study of multichannel communication: Russian Pear Chats and Stories. Psychol. J. High. School Econ. **15**, 191–200 (2018). https://doi.org/10.17323/1813-8918-2018-2-191-200
16. ELAN [Computer software]. Max Planck Institute for Psycholinguistics, The Language Archive, Nijmegen (2020). https://archive.mpi.nl/tla/elan
17. Kibrik, A.A., Korotaev, N.A., Fedorova, O.V., Evdokimova, A.A.: Unified multichannel annotation: A tool for analysing natural communication, Единая мультиканальная аннотация как инструмент анализа естественной коммуникации. In: Computational Linguistics and Intellectual Technologies: Proceedings of the International Conference “Dialogue”, vol. 18, pp. 265–280 (2019)
18. Kibrik, A.A., Korotaev, N.A., Podlesskaya, V.I.: Russian spoken discourse: local structure and prosody. In: Izre’el, S., Mello, H., Panunzi, A., Raso, T. (eds.) In Search of Basic Units of Spoken Language: A Corpus-Driven Approach, pp. 37–76. John Benjamins, Amsterdam (2020). https://doi.org/10.1075/scl.94.01kib

19. Chafe, W.: Discourse, Consciousness, and Time: The Flow and Displacement of Conscious Experience in Speaking and Writing. The University of Chicago Press, Chicago (1994)
20. Korotaev, N.A.: Questions and semi-statements in multichannel discourse, Вопрос и полуутверждение в структуре мультиканального дискурса. In: The Eighth International Conference on Cognitive Science. Abstracts. pp. 1311–1313. Institute of Psychology RAS, Svetlogorsk (2018)
21. Kendon, A.: Some functions of gaze-direction in social interaction. Acta Physiol. **26**, 22–63 (1967). https://doi.org/10.1016/0001-6918(67)90005-4
22. McNeill, D.: Hand and Mind: What Gestures Reveal About Thought. The University of Chicago Press, Chicago (1992)
23. Seyfeddinipur, M.: Disfluency: INTERRUPTING Speech and Gesture. Radboud Universiteit Nijmegen, Nijmegen (2006)

Semantic Similarity of Words in RuWordNet Thesaurus and in Psychosemantic Experiment

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Abstract. In the paper we compare the structure of the Russian language thesaurus RuWordNet with the data of a psychosemantic experiment to identify semantically close words. The aim of the study is to find out to what extent the structure of RuWordNet corresponds to the intuitive ideas of native speakers about the semantic similarity of words. The respondents were asked to list synonyms to a given word. The words of the mental sphere were chosen for the experiment. As a result of the experiment, we found that the respondents mainly mentioned not only synonyms but words that are in paradigmatic relations with the stimuli. In 95% of cases, the words characterized in the experiment as semantically close were also close according to the thesaurus. In other cases, additions to the thesaurus were proposed.

Keywords: Thesaurus · Semantics · Psychosemantic experiment · Synonyms · Mental sphere

1 Introduction

Semantic similarity of words is an important parameter required in various tasks of natural language processing. It can be estimated in different ways: by corpus, using distributional methods [5,9]; expert assessments, including the results of psychosemantic experiments; using thesauri such as WordNet [4]. In this regard, it seems important to compare the semantic similarity estimates obtained by different methods.

Modern electronic thesauri are among the most demanded computer resources in natural language processing tasks. Such resources are built on the basis of synsets – sets of synonyms – linked by semantic relations such as hyponymy, hypernymy, antonymy, and some others. The automatic use of thesauri requires high quality descriptions of semantic senses and semantic relations between them. Thus, the urgent task is to test and verify thesauri, to improve the accuracy of displaying language data in them.

In this paper, we compare the results of a survey of respondents and the similarity of words according to the RuWordNet thesaurus [7] for the Russian

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language. The paper is structured as follows. Section 2 provides information on related work. Section 3 describes a psychosemantic experiment to determine the semantic similarity of words. Section 4 analyzes the data obtained. Section 5 discusses the results of the experiment.

2 Related Work

Recently, verification and enrichment methods have been systematically developed for the RuWordNet thesaurus. In [8], the following method for enriching the RuWordNet thesaurus was proposed. In a large text corpus, the authors searched for words having considerable discrepancy between similarity of words according to the corpus (based on the standard method for evaluating the semantic similarity of words [5,9]) and according to the thesaurus. The distance between words in the thesaurus is the length of the shortest path between them in the graph of semantic relations. For found words with such properties, the reasons for such discrepancy are analyzed. The analysis of the data presented in [8] was continued in [2].

In work [12], RuWordNet synsets were compared with synonymous sets according to published 10 dictionaries of Russian synonyms. The work [3] presents the results of an experiment, in which the respondents were asked to list synonyms for a given word. The results are compared with the RuWordNet synsets. In [13], an innovative approach is proposed, which consists in the analysis of pairs of quasi-synonyms and the distance between them in RuWordNet. It was expected that quasi-synonyms, as semantically close words, should be located at a short distance in the thesaurus.

The general result of all these studies is as follows. RuWordNet data, including the composition of synsets and the structure of semantic relations, correlate well with all the other considered sources of information about semantically close words. At the same time, a number of gaps in RuWordNet were identified, taking into account of which allows improving the thesaurus. Such an integrated multidimensional approach to testing and enriching thesauri is used for the first time in the world practice. This article continues research in this direction.

3 Experiment Setting

In the current study we present the results of a psychosemantic experiment [3] carried out in accordance with the methodology described in [11]. The experiment reveals semantically close words (synonyms) in the representation of native speakers.

The experiment is as follows. The respondents receive a number of words, and they have to list synonyms for these words in a limited time. The respondents are students (18–23 years old, 200 people) of Kazan Federal University. About half of the students are philologists, the second half are non-philological students. The definition of a synonym is not explained to the respondents. We rely on intuitive understanding of the language by native speakers. The results of philologists and non-philologists differ insignificantly [3]. For the experiment, words related to the mental sphere were selected. This semantic area is the most difficult for clear differentiation of synonym and other semantic relations of words.

Since the respondents did not use any criteria of synonymy and did not have much time to complete the task, they suggested words that have something semantically in common with the given word, but not necessarily synonyms in the strict sense of the term. For example, for the word *мечта* (dream as imaginative thoughts), the following words are listed as synonyms in RuWordNet: *греза, мечтание* (dream), *фантазия* (fantasy). The respondents most often indicated the following words: *желание* (desire), *цель* (goal), *фантазия* (fantasy), *грезы, стремление* (aspiration), *надежда* (hope). Only two of them are synonymous. The rest of the words – *желание* (desire), *цель* (aim), *стремление* (aspiration), *надежда* (hope). At first glance the answers may seem like associations with the given word. However, this assumption is not true.

In the Karaulov's dictionary of Russian associations [6], we can see that for the word *мечта* (dream) the most frequent associations are as follows: *голубой* (blue), *жизнь* (life), *моя* (mine), *сбылась* (come true), *идиота* (idiot), *несбыточная* (unrealizable), *розовая* (pink). The words *желание* (desire), *стремление* (aspiration), *надежда* (hope) are not mentioned as associations in the dictionary at all, and the word *цель* (goal) is mentioned only once in 101 responses. We can suppose that in fact words having syntagmatic relations with the original one are mostly mentioned as associations by respondents for the given word. But in the current experiment, when asked to list synonyms, the respondents indicated words that were not in syntagmatic but in paradigmatic relations with the stimulus. Rather, the listed synonyms can be characterized as belonging to the semantic field of the original word or as its analogues.

Note that in the dictionary [1] the words *намерение* (intention) and *мысль* (thought) are considered as analogues (quasi-synonyms) of the word *мечта* (dream) (its synonyms are not given in the dictionary). For the verb *мечтать* (to dream), the synonyms, according to [1], are *хотеть* (to want), *желать* (to desire), and the analogue is the word *надеяться* (to hope). Thus, the words indicated by the respondents are close in meaning to the word *мечта* (dream). Our experiment can be characterized as aimed at identifying paradigmatic associations, while the Karaulov's dictionary [6] in fact turned out to be a dictionary of syntagmatic associations.

4 Analysis of Results

In this work, the associations for the words *обида* (offense, as a feeling caused being offended), *радость* (joy), *талант* (talent), *страсть* (passion), *любовь* (love), *мысль* (thought), *восторг* (delight) are considered. For each stimulus word, six most frequently mentioned responses are studied.

Обида (offense feeling). The informants most often indicated the words: *огорчение* (grief), *досада* (annoyance), *боль* (pain), *грусть* (sadness), *разочарование* (disappointment), *злость* (anger). The first of them is interpreted in

RuWordNet as a hypernym for *обида*. The word *грусть* (sadness) in RuWordNet also has a direct connection with обида – it is a hypernym-hypernym for *обида*. *Досада* (annoyance) is a co-hyponym for *обида*, having a joint hypernym *недовольство* (discontent). There is also a short path between the words *обида* and *разочарование* (disappointment): *обида* (offense) – *недовольство* (discontent) – *душевное переживание* (emotional experience) – *разочарование* (disappointment). There is a similar path between the words *обида* (offense) and *разочарование* (disappointment): offense – discontent – emotional experience – disappointment. Finally, the path between the words *боль* (pain) and *обида* is only slightly longer: pain – suffering – emotional experience – discontent – offense. Semantic distances of four steps or less are treated in [8] as short. All semantic relations are hypo-hypernymic.

Радость (joy). For this word, respondents indicate the following word associations: *счастье* (happiness), *восторг* (delight), *веселье* (fun), *улыбка* (smile), *ликование* (exultation), *удовольствие* (pleasure).

The words *веселье* (fun), *ликование* (exultation), *удовольствие* (pleasure) are hyponyms in relation to *радость* (joy). The words *восторг* (delight) and *счастье* (happiness) are co-hyponyms with *радость* (joy) with a common hypernym – *душевное переживание* (emotional experience). But between the words *радость* (joy) and *улыбка* (smile) there is only a very long way: *радость* (joy) – *душевное переживание* (emotional experience) – *ментальный объект* (mental object) – *абстрактная сущность* (abstract entity) – *качество* (quality) – *внешность* (appearance) – *выражение лица* (facial expression) – *улыбка* (smile). Such a long path reflects the fact that in RuWordNet the word *улыбка* (smile) is interpreted only as a facial expression and, accordingly, *радость* (joy) and *улыбка* (smile) in RuWordNet refer to different spheres—the mental world and the physical.

If to compare, Princeton WordNet [4] presents the point of view that a person smiles to communicate something to others about his condition (to change one's facial expression by spreading the lips, often to signal pleasure) and thus it is classified as communication. Still, it should be noted that a person can smile at own thoughts, pleasant memories while alone with yourself, i.e. a smile is also possible outside the communication situation. As we can see, the situation here is very difficult. According to the Russian explanatory dictionary [10], *улыбка* (smile) has the following definition is "mimic movement of the face, lips, eyes, showing disposition to laughter, expressing pleasure or ridicule and other feelings (translation from Russian)". This definition takes into account both facial expressions and communicative intentions.

It is possible to take into account the intuition of native speakers and the dual nature of a smile by making certain changes to the thesaurus. It can be described with the entailment relationship between concepts *улыбаться* (to smile) and *радоваться* (to joy). If a person smiles, then usually this person is really happy, or at least seeks to show happiness to others. Conversely, if a person is really happy about something, then this manifests itself in a smile.

Талант (talent). For this word, the respondents indicate the following synonymous words: *способность* (ability), *дар* (gift), *умение* (skill), *дарование*, *одаренность* (giftedness), *гений* (genius). In RuWordNet *дарование* (giftedness), *дар* (gift), are listed as synonyms to the word *талант* (talent). *Способность* (ability) is a hypernym for *природная способность* (natural ability), which is a hypernym for *талант* (talent). *Умение* (skill) is a co-hyponym with *талант* (talent) through the general hypernym *природная способность* (natural ability). *Одаренность* (giftedness) is a hyponym in relation to *способность* (ability), i.e. is at distance 3 from the word *талант* (talent). The word *гений* (genius) is a hyponym in relation to *одаренность* (giftedness), at a distance 4 from the word *талант* (talent).

Страсть (passion). For the word *страсть* (passion), the respondents indicate the synonymous words: *желание* (desire), *влечение* (attraction), *любовь* (love), *увлечение* (infatuation), *похоть* (lust), *интерес* (interest). In RuWordNet, *увлечение* (infatuation) is a hypernym for *страсть* (passion). *Интерес* (interest) is a hypernym of the hypernym for the word *страсть* (passion). The words *влечение* (attraction), *желание* (desire), *любовь* (love) are co-hyponyms with the word *увлечение* (infatuation) with a common hypernym, *душевное переживание* (emotional experience), i.e. are at a distance of 3 from *страсть* (passion). *Похоть* (lust) is a hyponym in relation to влечение (attraction), i.e. is at a distance of 4 from the initial word *страсть* (passion). The scheme of semantic relations in this group of words can be represented in Fig. 1. The arrows show links from hypernyms to hyponyms. This is a typical scheme for words in the experiment.

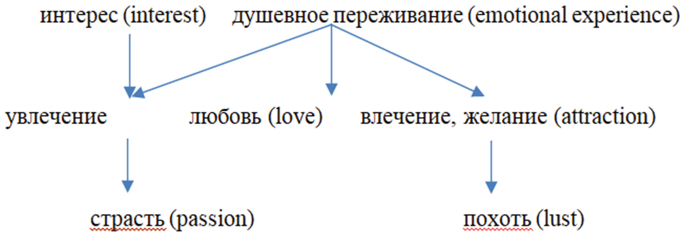

Fig. 1. The scheme of semantic relations for страсть associations

Любовь (love). For the word *любовь* (love), the respondents list the following words: *привязанность* (attachment), *влюбленность* (falling in love), *симпатия* (sympathy), *страсть* (passion), *нежность* (tenderness), *влечение* (attraction).

We saw above that *любовь* (love) is at a distance of 3 from *страсть* (passion) and at a distance of 2 from *влечение* (attraction). *Привязанность* (attachment) is a hypernym for *любовь* (love). *Любовь* (love) and *влюбленность* (falling in love) are co-hyponyms with common hypernym *эмоциональное переживание* (emotional experience). *Симпатия* (sympathy) is a co-hyponym with *влюбленность* (falling in love) through the hypernym *личностные отношения* (personal relationships). Thus, between the words *симпатия* (sympathy) and *любовь* (love) there is a distance of length 4. But *нежность* (tenderness) is interpreted in RuWordNet only as a character trait (two other senses: *нежность*1 – soft, gentle to the touch, *нежность*3 – fragile, here are not discussed as irrelevant), and not as *душевное переживание* (emotional experience). Thus, there is no close way between the words *любовь* (love) and *нежность* (tenderness).

Apparently, one of the senses of word *нежность* (tenderness) is missing in RuWordNet. In the explanatory dictionary [10], noun *нежность* (tenderness) refers to the adjective *нежный* (tender), which is interpreted (in this sense) as "affectionate, full of love: tender feelings". According to Wikipedia, "tenderness is a form of affection ... towards another person, caused by love towards him" (translation from Russian). According to the dictionary [1], "нежный – проявляющий в общении с каким-либо человеком чувство любви или расположения" (tender is showing a feeling of love or affection in communication with any person).

Thus, in the interpretation of the word *нежность* (tenderness), the word *любовь* (love) invariably appears, indicating the correctness of the students' answers. If the character of a person persists throughout his/her life, or at least a significant part of his/her life, then *нежность* (tenderness) is manifested more often in shorter periods of time and only in relation to a specific person. In this aspect, it comes closer to *душевное переживание* (emotional experiences). It is recommended to add a new sense to the word *нежность* (tenderness), in accordance with the above-mentioned dictionary definitions, and to establish its relation as a hyponym to the synset *душевное переживание* (emotional experience). Consideration should also be given to linking the word *нежность* (tenderness) in this sense as a hyponym for the word *привязанность* (affection).

Восторг (delight). The respondents indicate the following synonymous words: *радость* (joy), *восхищение* (admiration), *удивление* (surprise), *счастье* (happiness), *ликование* (jubilation), *воодушевление* (inspiration).

In RuWorNet, *восторг* (delight) and *восхищение* (admiration) are presented as synonyms, *счастье* (happiness), *удивление* (surprise) and *радость* (joy) are co-hyponyms with *восторг* (delight) with common hypernym *эмоциональное переживание* (emotional experience). *Ликование* (jubilation), as noted above, is a hyponym in relation to *радость* (joy), that is located at the distance of 3 from *восторг* (delight). *Воодушевление* (inspiration) is a co-hypernym with the word *радость* (joy) with the general hyponym *эйфория* (euphoria), that is presented at the distance of 4 from *восторг* (delight).

Мысль (thought). The respondents indicated the following words as associations: *идея* (idea), *дума* (thought), *мнение* (opinion), *догадка* (guess), *соображение* (consideration), *суждение* (judgment). *Соображение* (consideration) and *дума* (thought) are synonyms to *мысль* (thought). *Идея* (idea) is a hyponym for *мысль* (thought), *суждение* (judgment) is a hypernym from *мысль* (thought). *Мнение* (opinion) is a co-hyponym with word *мысль* (thought) having hypernym *суждение* (judgment). Between the words *мысль* (thought) and *догадка* (guess), there is a path of length 4: *мысль* (thought) – *суждение* (judgment) – *мнение* (opinion) – *предположение* (assumption) – *догадка* (guess).

5 Discussion

We analyzed 40 word pairs (out of a total of $7 \times 6 = 42$ pairs, two pairs were repeated). In 38 cases (95%), word pairs listed by the respondents as synonyms are also close according to the thesaurus descriptions: 13 pairs are at a thesaurus distance of 1, 12 pairs at a distance of 2, 7 pairs at a distance of 3, 6 pairs at a distance of 4. The number of mentioned words located at a certain path distance in the thesaurus decreases monotonically with an increasing position in respondent answers. In all these cases, it was sufficient to consider only hypo-hypernymic relations. In two cases, it is necessary to make certain changes in the thesaurus to obtain smaller distance for semantically close words. These pairs of words are as follows: *любовь* (love) – *нежность* (tenderness) and *радость* (joy) – *улыбка* (smile). In the first case, it is proposed to add a new sense of the word *нежность* (tenderness) in the thesaurus and to establish the necessary additional relation of hyponymy, in the second case we suggest to add the relation of entailment.

Thus, most words frequently mentioned by respondents or are located close to the stimulus word in RuWordNet, which indicates good consistency of the thesaurus with the intuition of native speakers. To study if there is a correlation between the frequency of a response word and the distance in the thesaurus from the stimulus word to the response word, we sort words-reactions according to the frequency of their mention. Table 1 summarizes the obtained data. We can see that the words mentioned more often are at a shorter distance from the stimulus word in the thesaurus, which is also a good confirmation of the correct structure of the thesaurus and the adequacy of the experiment.

Table 1. Relationships between positions, frequencies of association, and relation distances in RuWordNet for word associations.

Position	1	2	3	4	5	6
Frequency of responses	40.3	31.3	22.7	13.9	12.7	12.4
RuWordNet distance	1.7	2.1	2.0	2.1	2.6	2.6

6 Conclusion

Thesauri are created by professionals who rely on both the theory of language and their ideas about the semantics of linguistic units. Taking this into account, it is of natural interest to compare thesaurus data with the linguistic intuition of native speakers, manifested in psychosemantic experiments. In the paper we presented the results of a psychosemantic experiment, when respondents were asked to list synonyms for stimulus words. It was found that the respondents mainly mentioned not only synonyms but other words in paradygmatic relations with an initial word.

Most words frequently mentioned by respondents are synonyms to the stimulus word in RuWordNet or located close to it in the thesaurus, which indicates good consistency of the thesaurus with the intuition of native speakers. This also confirms the high quality of the RuWordNet thesaurus. At the same time, it was possible to identify some problems in the thesaurus and to suggest corrections.

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References

1. Apresian, Y.D. (ed.): New Explanatory Dictionary of Russian Synonyms. Iazyki slavianskoi kul'tury, Moscow, Vena (2004) (in Russian)
2. Bayrasheva, V.: Corpus-based vs thesaurus-based word similarities: expert verification. In: The XXth International Scientific Conference "Cognitive Modeling in Linguistics", pp. 56–63 (2019)
3. Erofeeva, I.V., Solovyev, V.D., Bayrasheva, V.R.: Psychosemantic experiment as a tool for objectifying data on the ways of representing synonymy in modern Russian language. Bull. Volgogr. State Univ. Series 2: Linguistics **19**(1), 178–194 (2020) (in Russian)
4. Fellbaum, C.: WordNet: An Electronic Lexical Database. MIT Press, Cambridge (1998)
5. Grave, E., Bojanowski, P., Gupta, P., Joulin, A., Mikolov, T.: Learning word vectors for 157 languages. arXiv preprint arXiv:1802.06893 (2018)
6. Karaulov, Yu.N., Cherkasova, G.A., Ufimtseva, N.V., Sorokin, Yu.A., Tarasov, E.F.: Russian associative dictionary. M.: AST-Astrel (2002) (in Russian)
7. Loukachevitch, N., Lashevich G., Dobrov B.: Comparing two thesaurus representations for Russian. In: Global WordNet Conference GWC-2018, pp. 35–44 (2018)
8. Loukachevitch, N.: Corpus-based check-up for thesaurus. In: 57th Annual Meeting of the Association for Computational Linguistics ACL-2019, pp. 5773–5779 (2019)
9. Mikolov, T., Sutskever, I., Chen, K., Corrado, G. S., Dean, J.: Distributed representations of words and phrases and their compositionality. In: Advances in Neural Information Processing Systems, pp. 3111–3119 (2013)
10. Ozhegov, S.I., Shvedova, N.Yu.: Explanatory dictionary of the Russian language. In: Russian Academy of Sciences. Institute of the Russian Language named after V.V. Vinogradov. 4th ed. M., Azbukovnik (1997) (in Russian)
11. Petrenko, V.F.: Fundamentals of Psychosemantics. M.: Eksmo (2010) (in Russian)
12. Solovyev, V., Gimaletdinova, G., Khalitova, L., Usmanova, L.: Expert assessment of synonymic rows in RuWordNet. In: Analysis of Images, Social Networks and Texts (AIST'2019), CCIS, vol. 1086, pp. 174–183 (2020)
13. Usmanova, L., Erofeeva, I., Solovyev, V., Bochkarev, V.: Analysis of the semantic distance of words in the RuWordNet thesaurus. In: DAMDID/RCDL'2020 Conference (2020)

Human Functional States

Influence of Meditation on Brain Mechanisms: Methodological Aspects

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Abstract. Despite 50 years of research, there is still no common understanding of neurophysiological processes underlying meditation practice since the data obtained are often quite contradictory. For overcoming these difficulties, the literature suggests paying more attention to describing the type of meditation, practitioners' experience, and other subjective factors (for example, discomfort from electrophysiological equipment or presented stimuli) that can influence the meditation process. In this article, we tried to consider these methodological recommendations and developed a special structured interview to take these factors into account. The results showed that neither field studies (investigation of meditation in conditions as close to natural as possible), nor the study of monks of the same tradition, from the same monasteries, having the same experience in meditation, does not guarantee that sufficiently homogeneous groups of subjects can be formed. A detailed analysis of the proposed structured interview may be necessary to research meditation's influence on brain mechanisms.

Keywords: Meditations · Methodology · Subjective measures · ERP · Mismatch Negativity

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1 Introduction

Over the past 50 years, neurophysiological research on meditation has become very popular. Yet, there is still no consensus about the neurophysiological processes underlying meditation practice. The data received are often contradictory [see the reviews: 1, 2]. To overcome these, besides describing the practitioner's experience and the type of meditation, it is proposed to pay more attention to other subjective factors that can influence the meditation process. Factors affecting the meditation state may include whether the setting is a place usually used for meditation or a laboratory, the intrusiveness and discomfort of the psychophysiological measures, the presence of others in the meditation space, and others subjective factors [1].

In this article, we tried to take into account these methodological recommendations. To systematize various subjective factors, we developed a structured interview and, on its basis, calculated the level of experience of meditation practices and the level of discomfort during the study.

This article aims to research the physiological mechanisms of the system of traditional Buddhist meditation practices. According to Buddhism, considered here system of meditative techniques, thoroughly based upon one-pointed concentration, is characterized by the gradual withdrawal of gross levels of consciousness related to five senses [3, 4]. Therefore, at the first stage of the study, researchers concentrated on how the above system of meditations affects the processes of perception, recognition, and differentiation of sensory, auditory signals.

For this purpose, the method of the event-related potentials in the oddball paradigm and the analysis of Mismatch Negativity (MMN) were used. Traditionally, MMN is considered as an automatic response of the brain cortex to any change in the stream of sound stimuli generated in auditory and frontal cortical zones [5, 6]. In other words, MMN is an indicator of the automatic differentiation of acoustic signals. We were supposed to find that considered meditative practices associated with the withdrawal of gross levels of consciousness (sensory consciousness) led to a decrease of MMN amplitude. We also examined how various subjective factors (the level of discomfort; experience of practitioners) influenced the MMN amplitude during meditation.

2 Methods

2.1 Participants

The Ethics Committee of N.P. Bechtereva Institute of the Human Brain of RAS approved this study. All subjects were familiarized with the study's procedure and signed an informed consent drafted following the ethical standards stated in the Helsinki Declaration (The World Medical Association, 2013).

The informed consent was written in English. As some of the subjects were not proficient in English, the text of the informed consent was translated and explained to them in their native Tibetan language with the assistance of monks-researchers who spoke both English and Tibetan.

Ninety-four persons, the expert monks from the Tibetan monasteries of the South of India and the retreat village in Dharamsala, Gelug-pa tradition, aged from 25 years up to 80 years (middle age 40 ± 12.24) took part in the research.

2.2 Structured Interview

Before and after each research session, the survey of practitioners was done using a structured interview developed following existing recommendations [1]. The interview allowed maintaining a similar context for posing questions to all the respondents and ensured standardization of recording answers.

As a result of the interviews, the entire group of monks-subjects was divided by experience level. We evaluated their experience in meditation, based not only on the overall period of training (the number of years since the beginning of the meditation practice) but also its intensity (the number of hours per day), regularity (does one meditates every day). We also noted how many various types of meditation one has mastered. The level of experience was calculated as a sum of the number of years from the beginning of meditative practice (1 year – 1 point); the number of minutes of meditation per day (10 min – 1 point), and the number of various types of meditation (1 type – 1 point).

The structured interview conducted after the meditation was also allowed to consider situational factors affecting the meditation state (discomfort level, a distraction from meditation, subjective evaluation of the success of meditation) [1]. An answer to each question was evaluated on a scale from 1 to 10 points. The discomfort level during the experimental session was calculated as a sum of points in response to each question.

2.3 Meditative States

In the study, all monks carried out the core practice, which they usually carry out. According to an interview, 64 monks carried out the one-pointed concentration meditation (Sanskrit: *Shamatha*) on emptiness, *bodhicitta*, impermanence, or compassion, 20 monks carried out analytical meditation (Sanskrit: *Vipashyana*) on the same objects, 10 monks carried out Tantric practice.

The term «one-pointed concentration» suggests that concentration of attention on a chosen object leads to the reduction of distracting influence of the stream of sensory information and the practitioner's thoughts and emotions [7].

Analytical meditation, in general, represents the concentration of attention on the analytical process and can be practiced by itself or as a preliminary stage preceding one-pointed concentration on the same object.

The objects of one-pointed concentration used in the study were quite sophisticated. These were, for instance, the key Buddhist concept of emptiness, or interdependence of all phenomena (Sanskrit: *shunyata*), or an altruistic aspiration to enlightenment for the sake of all sentient beings (Sanskrit: *bodhicitta*). Some practitioners also concentrated on the notion of the impermanence of all things (Sanskrit: *anytia*) and compassion (Sanskrit: *karuna*). In these meditations, the analytical process invariably preceded one-pointed concentration and was repeated throughout the practice.

Maintaining both one-pointed concentration and analytical meditation on *bodhicitta* and emptiness is a necessary condition for the transition to tantric practices. These tantric practices are involved sophisticated visualizations of Buddhist deities, their mansions (Sanskrit: *mandala*), the energy structure of the human body, and the stage-by-stage process of dying with the dissolution of the body elements and grosser levels of consciousness [8, 9].

According to Buddhism, considered meditations base upon one-pointed concentration. All these practices are united by the process of concentration of attention, so they can be considered a single meditation system.

2.4 Mismatch Negativity Paradigm

We used the three stimuli test in the oddball paradigm. In the test 1600 low-pitch tones - 1000 Hz (standard stimuli) and 200 high-pitch tones - 1300 Hz (deviant stimuli) were presented. Also, 200 difficult sound tones (novel stimuli) were presented. These novel stimuli have consisted of a sequence of 5 tones lasting 20 ms and with a frequency of 500, 1000, 1500, 2000, 2500 Hz. The duration of the stimuli was 100 ms. The order of presentation of the three types of stimuli was randomized. The subjects performed the test in a passive paradigm. The sounds were presented to subjects during meditation and in a control state. In both cases, the subjects sat in a meditation posture in a darkened room with their eyes closed or semi-closed. Meditation and the control states were randomized for each subject. The research was carried out in one spaces within the monasteries, and the setting was as close as possible to normal conditions the monks are usually meditating in. During meditation, only a researcher was present at the same time as a practitioner. For psychological comfort, the majority of manipulations were carried out by a monk researcher.

2.5 EEG Recording and Analyses

Electroencephalogram (EEG) recording was conducted with an acquisition system “Mitzar EEG202” (Scientific and Production Company “Mitzar”, Saint-Petersburg, Russia). For EEG records, the WinEEG software package was used (Copyright V.A. Ponomarev, J.D. Kropotov, RF2001610516, 08.05.2001). EEG recording was conducted from 21 scalp sites - the international 10–20 system and two electrodes on left and right mastoids (M1, M2). The record was carried out in monopolar montage with a reference electrode on a nose tip. The ground electrode was located between FPz and Fz scalp sites. When processing EEG the high-pass filter (1.6 Hz) and the low-pass filter (30 Hz) were used for correct identification of an MMN wave in the noisy EEG records. Correction of artifacts was carried out using the WinEEG software package, the Independent component analysis method (ICA), and the algorithm “Infomax” was used.

The event-related potentials (ERP) for standard and deviant stimuli were calculated with the following parameters: 200 ms – prestimulus interval, 100 ms – duration of the stimulus, 500 ms – interval after the stimulation. The ERPs were averaged for each type of trial within the whole group of subjects. MMN was defined as the differential wave received at the subtraction of ERP on standard stimuli from ERP on deviant stimuli. On group ERPs, the wave of MMN was presented as a negative wave on a time interval of 100–150 ms after the beginning of sound stimuli. MMN has fronto-central location [5, 6], so three frontal scalp sites (F3, Fz, F4) were chosen as a region of interest.

For the statistical analysis (Statistica, version 11.0, the serial number AXA207F396330FA-5) repeated-measures ANOVA with factors: 3 groups x 2 states (meditation and control) × 3 electrodes (F3, Fz, F4) was used. Tukey HSD test demonstrated the electrode difference.

3 Results

We used the statistical analysis ANOVA (2 states × 3 electrodes) to determine the MMN amplitudes' differences between meditation and control states. ANOVA showed main effect of a factor "state" (F (1.93) = 4.19 p = 0.043) and factor "electrodes" (F (2.186) = 4.14 p = 0.017). The interaction of factors does not reach the level of significance. The electrode difference research with the Tukey HSD test gives significant differences for three EEG electrodes ($p < 0.05$). During meditation, there is a significant decrease in MMN amplitude in comparison with a control state (Fig. 1).

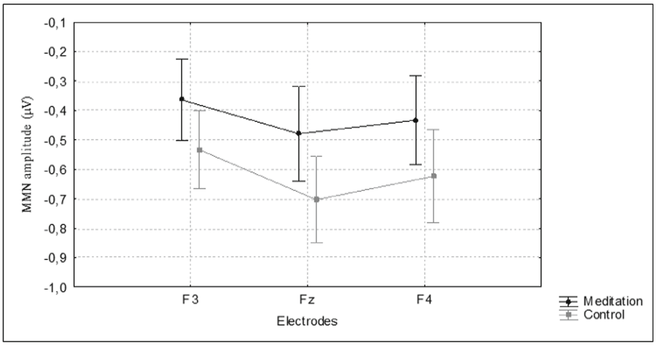

Fig. 1. MMN amplitude differs during meditation and control state. Vertical bars denote 0,95 confidence interval, and points represent mean MMN amplitude.

According to the interviews, three groups of practitioners with different experience levels were highlighted: 1) Less experienced group - 55 people, age 35.6 ± 9.2 years; 2) Intermediate group - 16 people, age 41.7 ± 9.1 years; 3) Group of skilled practitioners - 23 people, age 52.6 ± 12.2 years. We used the statistical analysis ANOVA (3 groups × 3 electrodes) to determine the MMN amplitudes' differences between those groups. ANOVA showed main effect of a factor "group" (F (2.91) = 5.1 p = 0.007), of a factor "electrodes" (F (2.182) = 4.02 p = 0.019). The interaction of factors does not reach the level of significance. ANOVA shows that the maximum MMN amplitude is observed in the group of less experienced practitioners, and the minimum amplitude in the group of skilled practitioners (Fig. 2). In a control state, there were no differences between the groups (Fig. 2).

Based on the interviews, three groups of practitioners with different level of discomfort were highlighted: 1) Group with the low discomfort level - 57 people, age 41.6 ± 13.5 years; 2) Group with the intermediate discomfort level - 27 people, age 38.6 ± 9.4 years; 3) Group with the high discomfort level - 10 people, age 41.9 ± 11.3 years. We used the statistical analysis ANOVA (3 groups × 3 electrodes) to determine the MMN amplitudes' differences between those groups. ANOVA showed main effect of a factor "group" (F (2.91) = 3.63 p = 0.03). The interaction of factors does not reach the level of significance. The minimum MMN amplitude was observed in the group with a high discomfort, the maximum MMN amplitude was observed in the group with an

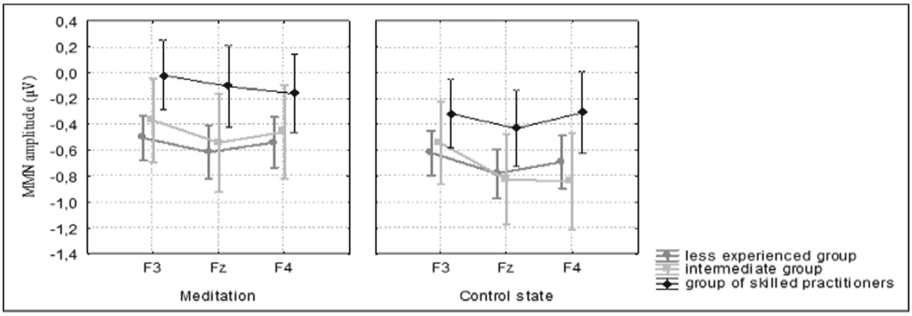

Fig. 2. MMN amplitude differs in groups with different levels of experience. Vertical bars denote 0,95 confidence interval, and points represent mean MMN amplitude.

intermediate discomfort level (Fig. 3). In a control state, the groups also were different - ANOVA showed the main effect of a factor "group" (F (2.91) = 3.63p = 0.03).

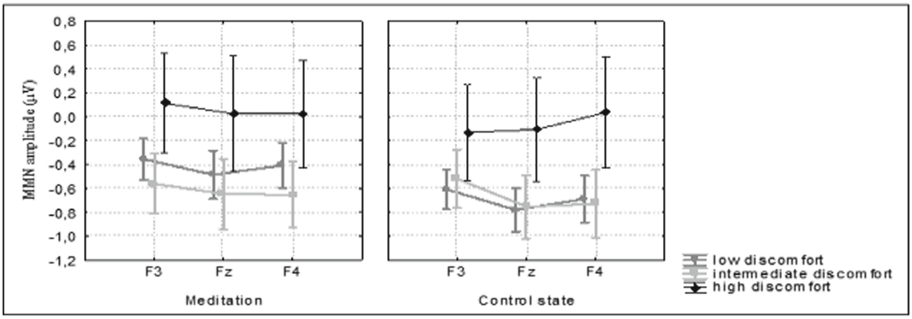

Fig. 3. MMN amplitude differs in groups with different levels of discomfort. Vertical bars denote 0,95 confidence interval, and points represent mean MMN amplitude.

4 Discussion and Conclusion

The study revealed the differences in the MMN amplitude that we expected to see. During performing the considered meditations system, a smaller amplitude of MMN was noted in comparison to the control state of relaxed wakefulness with closed eyes. The MMN is a stimulus-evoked electrophysiological response elicited by any changes in a sequence of repeating sensory stimuli and reflects that the brain has detected those changes [5, 6, 10]. Therefore, it is possible to conclude that the studied system of traditional Buddhist meditations is accompanied by a decrease of recognition of external sensory stimuli and leads to disengagement of attention from the external world.

The results also show that groups with different experiences differ in the MMN amplitude during meditation. The smallest MMN amplitude is observed in the group of highly experienced practitioners. But it is important to note that group selection based on the duration of meditative practice or assessment of monk's experience (criteria usually used for selection) leads to the fact that groups are varying by age. Usually, the experience of meditation grows with age. Since it is known that with age, there is a reduction of MMN amplitude and an increase of MMN latency [11, 12], age can be an additional factor influencing the results. In our case, the groups with different experiences differ only during meditation, but not in a control state. Therefore, we tend to associate these differences between groups with meditation experiences.

It is assumed that many situational factors can influence the meditation process's quality [1], so we tried to investigate how these factors (discomfort level) affect MMN amplitude during meditation. The high discomfort level (low success meditation) can prevent the withdrawal of the grosser forms of consciousness (sensory consciousness) during meditation. Thus, during meditation, the recognition of external sensory stimuli will not decrease. That is, there would be no decrease in the MMN amplitude. However, in the group with a high discomfort level, the minimum MMN amplitude was noted. This result could be explained by a rather higher concentration to meditation in this case. This high concentration may be caused by an attempt to resist distraction factors.

In conclusion, it is necessary to provide several important methodical remarks. Field studies, as in our case, allow us to explore meditation in conditions as close to natural as possible. As a result of the study, we obtained some significant MMN amplitude changes and confirmed our assumptions. Simultaneously, we should mention that the field study of monks of the same tradition, from the same monasteries, having the same experience in the same type of meditation, does not guarantee that homogeneous groups of practitioners can be formed. Considering the MMN amplitude in a group of all subjects and groups with different levels of experience or discomfort, we see a large dispersion of MMN amplitude (Fig. 1, 2 and 3). This can be explained by the fact that for young monks, too many factors (and each time different) distract them from the meditation. By contrast, experienced practitioners have their individualized meditation techniques developed over the years. That is the reason for developing a special structured interview. Most of the studies take into account the practice experience of meditating subjects. In addition to practitioners' experience, using the interview, we also tried to consider the influence of various subjective and situational factors that can influence the process of meditation and EEG-correlates of meditation. Our results conclude that the usual selection of meditators based on the history of practice and everyday meditation time is insufficient. A detailed analysis of pre- and post-meditation interviews may be necessary to form more homogeneous groups of subjects and obtain more meaningful results.

References

1. Thomas, J.W., Cohen, M.: A methodological review of meditation research. Front. Psychiatry **5**(74), 1–2 (2014)
2. Singh, N., Telles, S.: Neurophysiological effects of meditation based on evoked and event related potential recordings. Biomed. Res. Int. **406261**, 1–11 (2015)
3. Kamalashila, D.L., Jordhen, G.L., Ganchenpa, L.C., Russell, J.: Stages of Meditation: The Buddhist Classic on Training the Mind (Core Teachings of Dalai Lama Book 5). Shambala Publications, Inc., Boulder (2019)
4. Rinpoche, S.: Tibetan Meditation. Wisdom Tree, New Delhi (2011)

5. Näätänen, R., Gaillard, A.W.K., Mäntysalo, S.: Early selective-attention effect on evoked potential reinterpreted. Acta Psychol. **42**, 313–329 (1978)
6. Näätänen, R., Kujala, T., Light, G.: The Mismatch Negativity: A Window to the Brain. Oxford University Press, Oxford (2019)
7. Wallace, A.: Transcendent Wisdom by the The Dalai Lama. Lion Publications, Ithaca, New York (2009)
8. Tsongkhapa, J., Jinpa, T., Galvin, K.: A Lamp to Illuminate the Five Stages: Teachings on Guhyasamaja Tantra. Wisdom Publications, Boston (2013)
9. Jamspal, J., Kittay, D.R.K.: The Vajra Rosary Tantra: An Explanatory Tantra of the Esoteric Community Tantra. Wisdom Publications, Boston (2020)
10. Näätänen, R.: Mismatch negativity (MMN): perspectives for application. Int. J. Psychophysiol. **37**, 3–10 (2000)
11. Gaeta, H., Friedman, D., Ritter, W., Cheng, J.: An event-related potential study of age-related changes in sensitivity to stimulus deviance. Neurobiol. Aging **19**, 447–459 (1998)
12. Cooper, R.J., Todd, J., McGill, K., Michie, P.T.: Auditory sensory memory and the aging brain: a mismatch negativity study. Neurobiol. Aging **27**, 752–762 (2006)

Functional Neuroimaging of Self-ratings Associated with Cognitive Effort

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Abstract. It is widely accepted that higher order thinking, such as working memory and mathematical problem solving are associated with activation in the prefrontal cortex. Thinking about thinking, however, often referred to as metacognition is less well understood. Converging evidence suggests that the function of the prefrontal cortex is also key for meta-cognitive judgments, particularly the most anterior part of the prefrontal cortex, Brodmann Area (BA) 10. The current research examined functional magnetic resonance imaging (fMRI) signal associated with BA 10 during metacognition related to self-ratings of mental effort exerted during mathematical operations. We analyzed data from young adult participants who solved addition problems with three levels of difficulty. Our results showed fMRI signal in BA 10 is modulated during the metacognition task, with the left BA 10 showing decreasing fMRI signal with difficulty, whereas the right BA 10 is more stable. These preliminary findings point to further directions for research that should consider rostrolateral and medial aspects of BA 10, and individual differences in performance.

Keywords: Prefrontal cortex · Metacognition · Mathematical cognition · Self-reflection · Cognitive effort

1 Introduction

1.1 Functional Neuroimaging and Mathematical Cognition

Functional magnetic resonance imaging (fMRI) is a technique used to visualize brain activity. When neural activity is initiated in an area of the brain due to certain tasks or stimuli then instantly oxygenated blood is transferred to that area, to replace deoxygenated blood [1]. Oxygen rich hemoglobin is less magnetic than oxygen depleted hemoglobin. This results in an intensified magnetic resonance signal, which in turn allows us to map the locations which are at the time in need of resources, thus considered active.

fMRI studies of mathematical cognition examine brain responses to processing numbers in a range of tasks starting from simple numerical judgments, to complex math problem solving, as well as metaphorical processes that underlie our understanding of

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concepts such as infinity. Studies show that language and calculation processes belong to the same network but are regionally differentiated [2]. Arabic digit processing seems to rely on the left angular gyrus and no digit specific visual number form area exists in the ventral visual cortex [3]. The left angular gyrus seems to be responsible not only for Arabic digit processing but also for simple and complex mathematical calculations [4]. Numbers in digit format and dot format are deciphered in occipital, frontal, temporal and parietal areas [5].

Prefrontal cortices also play a key role in mathematical processes. The inferior frontal gyri are involved in calculating simple numerical tasks and if the cognitive load is increased the middle frontal gyri are also involved [6]. Consistent with this interpretation, research shows that working memory load of math problems is reduced with training and in turn reduces the implication of the prefrontal lobes [7]. Indeed, individual difference in math performance is related to prior training in mathematics as the latter occurs simultaneously with development of the prefrontal cortex [8]. Critically, neuroimaging studies of mathematical cognition rarely evaluate retrospective self-ratings associated with performance [9]. Self-ratings related to thinking of one's own thinking is referred to as metacognition.

1.2 Metacognition of Effort

Metacognition is our ability to be self-reflective regarding our own thinking and knowing [10]. The prefix meta leads us to assume that reflecting upon our own cognition comes, in time, after cognition itself [11]. Metacognition is related to learning and degree of success in math problem solving [11]. Neuroimaging studies suggest that metacognition is important for learning and this is indicated by activations in the rostrolateral prefrontal cortex and angular gyrus [12]. Activation of the bilateral hippocampus shows that judgments of learning are related to associative memory representations [13]. Metacognitive functions have been correlated with medial frontal brain areas, such as the anterior cingulate cortex, which are active during conflict resolution, error correction, and emotional regulation [14]. However, it is not clear whether the anterior cingulate serves all types of task setting, selective attention or for creating a link between emotional and cognitive control [15]. The anterior cingulate cortex monitors conflict, which in turn signals a need for greater cognitive control [16]. Cognitive control is then implemented by the left dorsolateral prefrontal cortex [17]. There is a link between metacognition and consciousness, however consciousness has the potential to dissociate from second order behavior and meta-level depiction [18].

Measuring metacognition has limitations. One of them is due to metacognitive bias; the fact that we can observe differences in subjective confidence when task performance does not change [19]. Different people have different ability in distinguishing between their own judgments (metacognitive sensitivity) and metacognitive sensitivity in the same individual may vary according to the level of difficulty of the task (metacognitive efficiency) [19]. Age also seems to affect metacognitive ability. Younger adults show fewer high confidence errors than older adults [20]. One type of metacognition relies on our procedural knowledge, which is the way we perceive the difficulty of a task.

Converging evidence of brain imaging findings suggest the prefrontal cortex, Brodmann Area (BA) 10 plays a major role in retrospective metacognitive judgments [9].

Critically, this hypothesis has not been directly investigated in mathematical tasks. Mathematical tasks can be complex and more demanding in terms of cognitive load than simple math tasks [21, 22]. For example, for most adults addition with single digits is easier that three-digit problems. This will be the first study to examine the role of BA 10 on mathematical operations of different difficulty in young adults. Specifically, participant's self-ratings on mental effort associated with addition problems of different difficulty were compared with fMRI signal elicited during the metacognitive task. We hypothesized that metacognitive self-rating of effort related to the arithmetic operation of addition will be associated with BA 10.

2 Methods

2.1 Participants

We report data on twelve healthy right-handed adults (6 females, 20 to 30 years old, 23.85 ± 3.27), without any MRI contraindications (i.e., metal in their body) and without formal expertise in mathematics (i.e., not math majors), who participated in the fMRI study. All participants provided a signed consent form and the ethics committee at National Research University Higher School of Economics approved all procedures (approval dated on 15th January, 2018). For taking part in the study, participants received 1000 rubles and an anatomical picture of their brain.

2.2 Materials

Parametric Math Task: In this task, mathematical operations are presented on the top of the screen together with four possible answer options at the bottom of the screen. Participants were asked to solve the problem and choose the correct option. The experiment consisted of four math operations (addition, subtraction, multiplication, division) and three levels of complexity, indexed by the number of digits for each math operation (1-, 2-, and 3- digits), which were presented in blocks. Task blocks also included control tasks for each difficulty level during which participants viewed numbers at the top of the screen and four possible answers at the bottom of the screen and were asked to identify which font the numbers on the top of the screen were printed in. Each condition appeared in a block and was randomly presented three times. The timing for each block was thirty-two seconds. During this time participants were asked to give as many correct answers as they could. As soon as their time run out, they were asked to indicate cognitive effort exerted on the task on a scale from one to four. Participants had up to five seconds to respond and were encouraged to answer honestly, as their answer would help us know their opinion on the task. After their evaluation, a fixation cross appeared on the screen, which indicated that they had a ten-second brake before the next task block.

Behavioral scores included accuracy and reaction time during task conditions and self-rating during the metacognition task.

2.3 Procedures

Participants received training in a behavioral session before completing the task in the MRI on separate days.

MRI Data Acquisition

Data were acquired with a Siemens Magnetom Verio (Syngo MR B17), 32-channel head coiled, 3 T scanner. Anatomy was collected with a 3D magnetization rapid gradient echo sequence (TR = 1470 ms; TE = 1.76 ms; 9° Flip angle; voxel size: 1mm × 1 mm × 1 mm). Functional scans were acquired using TR = 500 ms; 300 measurements per run; voxel size = 3 mm × 3 mm × 3 mm. During the runs behavioral responses were acquired with a key pair of MRI button box for left and right hands.

MRI Data Processing and Analyses

Data were pre-processed and analyzed using AFNI (Analysis of Functional Neuroimages, Medical College of Wisconsin; Cox, 1996). During pre-processing stage images were slice-time corrected, registered, normalized, motion corrected, masked and smoothed. Slice-time correction was performed using AFNI's "3dTshift", registration was done using the "align_epi_anat.py" command and normalization, motion correction smoothing and masking by using the commands "@auto_tlrc", "3dvolreg", "3dmerge", and "3dAutomask", respectively. In order to fit a model to the data a first level analysis was performed by using the timings for all mathematical operational conditions and the timings for the metacognition task for the mathematical operation of addition. This paper focuses on fMRI signal changes of metacognition tasks associated with addition problems. A region of interest analysis was conducted by creating separate anatomical masks for the left and right BA 10 of each participant (Fig. 1). Region of interest data associated with self-ratings of three levels of addition problems were extracted using AFNI's "3dmaskave" command.

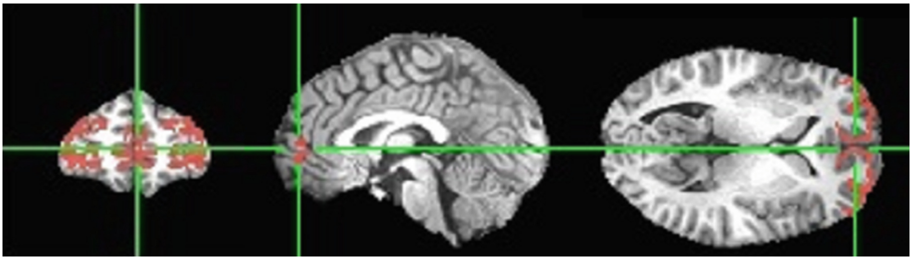

Fig. 1. Anatomical location of the region of interest BA10.

3 Results

3.1 Functional Neuroimaging and Mathematical Cognition

Average accuracy percentage for difficulty levels with 1-, 2-, and 3-digit addition problems were 97.48%. 89.76%, 78.85%. Self-ratings for difficulty levels with 1-, 2-, and

3-digit are illustrated on Fig. 2. Data of the region of interest analysis based on the Bold Oxygen Level Dependent (BOLD) signal change during the metacognition task of the mathematical operation of addition, for both left and right BA 10 for each level off difficulty are illustrated on Fig. 3.

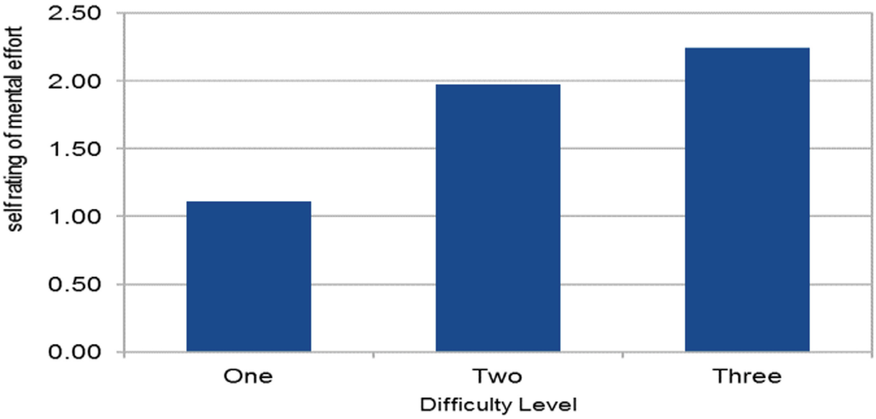

Fig. 2. Average self-rating of mental effort for each level of difficulty

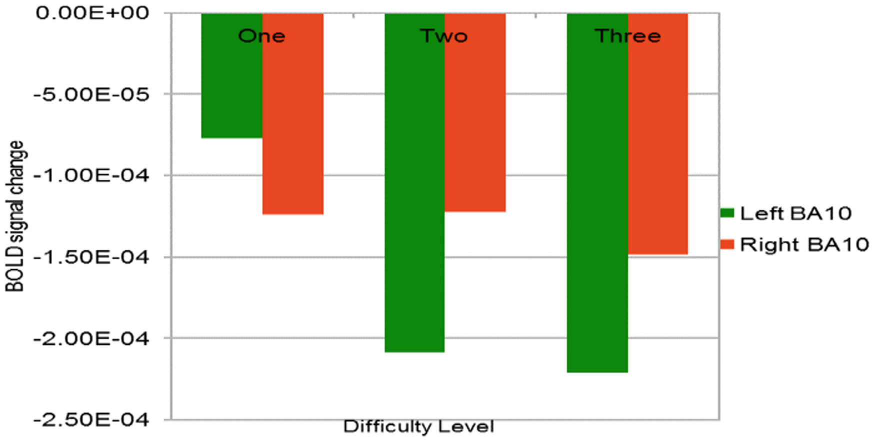

Fig. 3. BOLD signal change in BA 10 as a function of difficulty

4 Discussion

We examine brain signal in the most anterior regions of prefrontal cortex, BA 10, during a metacognition task that assessed cognitive effort exerted during addition problems with three levels of difficulty. Behavioral results show that self-ratings increase as a function of difficulty, as it was expected. Neuroimaging results show that brain signal in BA 10 is modulated by self-rating to different difficulty levels, albeit this relation differs by hemisphere. Negative BOLD signal change was observed for all three levels of difficulty. This preliminary finding was unexpected and potential explanation are discussed in terms of brain location and individual differences.

Our examination suggests that metacognition to increasing levels of difficulty differs by hemisphere of BA 10 and it is expressed as a deactivation. Specifically, metacognition to difficulty level one shows the least deactivation, whereas level three shows the most deactivation. Interestingly, the second level of difficulty shows approximately the same but not equal deactivation to level three in the left hemisphere. For difficulty levels two and three, the right hemisphere becomes less deactivated than the left, whereas for level one the left hemisphere is less deactivated than the right hemisphere. The prefrontal cortex occupies a substantial proportion of the cortex and BA 10 constitutes about 1.2% of the total brain volume [23]. BA 10 covers parts of the middle and superior frontal gyri. Its medial parts are adjacent to the anterior cingulate. It has complex functional correlates that are usually associated with higher complexity, abstract cognitive thoughts, as well as mind wondering [24, 25]. The proposal that BA 10 is involved in metacognition, thinking about thinking [9], appears to be consistent with this interpretation. Our data showed that BA 10 is modulated by ratings of mental effort and the relation varies by hemisphere. A potential explanation is that BA 10 is a large region of cortex and retrospective decisions may elicit activation in rostrolateral or ventromedial aspects of BA 10. Our anatomical mask did not distinguish between these regions and future analyses examining these regions separately may shed light into this explanation.

Variability in signal change may also relate to individual differences in performance. For example, it may be useful to match consistency in self-ratings and accuracy for each difficulty level. Specifically, a participant may have high accuracy on difficulty level three and rate the difficulty higher than another participant who has low accuracy on difficulty level three and rate this level with a low difficulty rating because the participant gave up trying. Further analyses are needed that consider signal change during task condition and individual differences in task performance.

5 Conclusion

Concluding, self-ratings to a metacognition task related to mental arithmetic modulate signal change in BA 10, however our findings suggest that this relation differs by hemisphere. Further research should consider more specific locations and examine relations in other regions that are highly interconnected with the most anterior parts of the frontal cortex. Understanding the brain correlates of metacognition would inform cognitive theories and practically benefit studies with individuals with cognitive impairments.

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References

1. Huettel, S.A., Song, A.W., McCarthy, G.: Functional magnetic resonance imaging (2 ed.) Sinauer, pp. 198–200, 208–211, Massachusetts (2009)
2. Andin, J., Fransson, P., Rönnberg, J., Rudner, M.: Phonology and arithmetic in the language–calculation network. Brain Lang. **143**, 97–105 (2015). https://doi.org/10.1016/j.bandl.2015.02.004
3. Price, G.R., Ansari, D.: Symbol processing in the left angular gyrus: Evidence from passive perception of digits. Neuroimage **57**(3), 1205–1211 (2011). https://doi.org/10.1016/j.neuroimage.2011.05.035
4. Delazer, M., Domahs, F., Bartha, L., Brenneis, C., Lochy, A., Trieb, T., Benke, T.: Learning complex arithmetic—an FMRI study. Cogn. Brain Res. **18**(1), 76–88 (2003). https://doi.org/10.1016/j.cogbrainres.2003.09.005
5. Bulthé, J., De Smedt, B., Op de Beeck, H.P.: Format-dependent representations of symbolic and non-symbolic numbers in the human cortex as revealed by multi-voxel pattern analyses. Neuroimage **87,** 311–22 (2014). https://doi.org/10.1016/j.neuroimage.2013.10.049
6. Arsalidou, M., Taylor, M.J.: Is 2+ 2= 4? Meta-analyses of brain areas needed for numbers and calculations. Neuroimage **54**(3), 2382–2393 (2011). https://doi.org/10.1016/j.neuroimage.2010.10.009
7. Ischebeck, A., Zamarian, L., Siedentopf, C., Koppelstätter, F., Benke, T., Felber, S., Delazer, M.: How specifically do we learn? Imaging the learning of multiplication and subtraction. Neuroimage **30**(4), 1365–1375 (2006). https://doi.org/10.1016/j.neuroimage.2005.11.016
8. Gogtay, N., Giedd, J.N., Lusk, L., Hayashi, K.M., Greenstein, D., Vaituzis, A.C., Nugent, T.F., Herman, D.H., Clasen, L.S., Toga, A.W., Rapoport, J.L.: Dynamic mapping of human cortical development during childhood through early adulthood. Proc. Natl. Acad. Sci. **101**(21), 8174–8179 (2004). https://doi.org/10.1073/pnas.0402680101
9. Fleming, S.M., Dolan, R.J.: The neural basis of metacognitive ability. Philos. Trans. Royal Soc. B. Biol. Sci. **367**(1594), 1338–1349 (2012). https://doi.org/10.1098/rstb.2011.0417
10. Fisher, R.: Thinking about thinking: Developing metacognition in children. Early Child Dev. Care **141**(1), 1–15 (1998). https://doi.org/10.1080/0300443981410101
11. Lucangeli, D., Coi, G., Bosco, P.: Metacognitive awareness in good and poor math problem solvers. Learn. Disabil. Res. Pract. **12**(4), 209–212 (1997)
12. Anderson, J.R., Lee, H.S., Fincham, J.M.: Discovering the structure of mathematical problem solving. Neuroimage **97**, 163–177 (2014). https://doi.org/10.1016/j.neuroimage.2014.04.031
13. Lam, D., Anne, T.A., Axmacher, N., Fell, J., Staresina, B.P., Gauggel, S., Wagner, T., Olligs, J., Weis, S.: Monitoring the mind: The neurocognitive correlates of metamemory. PLoS ONE **7**(1), e30009 (2012). https://doi.org/10.1371/journal.pone.0030009
14. Fernandez-Duque, D., Baird, J.A., Posner, M.I.: Executive attention and metacognitive regulation. Conscious. Cogn. **9**(2), 288–307 (2000). https://doi.org/10.1006/ccog.2000.0447
15. Shimamura, A.P.: Toward a cognitive neuroscience of metacognition. Conscious. Cogn. **9**(2), 313–323 (2000). https://doi.org/10.1006/ccog.2000.0450
16. Kerns, J.G., Cohen, J.D., MacDonald, A.W., Cho, R.Y., Stenger, V.A., Carter, C.S.: Anterior cingulate conflict monitoring and adjustments in control. Science **303**(5660), 1023–1026 (2004). https://doi.org/10.1126/science.1089910
17. MacDonald, A.W., Cohen, J.D., Stenger, V.A., Carter, C.S.: Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. Science **288**(5472), 1835–1838 (2000). https://doi.org/10.1126/science.288.5472.1835
18. Fleming, S.M., Dolan, R.J., Frith, C.D.: Metacognition: Computation, biology and function. Philos. Trans. Royal Soc. B. Biol. Sci. **367**(1594), 1280–1286 (2012). https://doi.org/10.1098/rstb.2012.0021

19. Fleming, S.M., Lau, H.C.: How to measure metacognition. Front. Hum. Neurosci. **8**, 443 (2014). https://doi.org/10.3389/fnhum.2014.00443
20. Chua, E.F., Schacter, D.L., Sperling, R.A.: Neural basis for recognition confidence in younger and older adults. Psychol. Aging **24**(1), 139 (2009). https://doi.org/10.1037/a0014029
21. Fehr, T., Code, C., Herrmann, M.: Common brain regions underlying different arithmetic operations as revealed by conjunct FMRI–BOLD activation. Brain Res. **1172**, 93–102 (2007). https://doi.org/10.1016/j.brainres.2007.07.043
22. Kong, J., Wang, C., Kwong, K., Vangel, M., Chua, E., Gollub, R.: The neural substrate of arithmetic operations and procedure complexity. Cogn. Brain Res. **22**(3), 397–405 (2005). https://doi.org/10.1016/j.cogbrainres.2004.09.011
23. Semendeferi, K., Armstrong, E., Schleicher, A., Zilles, K., Van Hoesen, G.W.: Prefrontal cortex in humans and apes: a comparative study of area 10. Am. J. Phys. Anthropol. **114**, 224–241 (2001). https://doi.org/10.1002/1096-8644(200103)114:3%3c224:AID-AJPA1022%3e3.0.CO;2-I
24. Christoff, K., Gabrieli, J.D.E.: The frontopolar cortex and human cognition: evidence for a rostro caudal hierarchical organization within the human prefrontal cortex. Psychobiology **28**, 168–186 (2000). https://doi.org/10.3758/BF03331976
25. Christoff, K., Gordon, A.M., Smallwood, J., Smith, R., Schooler, J.W.: Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. Proc. Natl. Acad. Sci. **106**(21), 8719–8724 (2009). https://doi.org/10.1073/pnas.0900234106

Comparative Analysis of the Stress Potential of Distance and Classroom Learning: A Pilot Study

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Abstract. A pilot study was carried out to assess the level of stress load among psychology students of Nizhny Novgorod State University ($n = 19$), who attended lectures in classroom and remotely. The lectures were balanced in complexity and duration (two academic hours). The condition of each student during the lecture was continuously monitored using the Event-related telemetry (ERT) method. The sequence of RR ECG intervals was registered and processed on-line, stress episodes were isolated automatically.

Simultaneously, audio-video recording of the context was made during the lectures for further verification of stress factors.

Having considered the publications devoted to the problem of stress during training, the authors identified factors that can cause a stress response during the lectures. In total, 30 factors were identified and grouped into clusters: infrastructure factors, occupation process factors, attitude factors, technical factors, factors of a random nature. This made it possible to compare the stress episodes identified by the ERT with the specific events recorded during the fixation of contexts.

Out of 30 possible factors, 19 have proven to be active. Stress factors for classroom learning were also active in distance learning. It was found that the frequency of stress episodes was significantly higher during remote lectures, and they possessed their own unique group of stress factors. Firstly, in the absence of direct contact, the lecturer is forced to ask questions more frequently, which causes excessive stress among students. Secondly, stress factors are directly related to the specifics of distance learning: the necessity of using additional technical equipment. A significant group of unverified stress factors was also identified, and in classroom learning their number turned out to be much higher.

Thus, the study, on the one hand, sheds light on the reasons for the low efficiency and insecurity of distance learning and, on the other hand, demonstrates the possibility of a massive and longitudinal objective study of the problem of stress in this form of training using ERT.

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Keywords: Acute stress · Stressors · Classroom learning · Distance learning · Event-related telemetry (ERT)

1 Introduction

The issue of stress potential of education in schools and universities is widely known. Suffice it to point out that examination stress is the most common natural stress pattern [1, 2]. But exams are not the only cause of stress. Classroom activities often involve stressful contexts as well. The result is an increase in the number of stress-induced health disorders in childhood and adolescence.

The possibilities of remote knowledge acquisition using Internet technologies, which have emerged in recent years, have given rise to the hope that the opportunity to study in a comfortable home environment will significantly reduce the stress load. As a result, the number of on-line courses has begun to grow exponentially. In addition, the 2020 pandemic has forced many students to shift to distance learning. It is obvious that today this problem has become particularly urgent.

2 Materials and Methods

We have conducted a pilot study to assess the level of stress load among psychology students of Nizhny Novgorod State University (n = 19), who attended lectures in standard classroom conditions and remotely using the Internet. The experimental design was as follows. Before the start of the lecture, electrocardiogram sensors were attached to the chest of each student for on-line registration and processing of heart rate variability indicators and automatic isolation of stress episodes using the event-related telemetry (ERT) method (Fig. 1). Throughout the lecture, in parallel with the continuous registration of the rhythmocardiogram, the audio-video context was recorded. The lectures in standard classroom conditions and remote lectures (using the Internet) were balanced in complexity and were two academic hours (90 min) long.

ERT method is based on the Internet-oriented technology for remote monitoring of heart rate variability developed by us [3–5]. It includes cardiac signal registration using a miniature non-invasive sensor platform ZephyrTMHxMTM Smart—Zephyr BIO PACH BH3-M1 (Zephyr Technology, USA), transfer of a digitized data packet via Bluetooth to a Smartphone, preprocessing and broadcasting the results to the didacted server system StressMonitor WEB application. The server carries out deep data processing according to the algorithm we have found, which includes spectral analysis of rhythmograms in pseudo-time and revealing the dynamics of the most informative indicators of heart rate autonomic regulation [5–7]. First of all, these are: (a) indicators of the total power of heart rate variability (TP), which reflect the adaptive potential; (b) indicators of low-frequency power (LF), which characterize the level of sympathetic regulation; (c) indicators of the high-frequency power (HF), which point to the activity of the parasympathetic regulation; and indicators of growth of autonomic balance (LF/HF), which characterize the ratio of the sympathetic and parasympathetic systems. In addition, based on the concept of stress developed by us [8–10], the ERT technology has been designed so as to detect episodes

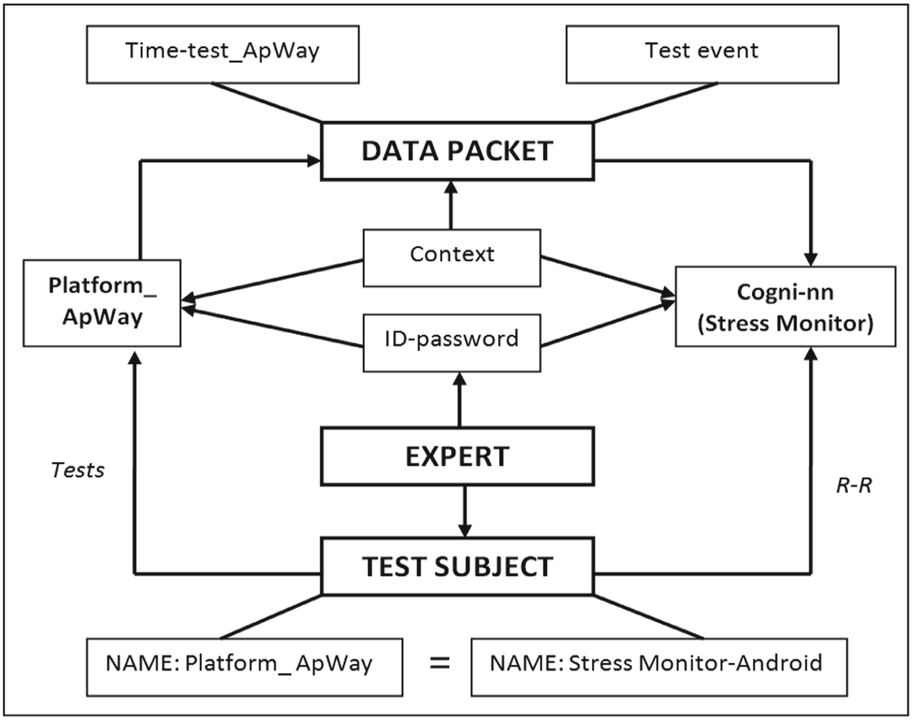

Fig. 1. Conceptual scheme of the Internet-oriented technology of event-related telemetry of heart rate variability (ERT).

of acute stress, manifested both in characteristic changes in the native cardiogram and in a sharp increase in LF/HF against the background of a synchronous decrease in TP, automatically.

A fundamentally important feature of ERT is the ability to simultaneously register the parameters of autonomic regulation of the heart rate and events (context) occurring with the subject, which can include the real natural activity of the subject as well as experimental tasks that are presented within the technology using the specially designed WEB-platform Apway. Recording the context makes it possible to objectively capture those specific manifestations of the context that are stressful for the subject. ERT technology has been successfully used to identify stressful contexts in road transport management, public speaking, simultaneous interpretation, school lessons, solving moral dilemmas, the work of installers and firefighters, etc. [4, 11–17]. Audio-video recording of the context was conducted throughout the experiment.

Statistical processing of the data was carried out using repeated measures ANOVA and chi-square distribution.

3 Results and Discussion

First of all, the conducted research showed that lectures in remote mode are significantly more stressful than those in classical classroom conditions (Fig. 2). Statistical processing of all rhythmocardiograms revealed an average of 20.1 stress episodes per classroom lecture, against 34.8 episodes per remote lecture ($p < 0.05$).

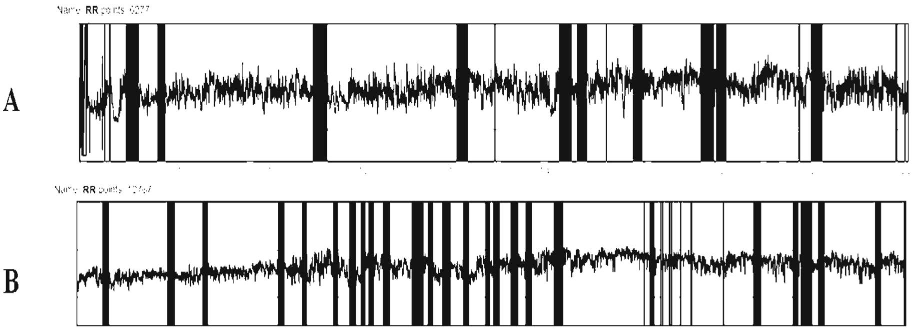

Fig. 2. An example of rhythmocardiograms of the same student during lectures in standard classroom conditions (A) and in remote mode (B). The duration of both recordings is 90 min. The vertical stripes mark episodes of acute stress.

This result was quite unexpected and required an explanation. To find the answer, an analysis of publications considering the stress potential of the educational process both in classroom and remote mode was carried out [1, 2, 16, 18–25]. It showed that in the study of the stress potential of the educational process, it is customary to distinguish several clusters of factors (Table 1).

As can readily be seen, the cluster of technogenic factors stands apart in the list of stress-generating factors of learning. In theory, it is characteristic precisely for the remote mode and is completely absent in classical classroom lectures. Indeed, distance learning has its own unique cluster of stress factors. Firstly, the lecturer and the students are not in the same room. Consequently, in order to maintain interest and attention of students, the lecturer is much more likely to ask guiding questions or questions to test knowledge.

The second group of stress factors is directly related to the specifics of distance learning, namely the need for additional technical equipment. One always needs a computer or a phone with appropriate software and a stable Internet connection to attend a remote lecture. As a result, technogenic stress factors should be active. Accordingly, when analyzing the results of cardiointervalography, it would be logical to assume that the significantly higher stress potential of lectures held in remote mode is primarily associated with technogenic problems.

After a detailed analysis of the video recording of the contextual content of the identified stress episodes, this hypothesis was confirmed only partially. Within our experiments, only 19 of the 30 factors we had identified in the analysis of publications showed activity.

Table 1. Distribution of learning stressors by clusters

Clusters	Specific factors
Infrastructure factors	- Furniture defects (hard seat/broken chair/uncomfortable table or chair height and lack of possibility to change the place) - Indoor climate (cold/hot/stuffy)
Lesson process factors	- Pen running out of ink - End of notebook/lack of paper - The beginning of the lesson - Time limit for the task - Organizational information (information about some special features of the next lesson, about the final test or report form, announcement of a deadline) - Error when answering a lecturer's question - Checking homework - High speed of presentation of the material by the lecturer - Student's sleepiness - Difficulties when recording material - Testing, checking current knowledge
Attitude factors	- Student's attitude to the lecturer - Attitude to the subject of the lecture - Style/type of lecture
Technogenic factors	- Program failure (error) - Problems with access to the remote lecture - Problems with video content - Problems with technical devices - Problems with Internet connection - Unfriendly interface (the student does not understand which buttons to press) - Problems with microphone - Problems with sound (headphones/speakers) - Computer breakdown
Factors that have a casual/distractive character	- Discussion or tackling an issue in social networks - Phone call - Interference of an outsider - Unexpected extraneoussound - Physical activity (leaving the classroom/getting up from the table)

In addition, distance lectures possessed their own unique structure of stress factors. Along with the predictable presence of the factors from the technogenic cluster, the dominance of factors from other clusters which had been indistinct during classroom lectures was revealed. For example, the stress potential of the answers to the control questions of the lecturer was significantly ($p < 0.05$) higher. Distracting factors also turned out to be an issue with distance lectures. In general, with distance lectures, the ratio of unverified stress factors (that is, factors not having a correlation with specific events in the context) to verified ones turned out to be significantly (almost twice, $p < 0.05$) less than in classroom lectures (Fig. 3).

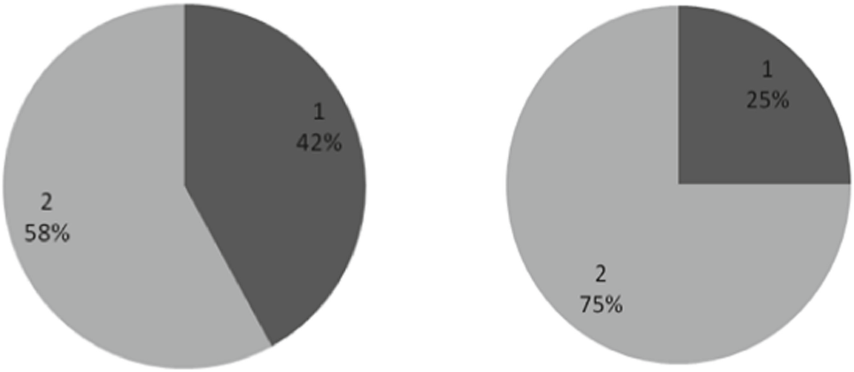

Fig. 3. The ratio of unverified (1) and verified (2) stress factors identified by the ERT method in classroom (left) and remote (right) lectures.

Perhaps this can be explained in terms of the concept of Brosschot & Thayer [6, 26, 27] on unconscious stress, according to which stress factors might be not only of external, but also of internal (pervasive or mental stress) origin.

4 Conclusion

Thus, our pilot study, firstly, partially sheds light on the reasons for the low efficiency and insecurity of distance learning [19, 20] and, secondly, demonstrates the possibility of a massive and longitudinal objective study of the issue of stress potential of remote learning activities using ERT method.

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References

1. Essel, G., Owusu, P.: Causes of students' stress, its effects on their academic success, and stress management by students. Seinäjoki Univ. Appl. Sci. **2**, 82–88 (2017) https://urn.fi/URN:NBN:fi:amk-201704134793
2. Rana, A., Gulati, R., Wadhwa, V.: Stress among students: an emerging issue. Integr. J. Soc. Sci. **6**(2), 44–48 (2019). https://pubs.iscience.in/ijss

3. Polevaia, S., Parin, S., Eremin, E., Bulanov, N., Chernova, M., Parina, I., Chikov, M., Chernigovskaya, T.: Event-related telemetry (ERT) technology for study of cognitive functions. Int. J. Psychophysiol. **108**, 87–88 (2016). https://doi.org/10.1016/j.ijpsycho.2016.07.274
4. Polevaia, S., Parin, S., Demareva, V., Polevaia, A.: Cardiac telemetry for stress assessment. Int. J. Adv. Life Sci. **3–4**, 117–126 (2017). https://www.iariajournals.org/life_sciences/lifsci_v9_n34_2017_paged.pdf
5. Polevaya, S.A., Eremin, E.V., Bulanov, N.A., Bakhchina, A.V., Kovalchuk, A.V., Parin, S.B.: Event-related telemetry of heart rhythm for personalized remote monitoring of cognitive functions and stress under conditions of everyday activity. Sovremennye tehnologii v medicine **11**(1), 109–115 (2019). https://doi.org/10.17691/stm2019.11.1.13
6. Thayer, J.F., Yamamoto, S.S., Brosschot, J.F.: The relationship of autonomic imbalance, heart rate variability and cardiovascular disease risk factors. Int. J. Cardiol. **141**(2), 122–131 (2010). https://doi.org/10.1016/j.ijcard.2009.09.543
7. Thayer, J.F., Ahs, F., Fredrikson, M., Sollers, J.J., Wager, T.D.: A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. Neurosci. Biobehav. Rev. **36**(2), 747–756 (2012). https://doi.org/10.1016/j.neubiorev.2011.11.009
8. Parin, S.B., Bakhchina, A.V., Polevaia, S.A.: A neurochemical framework of the theory of stress. Int. J. Psychophysiol. **94**(2), 230 (2014). https://www.journals.elsevier.com/international-journal-of-psychophysiology
9. Parin, S.B., Vetyugov, V.V., Bakhchina, A.V., Polevaya, S.A.: The role of the endogenous opioid system in the control of heart rate variability under cognitive loads of various levels. Sovremennye tehnologii v medicine **6**(4), 116–126 (2014). https://www.stm-journal.ru/ru/numbers/2014/4/1103/pdf
10. Parin, S., Polevaia, S., Gromov, K., Polevaia, A., Kovalchuk, A.: Short-term variability of R-R intervals during acute stress in healthy adults: neuromorphic model, experiment data, monitoring of daily life activity. Int. J. Psychophysiol. **108**, 88 (2016)
11. Runova, E.V., Grigoreva, V.N., Bakhchina, A.V., Parin, S.B., Shishalov, I.S., Kozhevnikov, V.V., Nekrasova, M.M., Karatushina, D.I., Grigoreva, K.A., Polevaya, S.A.: Vegetative correlates of conscious representation of emotional stress. Sovremennye tehnologii v medicine **5**(4), 69–77 (2013). https://cyberleninka.ru/article/n/vegetative-correlates-of-conscious-representation-of-emotional-stress
12. Bakhchina, A.V., Shishalov, I.S., Parin, S.B., Polevaya, S.A.: The dynamic cardiovascular markers of acute stress. Int. J. Psychophysiol. **94**(2), 230 (2014)
13. Chernigovskaya, T.V., Parin, S.B., Parina, I.S., Konina, A.A., Urikh, D.K., Yachmonina, Y.O., Chernova, M.A., Polevaya, S.A.: Simultaneous interpreting and stress: pilot experiment. Int. J. Psychophysiol. **108**, 165 (2016)
14. Chernigovskaya, T.V., Parina, I.S., Alekseeva, S.V., Konina, A.A., Urich, D.K., Mansurova, Y., Parin, S.B.: Simultaneous interpreting: characteristic of autonomic provision of extreme cognitive loads. Sovremennye tehnologii v medicine **11**(1), 132–140 (2019). https://doi.org/10.17691/stm2019.11.1.15
15. Petukhov, A.Y., Polevaya, S.A.: Dynamics of information images in the mind of an individual during simultaneous interpretation. Procedia Comput. Sci. **123**, 354–359 (2018). https://doi.org/10.1016/j.procs.2018.01.055
16. Prokofieva, V., Kostromina, S., Polevaia, S., Fenouillet, F.: Understanding emotion-related processes in classroom activities through functional measurements. Front. Psychol. **10**, 2263 (1–11) (2019). https://doi.org/10.3389/fpsyg.2019.02263
17. Sozinova, I.M., Alexandrov, Y.I., Arutyunova, K.R.: Spectral parameters of heart rate variability as indicators of the system mismatch during solving moral dilemmas. Stud. Comput. Intell. **856**, 138–143 (2020). https://doi.org/10.1007/978-3-030-30425-6_15

18. Stevenson, A., Harper, S.: Workplace stress and the student learning experience. Q. Assur. Educ. **14**(2), 167–178 (2006). https://doi.org/10.1108/09684880610662042
19. Bataineh, M.Z.: Academic stress among undergraduate students: the case of education faculty at king saud university. Int. Interdisc. J. Educ. **2**(1), 82–88 (2013). https://iijoe.org/v2/IIJOE_05_01_02_2013.pdf
20. Waghachavare, V.B., Dhumale, G.B., Kadam, Y.R., Gore, A.D.: A study of stress among students of professional colleges from an urban area in India. Sultan Qaboos Univ. Med. J. **13**(3), 429–436 (2013). https://pubmed.ncbi.nlm.nih.gov/23984029/
21. Bergin, A., Pakenham, K.: Law student stress: relationships between academic demands, social isolation, career pressure, study/life imbalance and adjustment outcomes in law students. Psychiatry, Psychol. Law. **22**(3), 388–406 (2015). https://doi.org/10.1080/13218719.2014.960026
22. Khan, Z., Lanin, A.B., Ahmad, N.: The level of stress in male and female school students. J. Educ. Pract. **6**(13), 166–168 (2015). https://files.eric.ed.gov/fulltext/EJ1080498.pdf
23. Stallman, H.M., Hurst, C.P.: The university stress scale: measuring domains and extent of stress in university students. Aust. Psychol. **51**, 128–134 (2016). https://doi.org/10.1111/ap.12127
24. Shearer, A., Hunt, M., Chowdhury, M., Nicol, L.: Effects of a brief mindfulness meditation intervention on student stress and heart rate variability. Int. J. Stress Manage. **23**(2), 232–254 (2016). https://doi.org/10.1037/a0039814
25. Pascoe, M.C., Hetrick, S.E., Parker, A.G.: The impact of stress on students in secondary school and higher education. Int. J. Adolescence Youth **25**(1), 104–112 (2020). https://doi.org/10.1080/02673843.2019.1596823
26. Brosschot, J.F., Verkuil, B., Thayer, J.F.: Conscious and unconscious perseverative cognition: Is a large part of prolonged physiological activity due to unconscious stress? J. Psychosom. Res. **69**(4), 407–416 (2010). https://doi.org/10.1016/j.jpsychores.2010.02.002
27. Brosschot, J.F.: Ever at the ready for events that never happen. – Eur. J. Psychotraumatolgy **8**(1), 1309934 (2017). https://doi.org/10.1080/20008198.2017.1309934

Neuronal Correlates of Spontaneous Awakening and Recovery of Psychomotor Performance

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Abstract. The study of consciousness is crucial to understand how the human mind functions. Within the last twenty years new approaches to this question have been formulated and "establishing neural consciousness correlations" is one of the most promising. The sleep-wake paradigm is one of the most promising methodologies in this field, allowing the study of healthy subjects without medical interventions. We developed a monotonous psychomotor test that induces several episodes of losing consciousness because of falling asleep and its full or partial recovery while awakening within the 60 min. The following behavioral measures of consciousness level were noted: counting accuracy, time between presses, pressing force, so one could observe not only lapses, but also light sleep when subject starts to make mistakes. In our recent study, this method allowed us to assess 441 short episodes of falling asleep ("microsleep"), followed by spontaneous awakenings in 23 experimental sessions. Two different electroencephalographic patterns of awakening were observed. After deeper sleep stages the performance restoration was preceded by K-complexes. According to recent studies, it confirms that K-complex not only helps to maintain sleep, but also eases necessary awakenings. Our recent data suggest that not only external stimuli, but also the internal test instruction recall could start such awakening process. We believe that our experimental design could be used for wide range of consciousness studies because it gives researchers several continuous and objective indices of the subject's mind state.

Keywords: EEG · K-complex · Consciousness · Microsleep · Spontaneous awakening · Psychomotor test

1 Introduction

The study of consciousness is an essential task of cognitive science. It is critical for understanding the function of the human mind. In recent years, new approach to this question was formulated as a "search of neural consciousness correlations" (NCC) [1]. This approach is based on the axiom of existing causal links between brain activity and mind contents. There are two strategies within this approach, i.e. study of consciousness

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level or its contents [2]. Consciousness level is often defined as a byword of activation or an awakening level. Mind contents, on the other hand, is associated with comprehension or subjective experience [3]. Many authors emphasize the need for experimental tests uniting both aspects [4]. Studies on mind contents based on subject's reports have many limitations. Therefore, several new objective, "no-report" paradigms were recently developed [5].

Comparisons of sleep and wakefulness is very easy using the effective experimental model of NCC that allows researchers to assess various consciousness levels of healthy subjects without any medical interventions. Consciousness "extinguishes" during sleep and "switches on" while awakening. Depolarization of cortical neurons observed in wakefulness is the prerequisite for the conscious state. It is hypothesized that unconscious state during sleep is caused by cortical neurons' bi-stable state, i.e. synchronous periodical polarization and depolarization that make complex all-over-brain synchronization impossible [6].

2 Methods

Within the sleep-wake paradigm we developed an experimental model of consciousness activation during spontaneous awakening [7–10]. The design is described below.

28 healthy subjects (6 females) were recruited among university students. 5 subjects were excluded from further analysis because there were no short episodes of falling sleep during their experimental sessions. Each subject was informed in detail about the experimental procedures and gave his/her written consent. The study protocol was approved by the Ethics Committee of the Institute of Higher Nervous Activity and Neurophysiology (No. 046/19), and all experimental procedures were performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

Experiments were performed in daytime, started at 1–3 p.m. The subject lay on bed in a dark and quiet room, with eyes closed, counting from one to ten and pressing two pneumatic buttons holding on with thumbs and index fingers of each hand. To prevent buttons from falling, they were fixed with adhesive plaster to the subject's hand. The subject was instructed to press the buttons once a second in rotation (10 presses with the right hand, 10 presses with the left hand and so on). Thus, several behavioral measures of the subject's consciousness state were available during the experiment: counting accuracy, time between presses, pressing force. Electromyogram (EMG) from both thumb fingers (*musculus abductor pollicis brevis*) was recorded in addition to buttons mechanograms. Electroencephalogram (EEG) was also registered continuously, providing brain activity information. Standard 10–20 system with 19 channels was used to record EEG filtered in 0.1–70 Hz frequency range.

Each subject participated in two experimental sessions with 1–10 days in between. During the first training session periodical sound was used to instruct the subject to maintain 1-s intervals. This session was about 10–15 min long. Second (main) session lasted for 55–60 min.

This monotonous psychomotor test causes several short episodes of sleep and spontaneous awakening over the period of 1 h. EEG patterns of 2nd or even 3rd sleep stage could be observed during such short episodes of falling sleep ("microsleep") lasting from 10 s to several minutes (see Fig. 1).

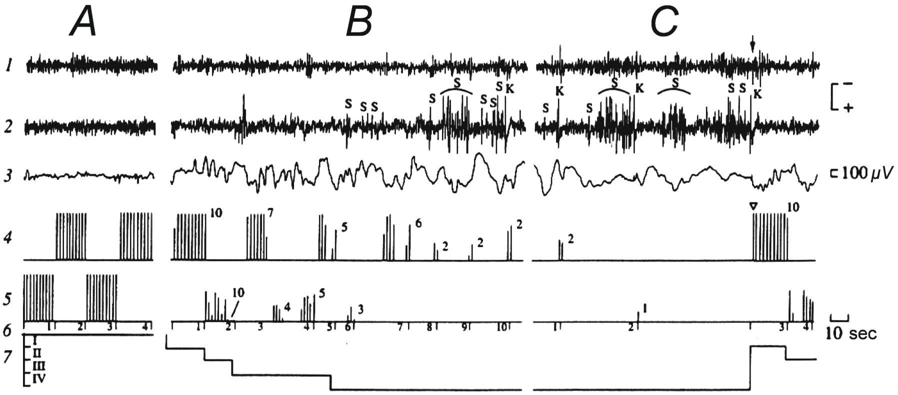

Fig. 1. EEG correlates of psychomotor test errors for various short episodes of falling sleep observed in single experiment. A — wakeful state, B — drowsiness and light sleep (1st stage), C — more deep sleep, (2nd stage — "microsleep"). 1,2 — O1 and C3 EEG electrodes, 3 — EOG (left eye), 4,5 — button presses for right and left hands, 6 — number of press in the batch, 7 — performance level. S — vertex sharp waves, K is for K-complexes. Arrow marks awakening sound. Performance levels are the following: I — correct task performance, II — lowered press power, II — lowered press power with errors, IV — "microsleep" episode.

3 Results

During the test, performance varied greatly, from totally correct 10–10 press batches to counting errors, short pauses, single presses and finally sleep episodes, providing good objective measures of subject's current consciousness level. Overall 441 "microsleep" episodes were found in 23 successful experiments of our recent experimental session (pause between presses equal to or more than, 10 s). In each successful experimental session 2–48 short episodes of falling sleep were observed. Lapses ("microsleep") duration varied from 20 s to several minutes, with median value about 52 s. Five subjects that didn't fall asleep at all were excluded from further analysis.

It was already shown in our studies that spontaneous renewal of psychomotor test performance goes hand in hand with two types of EEG patterns. The first one was mostly observed during awakening from 1st sleep stage, including alpha spindles with higher frequencies inclusions. 2nd pattern type followed awakenings after 2nd and 3rd sleep stages and includes not only alpha activity, but also slow-wave components or can even be preceded by K-complex (single high amplitude slow wave). Thus, our data confirms the well-known fact that phasic activation patterns in EEG depend on previous sleep depth [11]. Examples of such EEG patterns are presented in Fig. 2.

Figure 2 illustrates spontaneous awakenings followed by button presses after different sleep stages. Awakenings after episodes of light sleep (EEG markers of stage 1) usually demonstrate phasic activation patterns of 1st type (alpha waves). This patterns starts at the same time as the 1st button is pressed (see subplot A). 2nd type of pattern (subplot B) demonstrates isolated late component of K-complex immediately leading to presses renewal. At the subplot C one could observe classical high-amplitude

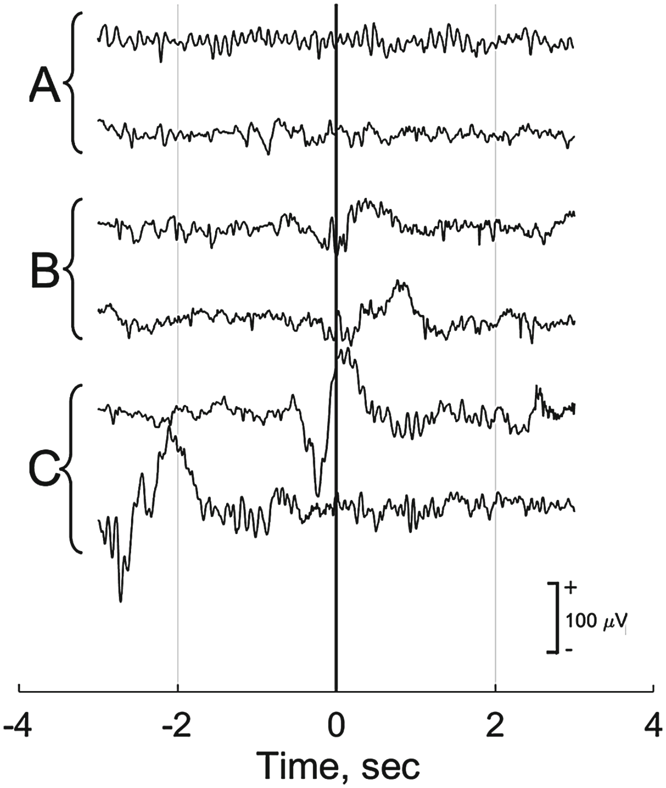

Fig. 2. EEG patterns (derivation Fp1) of spontaneous awakening and performance renewal after sleep episodes. A — light sleep (1 stage), pattern type 1 (alpha waves), alpha activity increases along with performance renewal, B — more deep sleep, 2 stage (late component of K-complex accompanies performance renewal), C — high-amplitude K-complex precedes alpha activity. Vertical line marks first button press after sleep episode.

(up to 300 μV) K-complex after sleep episode of stage 2 accompanied by alpha range oscillations.

We suggest that spontaneous performance renewal after falling sleep is initiated by test instruction "to press button and count" retrieval during sleep. The very moment of such retrieval can be determined precisely using EEG predictors, particularly K-complex. First button pressing doesn't occur immediately after EEG activation and instead takes some time [10]. According to recent scientific knowledge about awakening this time lapse is necessary to re-connect neuronal ensembles in different brain regions. This so-called "binding process" [12] is a crucial pre-condition of the consciousness state.

An experimental session within fMRI was also performed. Although co-registration of EEG and fMRI data is very difficult, button presses are still available for detailed analysis. Even with the high noise level of fMRI device, 2–48 episodes of "microsleep" were registered from 10 subjects during 1-h experiments. An increase in the activity of the visual regions (the region of the calcarine sulcus) of the cerebral cortex, left precuneus/cuneus during sleep and regions of the right thalamus, left cuneus, cerebellar zones, stem structures at the moment of awakening and resumption of conscious activity were observed [9].

4 Discussion

The scientific meaning of sleep state has changed in recent decades. The view now is that the sleeping subject has some limited access to environmental signals and is able to awake immediately if something changes drastically [13]. Instead of being totally isolated from environmental events, the sleepy brain combines sensory isolation with oversight elements and chooses between sleep and awakening continuously.

In recent research [14] the split “personality” of K-complex is discussed in detail. Different phases of this EEG phenomenon are balanced between suppression and facilitation of outer stimuli. Starting with some initial activation, the K-complex then includes a short downstate period followed by an upstate component (900 ms from the start, or P900). This upcoming front opens a potential “window of wakefulness” for stimuli processing [15], and it has already been demonstrated that at such moments the information could be processed or even learned [16]. There is also evidence that speech processing during non-REM sleep is suppressed, but significantly improves just after it [17]. Therefore, the K-complex correlates with suppression of isolated environmental signals and improved reaction to repeating events at the meantime, i.e. is involved in creation of ‘windows of wakefulness’ within sleep during which relevant environmental or inner inputs can be processed [14].

5 Conclusion

As Andrillon and Kouider [14] assume, the sleeping subjects maintain a certain amount of minimal vigilance, a stand-by mode allowing the quick reversal to wakefulness, if necessary. It is well-known that K-complex can be caused not only by environmental, but also by internal stimuli [18]. Hypothetical instruction “to press button and count” could act as such internal stimuli, given it is retained in the short-time memory and gains access to brain executive structures when the “windows of wakefulness” opens [15]. Hence, its emergence just before spontaneous awakenings in our experiment could signify the test instruction retrieval followed by further cortex activation and neuronal activity integration.

We therefore suggest that “spontaneous” awakenings occur when hypothetical instruction “to press button and count” successfully gains access to brain executive structures. Thus, high-amplitude K-complex could play its role in urgent activation and further synchronization of these executive neural networks.

We assume that subject’s performance after “microsleep” episode could be used as an objective, “no-report” measure of consciousness level. We also believe that EEG phasic patterns during spontaneous awakening represent a binding process between neurons of various brain regions, that in turn builds a foundation to gradual consciousness activation.

It was also shown in our studies that the psychomotor test could be successfully combined with functional magnetic resonance imaging. Preliminary results about the activity of the brain structures during spontaneous awakening, were obtained using such experiments [9].

One could expect that the performance resuming is preceded by cognitive processes of remembering the instruction “to press button and count” followed by activation of neural networks involved in mental counting and finally launching the effector process of actually pressing the button. This sequence of processes meets all requirements to the neural correlate of consciousness in the frame of our experimental model of consciousness in the sleep-wake paradigm [9, 10]. We suggest that further research of EEG features during successful and partial awakening episodes will allow us to localize and interpret electrophysiological correlates of the consciousness level increase during awakening.

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References

1. Koch, C., Massimini, M., Boly, M., Tononi, G.: Neural correlates of consciousness: progress and problems. Nat Rev Neurosci **17**(5), 307–321 (2016) https://doi.org/10.1038/nrn.2016.22
2. Overgaard, M., Overgaard, R.: Neural correlates of contents and levels of consciousness. Front. Psychol. **5**, 940 (2010). https://doi.org/10.3389/fpsyg
3. Laureys, S., Boly, M., Moonen, G., Maquet, P.: Two dimensions of consciousness: arousal and awareness. Encycl Neurosci **2**, 1133–1142 (2009)
4. Aru, J., Suzuki, M., Rutiku, R., Larkum, M.E., Bachmann, T.: Coupling the state and contents of consciousness. Front Syst. Neurosci. pp. 13–43 (2019). https://doi.org/10.3389/fnsys.2019.00043
5. Tsuchiya, N., Wilke, M., Frässle, S., Lamme, V.A.F.: No-report paradigms: extracting the true neural correlates of consciousness. Trends Cogn. Sci. **19**(12), 757–770 (2015). https://doi.org/10.1016/j.tics.2015.10.002
6. Pigorini, A., Sarasso, S., Proserpio, P., Szymanski, C., Arnulfo, G., Casarotto, S., Fecchio, M., Rosanova, M., Mariotti, M., Lo Russo, G., Palva, J.M., Nobili, L., Massimini, M.: Bistability breaks-off deterministic responses to intracortical stimulation during non-REM sleep. Neuroimage **112**, 105–113 (2015). https://doi.org/10.1016/j.neuroimage.2015.02.056
7. Dorokhov, V.B.: Alpha-bursts and K-complex: phasic activation pattern during spontaneous recovery of correct psychomotor performance at difference stages of drowsiness. Zh Vyssh Nerv Deiat Im I P Pavlova **53**(4), pp. 503–512 (2003)
8. Cheremushkin, E.A., Petrenko, N.E., Gendzhalieva, M.S., Yakovenko, I.A., Malakhov, D.G., Dorokhov, V.B.: EEG Activity preceding spontaneous restoration of psychomotor activity after microsleep episodes. Russ. J. Physiol. **105**(8), 1002–1012 (2019). https://doi.org/10.1134/S086981391908003
9. Dorokhov, V.B., Malakhov, D.G., Orlov, V.A., Ushakov, V.L.: (2019) Experimental model of study of consciousness at the awakening: FMRI, EEG and behavioral methods. In: Samsonovich, A. (eds.) Biologically Inspired Cognitive Architectures BICA 2018, Advances in Intelligent Systems and Computing, vol. **848**. (2018). https://doi.org/10.1007/978-3-319-99316-4_11

10. Dorokhov, V., Gruzdeva, S., Tkachenko, O., Cheremushkin, E., Petrenko, N.: Experimental model of consciousness in the sleep-wake paradigm: determining consciousness activation using behavioral and Electromyographic indicators. Procedia Comput. Sci. **169**, 840–844 (2020). https://doi.org/10.1016/j.procs.2020.02.154
11. Peter-Derex, L., Magnin, M., Bastuji, H.: Heterogeneity of arousals in human sleep: A stereo-electroencephalographic study. Neuroimage **123**, 229–244 (2015). https://doi.org/10.1016/j.neuroimage.2015.07.057
12. Velik, R.: From single neuron-firing to consciousness — towards the true solution of the binding problem. Neurosci. Biobehav. Rev. **34**(7), 993–1001 (2010). https://doi.org/10.1016/j.neubiorev.2009.11.014
13. Halász, P., Terzano, M., Parrino, L., Bódizs, R.: The nature of arousal in sleep. J. Sleep Res. **13**(1), 1–23 (2004). https://doi.org/10.1111/j.1365-2869.2004.00388.x
14. Andrillon, T., Kouider, S.: The vigilant sleeper: neural mechanisms of sensory (de)coupling during sleep. Curr. Opin. Physiol. **15**, 47–59 (2020). https://doi.org/10.1016/j.cophys.2019.12.002
15. Destexhe, A., Hughes, S.W., Rudolph, M., Crunelli, V.: Are corticothalamic 'up' states fragments of wakefulness? Trends Neurosci **30**, 334–342 (2007). https://doi.org/10.1016/j.tins.2007.04.006
16. Cox, R., Korjoukov, I., de Boer, M., Talamini, L.M.: Sound asleep: processing and retention of slow oscillation phase-targeted stimuli. PLoS ONE **9**(7), e101567 (2014). https://doi.org/10.1371/journal.pone.0101567
17. Legendre, G., Andrillon, T., Koroma, M., Kouider, S.: Sleepers track informative speech in a multitalker environment. Nature Hum. Behav. **3**, 274–283 (2019). https://doi.org/10.1038/s41562-018-0502-5
18. Colrain, I.M.: The K-Complex: A 7-decade history. Sleep **28**(2), 255–273 (2005). https://doi.org/10.1093/sleep/28.2.255

Animal Cognition and Molecular Mechanisms

Subserving of Task Switching in Rabbits' Cingulate Cortex Neurons

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Abstract. Interruption of one behavior and transition to the execution of another are associated with cognitive load that leads to a decrease in task performance. The details of incipience of stable performance after switching on the level of single neurons remain unclear. Here we address two issues concerning the involvement of neurons in subserving of behavioral execution. First, the behavioral difference between the first and subsequent trials after switching lacks full explanation in terms of engagement of neurons that underlies task performance. Second, we asked whether functionally similar neurons belong to the same or different putative types of cells. We propose that the task switching requires selection of neurons akin to reinstatement of learning. Therefore, we hypothesized that the after-switch dynamics of neuronal activity is related to the degree of the neuron's involvement in task execution. This link has been revealed in rabbits' anterior and posterior cingulate single-cell activity recorded during alternation of two instrumental appetitive behaviors. We imply that the view of switching as a learning episode seems to disentangle the relationship between several aspects of cingulate activity: conflict monitoring, initiation and control of behavior after switching, novelty, and memory retrieval – they all include reorganization of individual experience. No relationship was found between the specialization of neurons and their putative cell-type. Since the cell-type coincides with the metabolic properties of neurons, we assume that the functional assembly of neurons is derived from complementarity of their divergent properties.

Keywords: Task switching · Learning · Single neuron · Rabbit · Neuronal selection · Reorganization of memory · Functional system · Complementarity

1 Introduction

The interruption of one behavior and the transition to the execution of another are associated with a decrease in the effectiveness of alternating tasks performance. It is conventionally considered as a manifestation of "task-set" reconfiguration that requires cognitive effort [1]. The brain underpinnings of task-switching are often described in

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terms of involvement of brain areas, especially in functional-anatomy studies. Conventionally, anterior cingulate cortex (ACC) is necessary during onset of task execution after switching [2, 3], but see [4], whereas posterior cingulate (PCC) supports its subsequent maintenance [5]. Meanwhile, PCC has been recently described as having an important role in "cognitive control" [6, 7]. Depending on the novelty and predictability of switching, maintenance-related activity in ACC [8, 9], as well as involvement of PCC in alteration [6, 10] has been revealed in imaging, inactivation, and single-cell studies (see also [11]).

It is often not possible to identify a single area of the brain, necessary for changes in behavior, because switch-related activity is task-specific [12, 13]. Accordingly, single-neuron recordings in ACC show that the firing increases when the behavior needs to be changed [14], and that the task selectivity of firing decreases following a task switch [15]. In PCC neurons the firing increased from the switch to repeat trials [16]. At the same time ACC and PCC neurons show stable selectivity to different aspects of task performance during its maintenance [17–20]. The inconsistency of these results is further complicated by the fact that the difference of firing frequency between switch and repeat trials may not appear unless the neurons are grouped by their specialization, i.e. involvement in task execution [16].

The task-specific aspects of ACC and PCC activity [21–23], as well as dynamics of this activity along with training or time [24–28] have been revealed with various methods, including single-unit activity recording in rabbits [17, 29–33]. Namely, ACC and PCC have been proposed to provide memory retrieval at the early [28, 34] and late [24, 25, 35] stages of learning (see also [21, 36, 37]). The ambiguity of functional descriptions of the ACC and PCC (switching and maintenance; recent and remote memories) can be solved by the assumption that both "memory retrieval" and "cognitive effort" during switching require memory reorganization and selection of units for subserving of behavior. Presumably, this reorganization is the "reorganizational reconsolidation" [38], i.e. modification of structure of individual experience without formation of a new element within that structure. This modification has been described within the approach to behavior as manifestation of the systems structure of individual experience [39–41]. On the basis of this assumption we hypothesized, firstly, that the after-switch dynamics of neuronal activity is related to the degree to which a neuron is task-related (i.e. to which it is "involved" in task execution).

Experiments with neuronal activity recording where animals consumed alcohol showed that a group of neurons of one specialization can be heterogeneous: only part of them changed their task-related activity during alcohol intake [42]. Here we aimed at characterization of the systems organization of behavior by assessing the correspondence between the specialization of neurons and their putative cell type. Importantly, the data on the correspondence between functional properties of a neuron and its putative cell type can be based on electrophysiological measures [43], whereas cell-types define the metabolic properties of neurons [44]. When the function is considered as a computation or information coding, then the functional and physiological properties would be expected to correspond (e.g. [43, 45]). However, the activity of a neuron provides metabolic changes, rather than transfer of information [46]. From the functional systems view [47], the function is achievement of a result by a system of divergent elements in brain and body, that conform their different degrees of freedom within a system and exchange their metabolic substrates. Developing this view, we propose, secondly, that the functional neuronal assemblies are constituted by various cell types – the latter are complementary in the sense of mutual cooperation in achieving the adaptive result (see also [48, 49]).

To address these issues, we recorded single-neuron activity in rabbits' ACC and PCC during switching between blocks of trials – cycles of two ways of food-acquisition, used by us previously (e.g., [17, 40, 50]). The rabbits have been successfully used in working memory setups (e.g., [51]). Therefore, we expected that the assessment of changes after transition from one behavior to another at the level of single neurons would unravel the incipience of stable performance after switching by covering both "cognitive effort" and "memory" descriptions of cingulate activity under the idea of reorganization of experience.

2 Methods

2.1 Subjects

Eight rabbits *Oryctolagus cuniculus* were food-deprived with ad libitum water to be trained in the experimental chamber (Fig. 1) to receive food. Their loss of weight did not exceed 15% from the weight of non-deprived animals of the same age. The experimental protocols are in accordance with the Council of the European Communities Directive of November 24, 1986 (86/609 EEC) and were approved by the ethics committee of the Institute of Psychology, Russian Academy of Sciences.

2.2 Behavioral Tasks and Training

The rabbits were trained to perform cyclic operant food-acquisition behavior on two symmetrical sides of the experimental chamber (Fig. 1, left), where each side is equipped with a pedal and a feeder in adjacent corners. A food pellet is delivered to the feeder if the corresponding pedal is pressed with paw(s) and if turning to the feeder is performed along the wall (the food is withdrawn if the animal turns to the center of the chamber on the way to the feeder).

The training started from the left side of the chamber for half of the animals to control for the differences between the two sides. The training was performed through 8 steps (Fig. 1, middle) made consecutively on each side of the experimental chamber: delivery of food to the feeder (steps 1 and 2), turning head and body from the feeder (3 and 4), turning to the pedal (5 and 6), pressing the pedal and turning to the feeder (7 and 8). These steps were also used to divide between acts within cycles of the resulting behavior with corresponding behavioral markers (Fig. 1, left) recorded in all sessions.

Each step of training is considered done if the criterion of 15 effective cycles in a row has been reached at any moment within a 40–60-min training session. After learning to press the pedal on two sides of the chamber separately (one side per session), the switching sessions are introduced, where the left and right sides of a symmetric chamber are made effective alternatively. The correct cycle was a loop (Fig. 1, right)

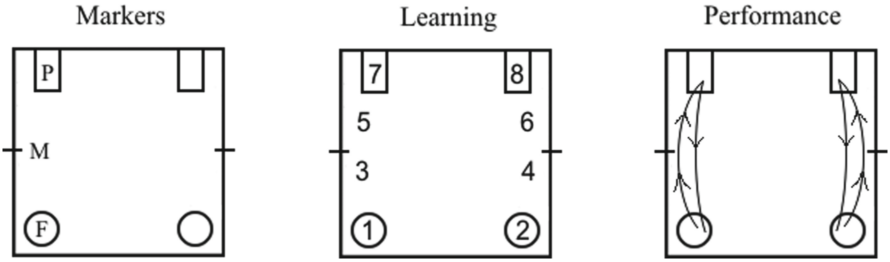

Fig. 1. The behavioral markers, order of learning, and cycles of alternated behaviors. Left. Schematic image of the experimental chamber with feeders (F) and pedals (P) on two symmetric sides. The actographic markers received from the chamber at all sessions including neuronal recordings are lowering the head into and raising the head from the feeders, crossing the middle line of the lateral walls (M), and pressing and releasing of the pedals. Middle. The order of steps of learning (1–8) in the same experimental chamber. Right. The resulting cycles of food-acquisition on the alternated sides of the chamber. See text for details.

from pressing a pedal through turning to corresponding feeder facing a wall to eating in the feeder, and turning back to the same pedal (if the effective side had not changed). A switch between the sides was initiated upon not less (and in most cases not more) than 7 effective cycles. These cycles (along with ineffective ones) constitute a block of cycles. The absence of food in the feeder after pressing the pedal along with delivery of food on the other side were the signals for switching.

2.3 Brain Activity Recording

The surgery procedures before training to press the pedals were followed by rest in a homecage with analgetics and no deprivation (not less than 3 days).The electrode intrusion started at the onset of switching sessions. Single-neuron activity was recorded with glass electrodes (2,5M KCl; 3–6 MOhm @ 1 kHz) from rabbits' anterior (AP-4 mm; ML $\pm$ 1$-$2mm; VD + 2–6 mm) or posterior (AP + 9 mm ; ML $\pm$ 1–2 mm) cingulate cortical areas during food-acquisition performed by alternating the blocks of cycles on each side of the experimental chamber. The signal from the electrode was pre-amplified with an in-lab-made head-stage, amplified with NBL-302 (Neurobiolab, Moscow, Russia), and digitized with E-14-140 external ADC (L-Card, Moscow, Russia), threshold-discriminated and sorted to identify spikes of single neurons with D-Main-4 in-lab software (Y. Raigorodski, A. Krylov).

Every record included at least one block of cycles on each side. The records were made in one cingulate area at a time for 3–5 days a week each. After two weeks the animals were sacrificed, their brains sliced and taken for morphological analysis to verify electrode location.

2.4 Variables and Data Analysis

The durations of movements from raising the head from the feeder to pressing the pedal (duration of approaching the pedal) and from pressing the pedal to lowering the head into the feeder (duration of returning to the feeder) were estimated on the basis of behavioral markers (Fig. 1, left). The number of ineffective acts from each shifting of the effective side by the experimenter (i.e. from the end of the last effective cycle) on one side to the start of the first effective cycle on the other side was count to assess the pace of switching.

The frequency of spikes was calculated for each behavioral act of each neuron, as well as the mean frequency for the whole session. All recorded cells were categorized as either "specialized" (in relation to a system of a behavioral act) or "unidentified" on the basis of probability of its activations in the separate acts (see Fig. 2). The significant increase of the firing rate above average frequency for the whole record that exceeds the factor of 1.5 in a given act was termed activation. If this probability reaches 100% in one or more acts, then the neuron is considered specialized, and the activations of a given act are called "specific" activations (see [40, 52] for more details). An illustration of a specific activation of a specialized neuron is presented in Fig. 3.

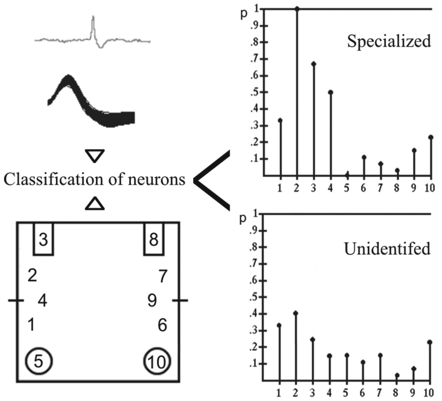

Fig. 2. Recording and analysis of neuronal activity includes digitizing raw signal, off-line sorting spikes after threshold discrimination (top left), and classification of neurons with respect to the acts of behavior (1–10): turning from the feeder, turing to the pedal, pressing the pedal and turning from the pedal to the middle of the lateral wall, and acquiring the food pellet from the feeder in the left (1–5) and right (6–10) sides of the experimental chamber (bottom left). The specialized neurons have at least one act with 1.0 activation probability (act #2 in a PCC neuron, top right), whereas unidentified neuron does not (a neuron with activation probability less than 1.0 in all acts, bottom right).

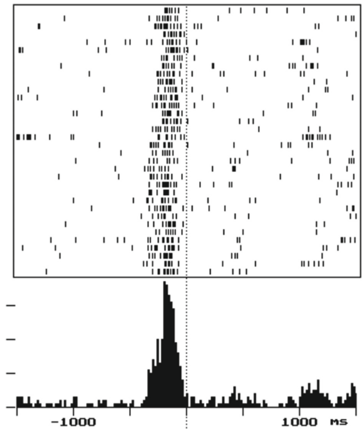

Fig. 3. The raster plot of a specialized PCC neuron with spikes (dashes) during successive turns of the animal towards a feeder vertically aligned to crossing the middle of the wall of the chamber. Below is the histogram of these spikes (20 ms in a bin, the ticks of the ordinate show tens of spikes) on the timeline with 500 ms division.

We defined putative cell types of all recorded neurons by clustering (hierarchical and K-means) using two measures of spike width (duration from initial negativity inflection point to trough and trough-to-peak duration), average firing rate, and depth in the cortex [43]. The spike-width parameters were extracted from the raw recordings before filtering. The correspondence between the specializations and clusters of neurons was assessed by Pearson's chi-square criterion. Pairwise comparisons of the electrophysiological measures between specializations (corrected) were performed with Mann-Whitney test.

To assess the changes after switching, in each block of cycles the measures of behavior and neuronal firing were assessed for the first, the second, and a median of not less than four subsequent cycles. These cycles were labeled "C1", "C2", and "C3", correspondingly. Consequently, a block was subjected to the analysis if the data had been recorded during not less than 6 effective cycles of behavior on each side of the experimental chamber after switching within the given record.

Two types of neuronal firing analyses were employed to assess the changes of brain activity after switch. First, the blocks with intermittent errors along with blocks of at least 6 effective cycles in a row were taken to assess the firing frequency. We decreased the sample of these records by removing unidentified cells with probability of activation that exceeds 0.6 (i.e. those with activations earlier called "non-specific", see [40]). An act with maximal average frequency was identified for expressing all frequencies in the units of this maximal average. A neuron was not included in this analysis if the side of the act with maximal frequency was not the side of the analyzed block.

Second, the removal of the blocks where ineffective feeder checking interrupted consecutive effective cycles has led to a dramatic decrease of available cases, since it is common for the rabbits to check the empty feeder even at the asymptotic performance level. Raw spike frequencies were used for this analysis, because the average frequencies in acts with low activation probability (less than 0.6) were estimated for each neuron (both specialized and unidentified) and compared separately from average frequencies in specific acts of specialized neurons. The recording of activity of a neuron could contain more than one switching with subsequent 6 or more effective cycles in a row, giving more that one case for one neuron in this analysis.

Calculation of firing frequency and movement durations were made with in-lab software D-Main-4 and Neuru (A. Krylov). The statistical analysis and graphics were performed with SPSS 11.0 and Python coding in IDLE.

3 Results

3.1 Behavioral Measures

The duration of behavioral cycles, as well as durations of pedal approaching and returning to the feeder did not differ between the groups with the left and right side of experimental chamber as the starting side (Mann-Whitney $U > 1000$; $p > 0{,}6$). The duration of behavioral cycles increased after switching. This difference was significant for comparisons between C1 and C3 (Wilcoxon test, $Z = -2.01$; $p = 0.044$), as well as C2 and C3 ($Z = -2.06$; $p = 0.040$) and was due to the successive increase of duration of returning to the feeder (C1-C3: $Z = -2.50$; $p = 0.012$. C2-C3: $Z = -1.87$; $p = 0.062$. Friedman test,

$p < 0.005$), whereas the duration of approaching the pedal did not change ($p > 0.4$ for all comparisons).

An additional analysis revealed that the duration of the whole cycle also differs between two consecutive weeks of the experiment: the duration of the cycles is higher during the second period in comparison to the first ($U = 829.0$; $p < 0.01$). The number of ineffective acts during the transition during the second period was less than that during the first period for the side of the experimental chamber trained first. The nonparametric Mann-Whitney criterion showed this difference at the trend level ($U = 1151.5$; $p = 0.065$), whereas it reached significance with the parametric T-criterion ($t_{110} = 2.09$; $p = 0.039$). Similar difference for the side trained second had the opposite direction, but was not significant ($U = 1194.0$; $t107 = -1.51$; $p > 0.1$). Repeated measures ANOVA revealed the interaction of the Period and Side ($F_{1,62} = 4.14$; $p = 0.046$).

3.2 Neuronal Activity

One hundred and fourty three single cells were selected for the analysis of firing dynamics after switching out of 214 that were recorded on the basis of their anatomic localization and the quality of spike sorting.

Blocks of Cycles with Errors. The analysis of data that included blocks of cycles with errors included 86 neurons with maximal frequency on the same side as the switching. Exclusion of task-related units left 63 neurons in the contrasting groups of specialized cells and cells with probability of activation that does not exceed 0.6. The specialized and unidentified neurons were characterized by opposite changes of the spikes frequency after switching (Fig. 4A). Namely, in the ACC, the spike frequency of specialized neurons increased, and that of the unidentified neurons decreased after switching, the difference achieving significance between the specialized and unidentified units in C3 ($U = 45.0$; $p = 0.006$). Separate ANOVA for the C3 has revealed the interaction of Specialization and Brain Area ($F_{1,59} = 5.59$; $p = 0.021$). In the PCC, the frequency of spikes decreased in specialized neurons. The similar analysis for C1 did not reveal significant differences ($p > 0.2$). However, if any, the changes in the PCC were in the opposite direction[1].

Blocks of Cycles without Errors. The analysis of data that excluded blocks of cycles with errors was performed for each switching. Consequently, 77 switches with corresponding spike frequencies were analyzed. The number of specialized neurons in this sample of neurons recorded with cycles without errors did not allow for separate analysis of ACC and PCC neurons. The combined sample has shown the dynamics similar to that of ACC in blocks of cycles with errors (Fig. 4B). Thus, the frequency in the specific acts increased after switching from C1 to C2 (Wilcoxon test, $Z = -2.10$; $p = 0.036$, the difference between C1 and C3 was at the tendency level $Z = -1.82$; $p = 0.069$), whereas the frequency in the acts with low activation probability decreased from C2 to C3 ($Z = -2.64$; $p = 0.008$, the difference between C1 and C3 was at the tendency level $Z = -2.70$; $p = 0.095$).

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[1] Although the changes of firing frequency of PCC neurons were less consistent, repeated measures ANOVA has revealed interaction of Cycle, Brain Area, and Specialization ($F_{2,118} = 3.38$, $p = 0.041$). However, the corresponding distributions differed from normal, and the lower-bound significance without sphericity assumption had been 0.71.

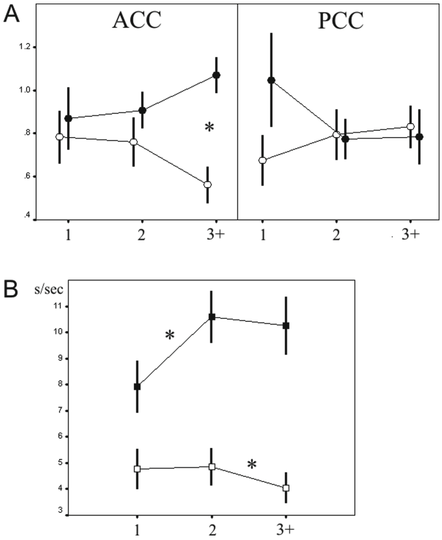

Fig. 4. The firing of specialized cells in specific acts after switching differed from firing in other acts and firing of unidentified cells. A. Spike frequency of specialized (black dots) and unidentified (white dots) cells in the units of maximal average frequency in ACC and PCC in the first, second, and median of at least four subsequent effective cycles in a row after switching (average ± SEM). The asterisk signifies significant differences ($p < 0,05$). B. Spike frequency of all cells in specific acts (black squares) and acts with low activation probability (white squares). Marked as in Fig. 4.

Putative Cell-Types. The analysis of putative cell-type relation to the specialization of neurons involved a sample of 113 neurons that had no missing values of the electrophysiological measures. Three clusters of cells have been identified on the basis of linkage distance with the most significant contribution of trough-to-peak duration (one-way ANOVA, $F_{110} = 321.09$; $p < 0.00001$). Two of the clusters with average trough-to-peak durations of 0.523 and 0.962 ms could be considered as putative inhibitory interneurons and putative pyramidal neurons, correspondingly (see Kawai et al. 2018). No correspondence between the specializations and clusters have been revealed (Pearson's χ^2; $p > 0,35$). Moreover, each of the clusters contained all of the specializations as well as unidentified neurons. Pairwise comparisons of the electrophysiological measures between clusters and specializations (corrected) have also not revealed significant differences (Mann-Whitney U, $p > 0,1$). If any, feeder-approaching neurons were found in deeper layers of posterior cingulate cortex, than the neurons specialized in relation to a preceding act of leaving the pedal (Kruskal-Wallis $H = 10,21$; $p = 0,016$), but the corresponding pair-wise differences were not significant.

4 Discussion

We checked whether the after-switch dynamics of neuronal subserving of behavior is related to the degree of the neuron's involvement in task execution, and whether the specialization of neurons corresponds to their putative cell type. This was done by recording the single-neuron activity in rabbits' ACC and PCC during alternation of two ways of operant appetitive behaviors. At this sample of neurons no relationship was found between the specialization of neurons and their putative cell-type: each cluster contained cells of all the specializations. This result is consistent with the assumption of heterogeneity of a group of neurons specialized in relation to a system of the same act of behavior. The putative cell-types are presumably related to metabolic properties of neurons (see [44]) besides their electrophysiological and morphological properties [53]. The contacts between neurons can be based on metabolic cooperation [54] and serve the metabolic needs of the cells [47]. Therefore, we consider the functional assembly of neurons to be derived from complementarity of their divergent properties.

The changes of firing of the neurons after switch did show functional relevance that differed between the two brain areas. Thus, the firing of specialized cells, i.e. cells necessary for the corresponding functional system, increased after switching, whereas the activity in other acts and firing of unidentified cells decreased. The effect was clearly evident in ACC, whereas PCC neurons did not show significant changes. This result is in correspondence with the previously described increase in the selectivity of neuronal firing in ACC after switching [15]. However, to our knowledge, this is the first demonstration of selectivity increase in cells of different involvement in subserving of behavior.

The dynamics of firing shown here for the ACC and PCC shows that greater activation of ACC in switch trials in relation to repeat trials revealed in functional anatomy studies, as well as the opposite PCC activation [5, 28] (but see [4]), might emerge from the activity of quantitatively prevailing units that do not specifically underpin task execution. In other words, the dynamics of "activations" in functional-anatomy studies does not reveal specific task-execution activity. Rather, it is due to activity of neurons without specific involvement. As argued earlier [42], unidentified neurons are specialized in relation to systems behavioral acts other than those formed in our setup. Therefore, the differences revealed presumably manifest the processes of reorganization of experience. Accordingly, task switching shares characteristics of novelty [55], and the onset of previously learned behavior after switching can be a selective process akin to reinstatement of learning (see [41]).

The change of speed after switching has not revealed any effects similar to "switch cost" [56], common for switching studies [1, 9]. Moreover, the duration of returning to the feeder in effective cycles increases after switching (as well as during repetitive overtraining during the experiment). Since the duration of approaching the pedals does not differ between successive cycles after switching, this effect can be explained by changes of motivation.

The rate of switching appeared to be associated with the history of learning the alternated behaviors: at the beginning of alternation, the transition to the first side was faster than to the second. These contrasts disappeared along with further training.

Variability and dynamics of switching are commonly explained by cognitive control process [1, 3, 4, 6]. We consider switching as a behavior that resembles learning and involves modification of prior experience [38, 49]. Behavior and brain activity analyses show that task alternation requires learning, principally similar to acquisition of the tasks proper [57]. Accordingly, switch-related brain activity is task-specific, rather than characteristic of a certain brain area[2]. Additionally, if the task switching requires formation of a new experience, we would expect the switch accuracy increase to be accompanied by the dynamics of interplay between the novel switching experience and the earlier formed task experience. This is to be verified in further studies, but the relation of switching rate to the order of learning may manifest this interplay.

5 Conclusion

Although task switching is alternation of behaviors that are known to the individual, every transition includes novelty and can be considered as a behavioral adaptation, or reorganization of experience. Therefore, starting a previously learned behavior can be viewed as reorganization of brain activity akin to learning, revealed here as increase of task-specific neuronal activity after switching in two areas of cingulate cortex. The functional groups of neurons that underpin newly formed behavior are proposed to consist of diverse cells that unite of the basis of complementarity of their properties.

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References

1. Monsell, S.: Task switching. Trends Cogn. Sci. **7**, 134–140 (2003). https://doi.org/10.1016/S1364-6613(03)00028-7
2. Hyafil, A., Summerfield, C., Koechlin, E.: Two mechanisms for task switching in the prefrontal cortex. J. Neurosci. **29**, 5135–5142 (2009). https://doi.org/10.1523/JNEUROSCI.2828-08.2009
3. Machinskaya, R.I.: The brain executive systems. Zh. Vyssh. Nerv. Deiat. Im. I P Pavlova. **65**, 33–60 (2015). https://doi.org/10.7868/s0044467715010086
4. Premereur, E., Janssen, P., Vanduffel, W.: Functional MRI in macaque monkeys during task switching. J. Neurosci. **38**, 10619–10630 (2018). https://doi.org/10.1523/JNEUROSCI.1539-18.2018
5. Sohn, M.H., Ursu, S., Anderson, J.R., Stenger, V.A., Carter, C.S.: The role of prefrontal cortex and posterior parietal cortex in task switching. Proc. Natl. Acad. Sci. U. S. A. **97**, 13448–13453 (2000). https://doi.org/10.1073/pnas.240460497
6. Pearson, J.M., Heilbronner, S.R., Barack, D.L., Hayden, B.Y., Platt, M.L.: Posterior cingulate cortex: Adapting behavior to a changing world. Trends Cogn. Sci. **15**(4), 143–51 (2011). https://doi.org/10.1016/j.tics.2011.02.002

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[2] According to our approach, the view of function as a product of a brain area is considered entrapping (see refs 37, 39, 41, and 47).

7. Nelson, A.J.D., Hindley, E.L., Haddon, J.E., Vann, S.D., Aggleton, J.P.: A novel role for the rat retrosplenial cortex in cognitive control. Learn. Mem. **21**, 90–97 (2014). https://doi.org/10.1101/lm.032136.113
8. Ma, L., Chan, J.L., Johnston, K., Lomber, S.G., Everling, S.: Macaque anterior cingulate cortex deactivation impairs performance and alters lateral prefrontal oscillatory activities in a rule-switching task. PLoS Biol. **17**, e3000045 (2019)
9. Umemoto, A., Holroyd, C.B.: Exploring individual differences in task switching: Persistence and other personality traits related to anterior cingulate cortex function. Prog. Brain Res. **229,** 189–212 (2016). https://doi.org/10.1016/bs.pbr.2016.06.003
10. Poulsen, C., Luu, P., Davey, C., Tucker, D.M.: Dynamics of task sets: evidence from dense-array event-related potentials. Cogn. Brain Res. **24**, 133–154 (2005). https://doi.org/10.1016/j.cogbrainres.2005.01.008
11. Ng, C.W., Noblejas, M.I., Rodefer, J.S., Smith, C.B., Poremba, A.: Double dissociation of attentional resources: prefrontal versus cingulate cortices. J. Neurosci. **27**, 12123–12131 (2007). https://doi.org/10.1523/JNEUROSCI.2745-07.2007
12. Calcott, R.D., Berkman, E.T.: Neural correlates of attentional flexibility during approach and avoidance motivation. PLoS ONE **10**, e0127203 (2015)
13. Dreher, J.C., Koechlin, E., Ali, S.O., Grafman, J.: The roles of timing and task order during task switching. Neuroimage **17**, 95–109 (2002)
14. Bryden, D.W., Brockett, A.T., Blume, E., Heatley, K., Zhao, A., Roesch, M.R.: Single neurons in anterior cingulate cortex signal the need to change action during performance of a stop-change task that induces response competition. Cereb. Cortex. **29**, 1020–1031 (2019). https://doi.org/10.1093/cercor/bhy008
15. Johnston, K., Levin, H.M., Koval, M.J., Everling, S.: Top-down control-signal dynamics in anterior cingulate and prefrontal cortex neurons following task switching. Neuron **53**, 453–462 (2007). https://doi.org/10.1016/j.neuron.2006.12.023
16. Alexandrov, Y.I., Shevchenko, D.G., Gorkin, A.G., Grinchenko, Y.: V: Dinamics of systems organization of behavior during consecutive trials [Dinamika sistemnoj organizacii povedenija v ego posledovatel'nyh realizacijah]. Psikholog. Zh. **20**, 82–89 (1999)
17. Alexandrov, Y.I., Grinchenko, Y.V., Järvilehto, T.: Change in the pattern of behavioural specialization of neurons in the motor cortex of the rabbit following lesion of the visual cortex. Acta Physiol. Scand. **139**, 371–385 (1990)
18. Gorkin, A.G., Shevchenko, D.G.: Stability of the behavioral specialization of neurons. Neurosci. Behav. Physiol. **21**, 222–229 (1991)
19. Sozinov, A.A., Averkin, R.G., Grinchenko, Y.V., Alexandrov, Y.I.: Involvement of previous memory in learning and the transfer effect. Int. J. Psychophysiol. **69**, 258 (2008). https://doi.org/10.1016/j.ijpsycho.2008.05.179
20. Weible, A.P., Rowland, D.C., Pang, R., Kentros, C.: Neural correlates of novel object and novel location recognition behavior in the mouse anterior cingulate cortex. J. Neurophysiol. **102**, 2055–2068 (2009)
21. Gabriel, M.: Discriminative Avoidance Learning: A Model System. In: Neurobiology of Cingulate Cortex and Limbic Thalamus. pp. 478–523. Birkhäuser Boston (1993)
22. Kuzina, E.A., Alexandrov, Y.I.: Differences in neuronal subserving of instrumental behavior, formed by one- and multi-stage learning procedures. Zhurnal Vyss. Nervn. Deyatelnosti im. I.P. Pavlov. **69**, 601–617 (2019)
23. Tse, D., Takeuchi, T., Kakeyama, M., Kajii, Y., Okuno, H., Tohyama, C., Bito, H., Morris, R.G.M.: Schema-dependent gene activation and memory encoding in neocortex. Science **333**, 891–895 (2011). https://doi.org/10.1126/science.1205274
24. Corcoran, K.A., Yamawaki, N., Leaderbrand, K., Radulovic, J.: Role of retrosplenial cortex in processing stress-related context memories. Behav. Neurosci. **132**, 388–395 (2018). https://doi.org/10.1037/bne0000223

25. Frankland, P.W., Ding, H.K., Takahashi, E., Suzuki, A., Kida, S., Silva, A.J.: Stability of recent and remote contextual fear memory. Learn. Mem. **13**, 451–457 (2006). https://doi.org/10.1101/lm.183406
26. Insel, N., Takehara-Nishiuchi, K.: The cortical structure of consolidated memory: a hypothesis on the role of the cingulate-entorhinal cortical connection. Neurobiol. Learn. Mem. **106**, 343–350 (2013). https://doi.org/10.1016/j.nlm.2013.07.019
27. Kuzina, E.A., Gorkin, A.G., Aleksandrov, Y.I.: Neuron activity in the retrosplenial cortex of the rat at the early and late stages of memory consolidation. Neurosci. Behav. Physiol. **46**, 789–793 (2016)
28. Tracy, J., Flanders, A., Madi, S., Laskas, J., Stoddard, E., Pyrros, A., Natale, P., DelVecchio, N.: Regional brain activation associated with different performance patterns during learning of a complex motor skill. Cereb. Cortex. **13**, 904–910 (2003)
29. Alexandrov, Y.I., Grinchenko, Y.V., Shevchenko, D.G., Averkin, R.G., Matz, V.N., Laukka, S., Korpusova, A.V.: A subset of cingulate cortical neurones is specifically activated during alcohol-acquisition behaviour. Acta Physiol. Scand. **171**, 87–97 (2001). https://doi.org/10.1046/j.1365-201X.2001.00787.x
30. Freeman, J.H., Gabriel, M.: Changes of cingulothalamic topographic excitation patterns and avoidance response incubation over time following initial discriminative conditioning in rabbits. Neurobiol. Learn. Mem. **72**, 259–272 (1999)
31. Gorkin, A.G., Shevchenko, D.G.: Distinctions in the neuronal activity of the rabbit limbic cortex under different training strategies. Neurosci. Behav. Physiol. **26**, 103–112 (1996). https://doi.org/10.1007/BF02359413
32. Sozinov, A.A., Laukka, S.J., Tuominen, T., Siipo, A., Nopanen, M., Alexandrov, Y.I.: Transfer of simple task learning is different in approach and withdrawal contexts. Procedia Soc. Behav. Sci. **69**, 449–457 (2012)
33. Talk, A., Kashef, A., Gabriel, M.: Effects of conditioning during amygdalar inactivation on training-induced neuronal plasticity in the medial geniculate nucleus and cingulate cortex in rabbits (Oryctolagus cuniculus). Behav. Neurosci. **118**, 944–955 (2004). https://doi.org/10.1037/0735-7044.118.5.944
34. Bontempi, B., Laurent-Demir, C., Destrade, C., Jaffard, R.: Time-dependent reorganization of brain circuitry underlying long-term memory storage. Nature **400**, 671–675 (1999). https://doi.org/10.1038/23270
35. Frankland, P.W., Bontempi, B., Talton, L.E., Kaczmarek, L., Silva, A.J.: The involvement of the anterior cingulate cortex in remote contextual fear memory. Science **304**, 881–883 (2004). https://doi.org/10.1126/science.1094804
36. Smith, D.M., Miller, A.M.P., Vedder, L.C.: The retrosplenial cortical role in encoding behaviorally significant cues. Behav. Neurosci. **132**, 356–365 (2018)
37. Weible, A.P.: Remembering to attend: The anterior cingulate cortex and remote memory. Behav. Brain Res. **245**, 63–75 (2013)
38. Aleksandrov, Y.I.: Learning and memory: Traditional and systems approaches. Neurosci. Behav. Physiol. **36**, 969–985 (2006)
39. Alexandrov, Y.I.: How we fragment the world: the view from inside versus the view from outside. Soc. Sci. Inf. **47**, 419–457 (2008)
40. Alexandrov, Y.I., Sozinov, A.A., Svarnik, O.E., Gorkin, A.G., Kuzina, E.A., Gavrilov, V.V.: Neuronal bases of systemic organization of behavior. In: Advances in Neurobiology. pp. 1–33. Springer, New York LLC (2018)
41. Shvyrkov, V.B.: Behavioral specialization of neurons and the system-selection hypothesis of learning. In: Klix, F., Hagendorf, H. (eds.) Human memory and cognitive capabilities. pp. 599–611. North-Holland: Elsevier, Amsterdam (1986)

42. Alexandrov, Y.I., Grinchenko, Y.V., Laukka, S.J., Järvilehto, T., Matz, V.N., Korpusova, A.V.: Effect of ethanol on hippocampal neurons depends on their behavioural specialization. Acta Physiol. Scand. **149**, 105–115 (1993). https://doi.org/10.1111/j.1748-1716.1993.tb09598.x
43. Trainito, C., von Nicolai, C., Miller, E.K., Siegel, M.: Extracellular spike waveform dissociates four functionally distinct cell classes in primate cortex. Curr. Biol. **29**, 2973−2982.e5 (2019). https://doi.org/10.1016/j.cub.2019.07.051
44. Pinto, L., Dan, Y.: Cell-type-specific activity in prefrontal cortex during goal-directed behavior. Neuron **87**, 437–450 (2015)
45. Zaitsev, A.V., Lewis, D.A.: Functional properties and short-term dynamics of unidirectional and reciprocal synaptic connections between layer 2/3 pyramidal cells and fast-spiking interneurons in juvenile rat prefrontal cortex. Eur. J. Neurosci. 38, (2013). https://doi.org/10.1111/ejn.12294
46. Edelman, G., Finkel, L.: Neuronal group selection in the cerebral cortex. In: Dynamic aspects of neocortical function. pp. 653–695. New York (1984)
47. Anokhin, P.K.: Biology and Neurophysiology of the Conditioned Reflex and Its Role in Adaptive Behavior. Pergamon Press, New York (1974)
48. Alexandrov, Y.I., Alexandrova, N.L.: Subjective experience and culture. structure and dynamics. Soc. Sci. A Q. J. Russ. Acad. Sci. **38**, 109–124 (2007)
49. Alexandrov, Y.I., Gorkin, A.G., Sozinov, A.A., Svarnik, O.E., Kuzina, E.A., Gavrilov, V. V: Consolidation and reconsolidation of memory: a psychophisiological analysis. Vopr. Psikhol. **3**, 133–144 (2015)
50. Sozinov, A.A., Kazymaev, S.A., Grinchenko, Y.V., Alexandrov, Y.I.: Percent of task-specialized cingulate cortex neurons does not change during training. In: FENS Abstracts, p. 114.08 (2012)
51. Weible, A.P., McEchron, M.D., Disterhoft, J.F.: Cortical involvement in acquisition and extinction of trace eyeblink conditioning. Behav. Neurosci. **114**, 1058–1067 (2000). https://doi.org/10.1037/0735-7044.114.6.1058
52. Alexandrov, Y.I., Grinchenko, Y.V., Shevchenko, D.G., Averkin, R.G., Matz, V.N., Laukka, S., Sams, M.: The effect of ethanol on the neuronal subserving of behavior in the hippocampus. J. Behav. Brain Sci. **03**, 107–130 (2013)
53. Barthó, P., Hirase, H., Monconduit, L., Zugaro, M., Harris, K.D., Buzsáki, G.: Characterization of neocortical principal cells and interneurons by network interactions and extracellular features. J. Neurophysiol. **92**, 600–608 (2004)
54. Subak-Sharpe, H., Bürk, R.R., Pitts, J.D.: Metabolic Co-Operation Between Biochemically Marked Mammalian Cells in Tissue Culture. J. Cell Sci. 4, (1969)
55. Barcelo, F., Escera, C., Corral, M.J., Periáñez, J.A.: Task switching and novelty processing activate a common neural network for cognitive control. J. Cogn. Neurosci. **18**, 1734–1748 (2006). https://doi.org/10.1162/jocn.2006.18.10.1734
56. Rogers, R.D., Monsell, S.: Costs of a predictible switch between simple cognitive tasks. J. Exp. Psychol. Gen. **124**, 207–231 (1995)
57. Timofeeva, N.O., Kotlyar, B.I., Popovich, L.D.: Analysis of the neuronal mechanism of conditioned-reflex switching. Neurosci. Behav. Physiol. **14**, 146–152 (1984). https://doi.org/10.1007/BF01185222

The Rapid Formation of CA1 Hippocampal Cognitive Map in Mice Exploring a Novel Environment

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Abstract. Cognitive maps are known as spatial patterns of activation of place cells, i.e. neurons that selectively fire only in certain spatial areas, which provide the navigation of animals in space. However, the dynamics of the formation of such maps when an animal is for the first time placed in a new environment remains mostly unknown. The technique of calcium in vivo imaging using head-mounted miniscopes allows the recording of a large number of neurons with cellular resolution from various brain structures of behaving animals without restrictions. In particular, this approach makes it possible to record the neural activity of the hippocampus in a model of free exploratory behavior in a new context. In this study, we obtained the neural activity of mice in a custom made circular track. Based on these data, the time series of place cell activity were reconstructed and the place fields constituting cognitive maps were identified. The properties of these cognitive maps were analyzed - specifically, it was found that place fields in the circular track are evenly distributed, without reference to the proximity of the prominent landmarks of the context. It was shown that the emergence of stable neural responses is relatively rapid and that most of the place fields emerge during the first three visits to the place field. These results provide important information for identifying cause-effect relationships between individual behavioral acts and the emergence of spatial specialization of neuronal ensembles.

Keywords: Place cells · Cognitive maps · Field CA1 · Hippocampus

1 Introduction

Spatial memory remains a very robust model for revealing the key mechanisms of learning and memory in the mammalian brain. The seminal work of John O'Keefe and Jonathan Dostrovsky [1] gave start to a broad spectrum of studies discovering properties of so-called cognitive maps, which are considered to be a system of receptive fields of spatially selective cells, located in the CA1 field of the hippocampus.

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The important innovation came in 2011 when Kunal Ghosh and Mark Schnitzer introduced a technique of calcium imaging in free behaving animals with head-mounted miniature microscopes [2]. The ability to simultaneously visualize hundreds of distinct neurons leveraged behavior-related cell recordings and in particular, place cell recordings, because the hippocampal field CA1 is a robust and relatively accessible structure, where a significant part of the whole granular cell layer can be captured in the single field of view. In a series of papers by Yaniv Ziv's group [3, 4], this technique was used to explore the long-term stability of place cells. Another study by Liron Sheintuch et al. showed that cognitive maps can be switched over different environments [5].

However, these and other studies exploited the paradigm using pre-trained animals, running for food or water reward. Given that, animals demonstrated more or less stereotypic behavior, which works well for longitudinal studies, but the dynamics of the formation of cognitive maps at the very first moment when an animal is placed in a new environment remained ill-defined in many aspects.

Here we focused on the latency of stabilization of individual place fields, i.e., the time required for place cells to begin firing in a spatially selective manner. To address this, we imaged mice with a head-mounted Inscopix nVista HD miniature microscope placed over a GRIN lens probes implanted in the CA1 field of the hippocampus (Fig. 1A), while the animals explored a completely novel environment. To avoid the confusion with a reinforcement-based goal-directed behavior we have developed a reward-free behavioral model in which animals are free to explore of a novel environment - a custom circular O-shaped track, surrounded by curtains with several visual cues (Fig. 1B).

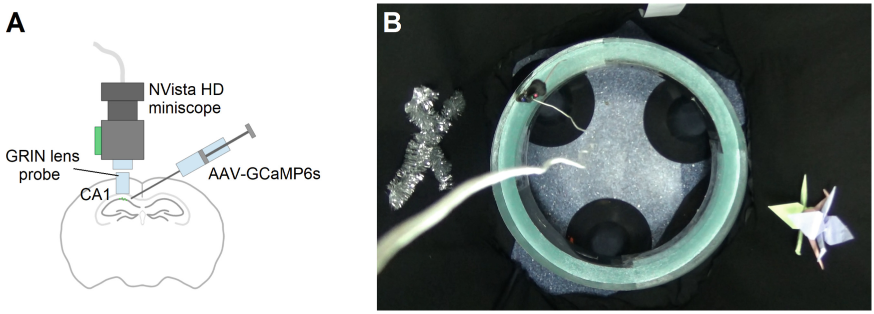

Fig. 1. A. A scheme of miniscopic calcium imaging in the CA1 field of the mouse hippocampus. **B.** The circular track with visual cues used in the free exploration task.

2 Results

We have recorded CA1 calcium activity and animal behavior for 15 min in 4 mice exploring the O-shaped track. During this time, each animal has made not less than 10 full laps around the track with average speed varying from 2.5 to 6.3 cm/s.

We have analyzed the recorded neural data with CNMF-E pipeline and obtained locations and activity traces of 1070 cell units in all 4 mice (for full statistics, see Table 1; samples can be seen in Fig. 2A, B). Next, we have aligned these traces with trajectories of mice and detected 705 spatial selective neurons (place cells), based on spiking statistics in every spatial bin of the track (Fig. 2C). We allowed each place cell to have multiple place fields, however, most of the cells (84%) appeared to have a single place field. The average width of a place field was 48.3° (~21 cm). The distribution of place field locations appeared to be relatively uniform (Fig. 3A), without significant perturbations related to visual cues proximity.

Next, we estimated the time elapsed before a place cell began to fire with respect to its place field (or fields). The vast majority (75%) of place cells started firing in at least one of their fields within the first 3 min of the mouse in the track (see distribution on Fig. 3B), with the average latency 142.7 s. However, since different animals have different dynamics of exploration of the environment, these latencies vary from animal to animal, so it was important to examine them not only in the time domain but also in behavioral terms. Therefore we have aligned these first activations with the individual trajectories of each animal (Fig. 3C). It can be seen that a significant fraction of cells (37%) specialize at the very first lap and the majority of cells (61%) do this within the first 3 laps.

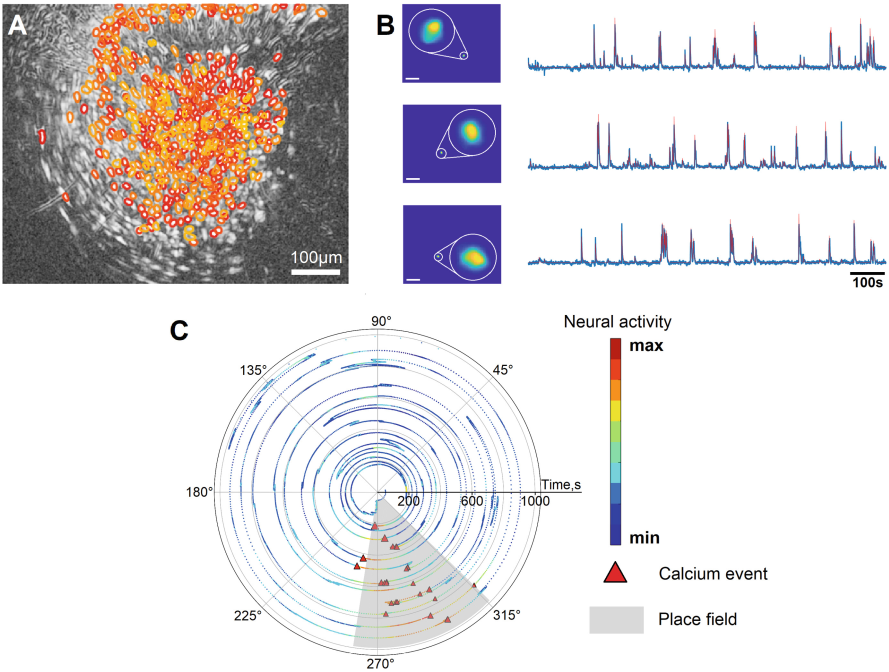

Fig. 2. **A.** Locations of detected cells in the miniscope field of view. **B.** Samples of activity traces of individual neurons. **C.** A schematic map of activation of an exemplary place cell: the trajectory is unfolded from the center to the periphery and colored with respect to the raw neural activity of the neuron.

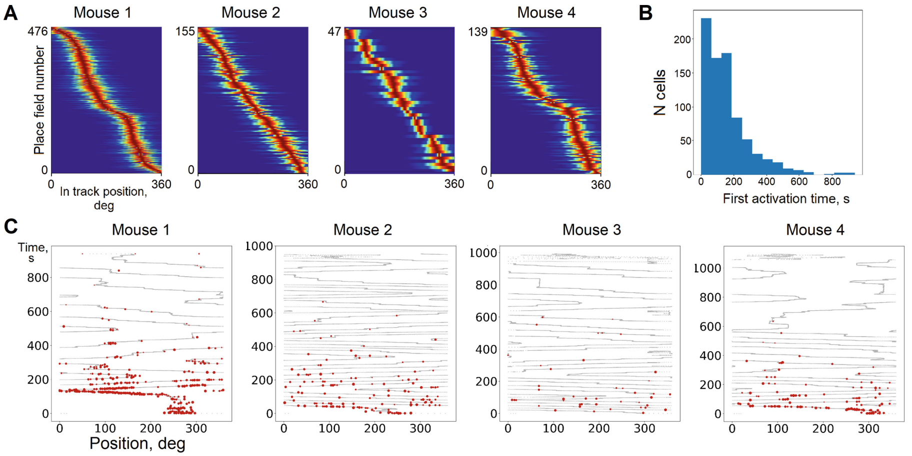

Fig. 3. **A.** Distributions of place field locations along the track for each mouse. **B.** Distribution of the first specific (in-field) activations of all place cells across all mice. **C.** Individual distributions of the first specific activations (dots) of place cells for each mouse, over their trajectories (curves)

Table 1. The statistics of detected place cells and place fields among the animals.

	Mouse 1	Mouse 2	Mouse 3	Mouse 4
Detected cells	549	214	76	231
Place cells	401	134	43	127
Place fields	476	155	47	139

3 Discussion and Conclusions

We have estimated the basic temporal parameters for the formation of CA1 spatial maps in a free exploration task in mice. Our results suggest that such formation takes a relatively short time, and the neuronal cognitive map is mostly formed after the animal completes its first laps in the new environment. This result is consistent with the previous finding in rats [6] showing that specific activity of place cells can emerge in a few minutes.

It should be noted that we have analyzed place cells separately. The obtained parameters should be also compared with the temporal parameters of cognitive map formation as a whole, at the population level. This constitutes a subject for future study.

Another important future task is the analysis of mouse behavior. Our paradigm makes it possible to align distinct behavioral acts of exploration and navigation (mainly running, sniffing, and rearing with and without support) to the timeline of neuronal activity and the spatial position of the animal. Correlating neuronal activity with behavior can reveal whether there are particular features in behavior which trigger cognitive map formation or if this process is governed by intrinsic neuronal dynamics.

4 Materials and Methods

Four male C57Bl/6 J mice aged 3 months at the beginning of the experiment were used in the study.

For delivery of viral vector encoding the GCaMP6s calcium sensor to the CA1 field of the hippocampus, animals were anesthetized with a zoletil-xylazine mixture (40 and 5 mg/kg, respectively) and fixed in a stereotaxic holder (Stoelting, Wood Dale, IL, USA). Then a circular 2-mm-diameter craniotomy was made (Bregma: – 1.9 mm AP, – 1.4 mm ML), and 500 nl of rAAV viral particles (AAV-DJ-CAG-GCaMP6s) were injected to a depth of 1.25 mm from the brain surface. Injections were performed through a glass micropipette with a 50 μm tip diameter (Wiretrol I, 5–000-1001, Drummond, USA) by UltraMicroPump with Micro4 Controller (WPI Inc., Sarasota, IL, USA) at a rate of 100 nl/min. After the injection, all exposed surfaces of the brain tissue were sealed with KWIK-SIL silicone adhesive (WPI).

Two weeks later, the animals were anesthetized and fixed in the stereotaxis again, the silicone cap was removed, and the dura matter was perforated and gently removed from the craniotomy site. Then, a 1.0 mm diameter GRIN lens probe (Inscopix Inc., Palo Alto, CA, USA) was lowered slowly to a depth of 1.1 mm while constantly washing the craniotomy site with sterile cortex buffer. Next, all the exposed brain tissue was sealed with KWIK-SIL, and the lens probe was fixed to the skull surface with dental acrylic (Stoelting).

After another two weeks, the animals were checked for a fluorescent calcium signal under light anesthesia (1/2 of the dose described above). The mice were fixed in the stereotaxis, the nVista HD miniature microscope (Inscopix) was lowered upon the GRIN lens probe and the most optimal field of view was chosen. Then a baseplate for chronic imaging was affixed to the scull surface with dental acrylic.

Finally, after a one-week recovery, awake mice with the attached nVista HD miniscope were placed for 15 min into a custom made circular O-shaped track (50 cm diameter, 5 cm width, with 5 cm height borders) with proximal (different border material) and distal (placed on a surrounding curtain 20 cm apart from the track) visual cues. Neural activity was recorded at 20 frames per second at resolution 1440 × 1080 px, and the video of mouse behavior was captured with a Sony HDR camera at 25 frames per second.

Image processing was performed with NoRMCorre [7] and CNMF-E [8] pipelines and custom MATLAB and Python scripts. First, movies were downsampled spatially by factor 2 to increase computation speed. Then, NoRMCorre routine was applied to spatially align movies to correct motion artifacts. Next, CNMF-E routine was applied to corrected movies and locations and activity traces of putative cell units were extracted and manually inspected. Then, significant ($>=$ 4 M.A.D.) calcium events were detected in the activity traces. Mouse trajectory was extracted from behavioral video recording with an open-source Bonsai visual programming media [9].

All obtained time series were synchronized and aligned to the beginning of the imaging session. To detect place cells we divided the space of the track into 40 spatial bins (sectors approx. 4 by 5 cm each) and calculated the number of spikes for each cell in each bin and divided it by the amount of time the animal occupied this bin. For each cell the distribution of spiking density was normalized and fitted by Gaussian mixture, the fitting curve was thresholded, and retaining bins were considered putative place fields (one cell could have more than one field). Next, we used a conservative approach and discarded all the fields except those where the cell fired at least 10 times or more than in 50% cases of visiting this field. The sample of an exemplary place field is shown in Fig. 2C. The time of the first specific in-field activation was determined for each place field as a time when the cell first fired in this place field.

All methods for animal care and all experimental protocols were approved by the National Research Center "Kurchatov Institute" Committee on Animal Care (NG-1/109PR of 13 February 2020) and were in accordance with the Russian Federation Order Requirements N 267 M3 and the National Institutes of Health Guide for the Care and Use of Laboratory Animals.

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References

1. O'Keefe, J., Dostrovsky, J.: The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. Brain Res. **4**(1), 171–175 (1971). https://doi.org/10.1016/0006-8993(71)90358-1.
2. Ghosh, K.K., Burns, L.D., Cocker, E.D., Nimmerjahn, A., Ziv, Y., Gamal, A.E., Schnitzer, M.J.: Miniaturized integration of a fluorescence microscope. Nat. Methods. **8**(10), 871–878 (2011). https://doi.org/10.1038/nmeth.1694
3. Ziv, Y., Burns, L.D., Cocker, E.D., Hamel, E.O., Ghosh, K.K., Kitch, L.J., El Gamal, A., Schnitzer, M.J.: Long-term dynamics of CA1 hippocampal place codes. Nat. Neurosci. **16**(3), 264−266 (2013) https://doi.org/10.1038/nn.3329
4. Rubin, A., Geva, N., Sheintuch, L., Ziv, Y.: Hippocampal ensemble dynamics timestamp events in long-term memory. Elife. **4**, e12247 (2015). https://doi.org/10.7554/eLife.12247
5. Sheintuch, L., Geva, N., Baumer, H., Rechavi, Y., Rubin, A., Ziv, Y.: Multiple maps of the same spatial context can stably coexist in the mouse hippocampus. Curr. Biol. **30**(8), 1467−1476.e6 (2020). https://doi.org/10.1016/j.cub.2020.02.018
6. Muller, R.U., Kubie, J.L., Ranck, J.B., Jr.: Spatial firing patterns of hippocampal complex-spike cells in a fixed environment. J. Neurosci. **7**(7), 1935–1950 (1987). https://doi.org/10.1523/JNEUROSCI.07-07-01935.1987
7. Pnevmatikakis, E.A., Giovannucci, A.: NoRMCorre: An online algorithm for piecewise rigid motion correction of calcium imaging data. J. Neurosci. Methods **291**, 83–94 (2017). https://doi.org/10.1016/j.jneumeth.2017.07.031
8. Zhou, P., Resendez, S.L., Rodriguez-Romaguera, J., Jimenez, J.C., Neufeld, S.Q., Giovannucci, A., Friedrich, J., Pnevmatikakis, E.A., Stuber G.D., Hen, R., Kheirbek, M.A., Sabatini, B.L., Kass, R.E., Paninski, L.: Efficient and accurate extraction of in vivo calcium signals from microendoscopic video data. Elife. **7**, e28728 (2018). https://doi.org/10.7554/eLife.28728
9. Lopes, G., Bonacchi, N., Frazão, J., Neto, J.P., Atallah, B.V., Soares, S., Moreira, L., Matias, S., Itskov, P.M., Correia, P.A., Medina, R.E., Calcaterra, L., Dreosti, E., Paton, J.J., Kampff, A.R.: Bonsai: an event-based framework for processing and controlling data streams. Front Neuroinform. **9**, 7 (2015). https://doi.org/10.3389/fninf.2015.00007

Selection for High Scores of Cognitive Abilities in the Laboratory Mice: Successes and Pitfalls

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Abstract. The paper is the short review of our experimental results, in which the complicated mechanisms of animal solving of elementary logic task were demonstrated. The selection of mice for high scores of cognitive trait (namely, the ability to extrapolate the direction of stimulus movement, which disappears from view) was performed. This trait scores had been elevated at the initial selection generations, but this prevalence became unstable later. At the same time the selected mice performed significantly above controls in another cognitive test (puzzle-box), which requires to "understand" the object permanence rule. The selected mice were also more successful in hyponeophagia test. These results mean that changes in the genotype of selected line took place. At the same time data indicated the high complex genetic determination of cognitive abilities in mouse and demonstrate the actual need to use the test battery to evaluate the behavioral trait.

Keywords: Animal cognition · Behavior genetics · Elementary logic problem · Extrapolation task · Puzzle-box · Selection · Laboratory mice

1 Introduction

Rodent cognitive abilities are traditionally analyzed basing on animal learning success in different conditioning paradigms, including even the habituation as non-association learning. Learning is the basic concept which underlie the adaptive behavior and which is the topic of numerous studies. Although it is evident, that cognitive abilities (and animal cognitive ability as well) include also the ability to solve the logic tasks (the problem which animal encounters for the first time, i.e. without previous learning). In case of our studies these are the abilities to solve elementary logic problems. The spatial navigation tasks (Morris water maze, Barnes and radial mazes) also require the ability to "grasp" the spatial map parameters and also could be attributed to this category of cognitive tasks (which of course involve different forms of memory). The ability to solve elementary logic task means that animal could (or could not) understand the laws, which connect objects and events in the external world (e.g. laws of movement or rule of object permanence), and solve the problem having no identical individual experience (i.e. previous learning). The ability of mice to extrapolate was assessed as the ability to choose the correct direction of (food) stimulus movement which started to move aside (to the left or to the right) when animal started to drink milk from the small food cup.

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After the few seconds the moving food cup disappeared from mouse view (Fig. 1a). The correct solution was to move in the respective direction and to find the food and drink milk via the side opening.

The notion of animal cognition, presented above, includes also the positive reaction of an animal to novelty (although reaction to new object and/or new environment depends on level of anxiety as well), and this problem is a topic of numerous studies, including testing the respective reactions in animals of different genotypes [1–3].

2 Results

Our work was based on previous findings in which rat and mouse ability to solve the extrapolation problem was analyzed. The attempt to select rats which solve this task successfully, failed. The parental generation consisted of genetically heterogeneous rats, derived from the hybrids between wild brown rats and laboratory rats of several strains. These animals displayed different degrees of ability to solve extrapolation task. Although at the level of F3-F4 selection generations practically all animals were extremely fearful in the experimental box (in spite of extensive handling and long laborious habituation sessions), and it was not possible to perform experiments with them. Mouse experiments demonstrated that most animals from the inbred strains were not able to solve the extrapolation task, while mice-carriers of the chromosomal mutation (robertsonian translocation, i.e., fusion, of chromosomes 8 and 17) resulted in successful solution of extrapolation problem, which was confirmed by special genetic experiments [4].

In parallel, the breeding of mice which differ in the relative brain weight permitted to show that among large brain strain animals which were able to solve the extrapolation problem were more numerous, than in low brain weight strain. Three mouse selection experiments for relative brain weight were performed, practically with similar results. These data encouraged us to make the attempt to select mice for high scores of extrapolation task. Having in mind the failure of previous rat selection the second trait for selection had been the lack of anxiety signs during task performance [5].

2.1 Extrapolation Task

The success in extrapolation task performance was measured by the percentage of correct task solutions in comparison with the 50% chance level and with the performance of other mice groups (differing by genotype as well). It was found that mice of the selected line (EX) solved the task with scores significantly above the chance level up to F9. The anxiety indices (elevated plus maze performance) of these mice were significantly lower, than those of the non-selected control population (CoEX). At the same time later, in further generations, the EX mice performances in both extrapolation task and anxiety probes became unstable and in sum the EX mice did not differ by this task indices from those of the control animals.

2.2 Puzzle-Box Task

Starting from F9, mice were tested in another cognitive task – the so called “puzzle-box” (Fig. 1b), introduced into laboratory practice by M. Galsworthy [6]. This test (in

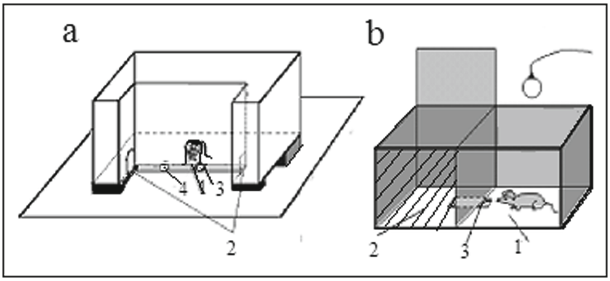

Fig. 1. Schematic drawings of experimental devices, in which mice were tested in the study of their cognitive abilities. a -"extrapolation box", made of the opaque plastic: 1- central opening, via this opening the animal starts to feed (by milk) from the cup, 2 – side openings, to one of them the food is displaced in each trial (6 trials in total), the choice, to which cup to move alternated by the experimenter in quasi-random way, 3 - food cup, which starts the movement (in this case - to the right), 4 - control food cup, which was invisible to mouse, but which moved simultaneously with the target cup (control of milk odor and movement noise). b – puzzle-box: 1 - brightly lit compartment, 2 – dark compartment, 3 – the underpass, which connects them. The walls of this device are non-transparent, the lid of the dark compartment is shown as opened, but during the test *per se* it is closed.

contrast to "food-motivated" extrapolation task) is based on animal urge to escape into the dark. Mouse is placed into the brightly lit part of the experimental box, which is provided by the underpass (sunken for 1.5 cm below the floor surface), and an animal can escape into more comfortable dark box compartment. At the start probes of the test the underpass was unobstructed, and mouse could penetrate into the dark compartment (in most cases – easily). At the next trials the underpass was masked. First, the wood shaving was used – the underpass is now hidden as the wood shaving filled it up to the floor surface, and the underpass is visible no more. In these trials an animal is given 180 s to solve the task. If it did not - the failure was recorded. At the next stage the underpass was closed by the light carton-plastic plug (which mouse could remove by teeth and/or paws and muzzle), the time to solve this stage was 240 s. In order to solve the puzzle-box successfully (i.e., enter in the dark during the scheduled time) animal had to know that the underpass, which had been perceived previously, is seen no longer, but it still exists. It could be detected even if it is not visible any more. This knowledge is classified as understanding the rule of object permanence - the object just perceived did not vanish - it is possible to find it. Object permanence rule had been initially introduced by J. Piajet, who observed the emergence of this understanding in children during their first months of life. The successful solutions of puzzle-box demonstrated by EX and CoEX differed especially in the "cognitive" trials (i.e. when the underpass was masked). EX mice performed significantly better, than controls.

3 Discussion

Thus, the selection of mice for high scores of the trait "extrapolation" did not result in statistically significant and stable elevation of the positive task solutions [7], while animals of the selected line EX performed significantly more efficiently than controls when tested for the solution of the "puzzle-box".

This seeming paradox could be explained. The trait "extrapolation" is much more complicated by its "internal structure" than the "puzzle-box". The brief analysis of requirements for the solution of extrapolation task is the following. *First*, the subject has to "grasp" the direction of food stimulus (cup with milk) movement. The food cup could be seen moving only for 2–5 s, and then disappears from view. *Second*, this event (the fact that the food disappeared) should be fixed in brief memory. *Third*, an animal has to overcome the state of frustration, which could develop after this event happened. This frustration frequently induced mouse to move rapidly away from the frontal wall (the food cup moves behind it, see Fig. 1a) and move towards the opposite box wall. After this it could approach the central opening again or move along the internal perimeter of the box and approach one of the side openings, shown as "2" in Fig. 1a). This approach could be the "correct" one (approach to the side opening where the food cup is now) or the opposite one (i.e. incorrect). The goal-directedness of animal behavior at this stage is displayed when mouse (after initial starting back) approached the central opening again and decided to choose moving in one of two directions. The decision of an animal in which direction to move could be based either on "catching" the direction of food displacement and approach the "correct" side opening or be made by chance - approach any side opening. Thus the success of task performance could be given as the prevalence of correct choices proportion over the 50% chance level. *Forth*, this paradigm required as well, that an animal had to inhibit the innate behavior - to alternate the direction of movement. Alternative movements to left and to right side openings (irrespective to direction of food movement) were frequent in mouse groups with poor extrapolation scores.

It should be noted that learning experience was of course present in these tests. It was evident that hungry animal learned to seek milk in the central opening and learned to approaches to side openings as well, although in many cases apart from the ability to grasp the direction in which food disappeared. In the puzzle-box test mice easily learned the position of the underpass, which leads into the dark (although not all mice understand that the masked underpass could be revealed).

The structure of puzzle-box test is simpler than that of the extrapolation test, although puzzle-box also belongs to the category of elementary logic problem. The prevalence of EX mice performance over that of controls in this test signifies that the selection for extrapolation did resulted in some of selection for behavior. As it was noted by Garland and Kelly [8] the "directional selection should favor alleles that increase phenotypic plasticity in the direction of selection, where phenotypic plasticity is defined as the ability of one genotype to produce changes in brain-behavior processes, Most of these factors should be revealed in further experiments, in particular, analyzing the effects more than one phenotype when exposed to different environments". This means that our knowledge of microevolution processes in cases of behavioral traits don't permit us yet to make more detailed conclusions.

Ex and CoEX mice were compared in neophagophobia test [5, 9], in which the food-deprived mouse was placed in the new small arena (not "frightening" device with dim illumination) and given the new food (small pieces of cheese). EX mice performed more successfully in this test than controls - the number of approaches to new food and the amount of cheese eaten had been significantly higher in EX groups during several selection generations (from F8 to F17). The EX mice prevalence in this paradigm is another indication that changes in EX phenotype occurred as the result of genetic selection [5, 9] and that EX mice are really genetically different from unselected control population CoEX. The reaction to novelty is the trait which is not only under "cognitive control", but is influenced by animal anxiety too [3, 10]. Our data could also mean that the lack of fear towards new food was also the result of selection against the high anxiety in experimental environment.

It should be noted that the mean relative brain weight of EX mice in the series of selection generations had been consistently higher that in CoEX [9]. This was in good accordance with our data on extrapolation and puzzle box solution data in mice with genetic differences in relative brain weight [5].

4 Concluding Remarks

In general animal cognitive abilities (and their expression in extrapolation and puzzle-box tests) really belong to the scope of the executive function concept [11, 12]. Created in order to categorize the human cognitive performance, this notion is successfully used to analyze animal behavior. In most cases this concept is the standpoint for analysis animal goal directedness, decision making and attention shift as applied to learned behavior (and to analyze the brain structures involved). Although one may note that in dogs the analysis of executive function revealed the correlation with the absolute brain weight indices [13]. The inclusion of extrapolation ability (and animal ability for elementary logic tasks in general) in the framework of "executive function" analysis will help to widen the scope of this concept. These abilities, which were analyzed in our work, demonstrate that not only learning could underlie the complex adaptation of animals and that the requirement for adaptation could involve the decision making on the basis of cognitive problem solving. The "animal logic" in comparison with human psychological issues of this capacity attracts the attention during last decades [14]. The analysis of the puzzle-box data in this light looks promising [15]. Thus, the inclusion of elementary logic problem solution in the framework of executive function analysis will be fruitfull.

Conflict of Interests. Authors declare no conflict of interests.

Bioethics. Experiments described meet all bioethical requirements of Declaration 2010/63/EU.

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References

1. Dulawa, S.C., Hen, R.: Recent advances in animal models of chronic antidepressant effects: the novelty-induced hypophagia test. Neurosci. Biobehav. Rev. **29**(4–5), 771–83 (2005). https://doi.org/10.1016/j.neubiorev.2005.03.017

2. Ennaceur, A., Michalikova, S., van Rensburg, R., Chazot, P.L.: Models of anxiety: responses of mice to novelty and open spaces in a 3D maze. Behav. Brain Res. **174**(1), 9–38 (2006). https://doi.org/10.1016/j.bbr.2006.07.001
3. Greiner, E.M., Petrovich, G.D.: The effects of novelty on food consumption in male and female rats. Physiol. Behav. **223**, 112970 (2020). https://doi.org/10.1016/j.physbeh.2020.112970
4. Poletaeva, I.I., Popova, N.V., Romanova, L.G.: Genetic aspects of animal reasoning. Behav. Genet. **23**(5), 467–75 (1993). https://doi.org/10.1007/bf01067982
5. Perepelkina, O.V., Tarasova, A.Yu., Ogienko, N.A., Lilp, I.G., Poletaeva, I.I.: Brain weight and cognitive abilities of laboratory mice. Biol. Bull. Rev. Pleiades Pub. (Tortola, British Virgin Islands) **10**(2), 91–101 (2020). https://doi.org/10.1134/s2079086420020061
6. Galsworthy, M.J., Paya-Cano, J.L., Liu, L., Monleón, S., Gregoryan, G., Fernandes, C., Schalkwyk, L.C., Plomin, R.: Assessing reliability, heritability and general cognitive ability in a battery of cognitive tasks for laboratory mice. Behav. Genet. **35**(5), 675–92 (2005). https://doi.org/10.1007/s10519-005-3423-9
7. Perepelkina, O.V., Lilp, I.G., Markina, N.V., Golibrodo, V.A., Poletaeva, I.I.: The first experience in selecting mice for high extrapolation ability. In: "The Development of Animal Behavior. Normal and Abnormal Aspects. The 100 anniversary of L.V. Krushinsky", Publ. House "Languages of Slavic Culture", pp. 263–296 (2013). (in Russian)
8. Garland, T., Kelly, S.A.: Phenotypic plasticity and experimental evolution. J. Exper. Biol. **209**, 2344–2361 (2006). https://doi.org/10.1242/jeb.02244
9. Perepelkina, O.V., Tarasova, A.Yu., Golibrodo, V.A., Lilp, I.G., Poletaeva, I.I.: Behavior of mice selected for high scores of cognitive trait. J. Vyssch. Nervn. Deyat. I. P. Pavlova **68**(4), 434–447 (2018). (in Russian)
10. Deacon, R.M.J., Rawlins, J.N.P.: Hippocampal lesions, species-typical behaviours and anxiety in mice. Behav. Brain Res. **156**, 241–249 (2005). https://doi.org/10.1016/j.bbr.2004.05.027
11. Nilsson, S.R., Alsiö, J., Somerville, E.M., Clifton, P.G.: The rat's not for turning: dissociating the psychological components of cognitive inflexibility. Neurosci. Biobehav. Rev. **56**, 1–14 (2015). https://doi.org/10.1016/j.neubiorev.2015.06.015
12. Funahashi, S.: Prefrontal contribution to decision-making under free-choice conditions. Front Neurosci. **11**(431), 2017 (2017). https://doi.org/10.3389/fnins.2017.00431.eCollection
13. Horschler, D.J., Hare, B., Call, J., Kaminski, J., Miklósi, Á., MacLean, E.L.: Absolute brain size predicts dog breed differences in executive function. Anim. Cogn. **22**(2), 187–198 (2019). https://doi.org/10.1007/s10071-018-01234-1
14. Watanabe, S., Huber, L.: Animal logics: decisions in the absence of human language. Anim. Cogn. **9**, 235–245 (2006). https://doi.org/10.1007/s10071-006-0043-6
15. Ben Abdallah, N.M., Fuss, J., Trusel, M., Galsworthy, M.J., Bobsin, K., Colacicco, G., Deacon, R.M., Riva, M.A., Kellendonk, C., Sprengel, R., Lipp, H.-P., Gass, P.: The puzzle box as a simple and efficient behavioral test for exploring impairments of general cognition and executive functions in mouse models of schizophrenia. Exp. Neurol. **227**(1), 42–52 (2011). https://doi.org/10.1016/j.expneurol.2010.09.008

Gene Expression Asymmetry in the Human Prefrontal Cortex

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Abstract. Advanced interhemispheric asymmetry considered to be a unique feature of the human brain. However, studies of the human brain asymmetry at the gene expression level are scarce and report contradictory results. In total, three healthy control and four schizophrenia adult human bilateral Brodmann area 10 (BA10) samples were used in the experiment. FOS, PDK4, CD44, and AQP1 genes had differential expression in the right and left BA10 in HC as revealed by RT-qPCR. In SZ FOS only showed differential expression. For the first time, a decrease of interhemispheric asymmetry of FOS, PDK4, CD44, and AQP1 gene expression in BA10 of schizophrenia patients was revealed. We propose that it might play a key role in the cognitive and social maladaptation. Immunohistochemistry revealed that Aqp1 localized in the GFAP-positive astrocytes of the infragranular cortical layers. Close proximity of AQP1-positive astrocytic endfeets to the cerebral vessels implies their participation in neurovascular coupling. Thus, our results are in good agreement with the hypothesis that evolutionarily novel mechanisms of brain functioning are disrupted in neuropsychiatric diseases.

Keywords: Human · Brain · Asymmetry · Gene expression · Schizophrenia

1 Introduction

1.1 Gene Expression Asymmetry Hypothesis

Advanced interhemispheric asymmetry considered to be a unique feature of the human brain [1]. Anatomical and functional lateralization made it possible to more efficiently implement specialized functions and reduce redundancy in a highly complex social and ecological environment in humans [2, 3]. Boris Velichkovsky [10] proposed, that the gene expression asymmetry might arise from the computational advantage of separating neural substrates for processing new information mediated mainly by the right hemisphere, and processing established cognitive tasks and representations maintained predominantly by the left hemisphere. However, studies of the human brain asymmetry at the gene expression level are scarce and report contradictory results.

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1.2 Gene Expression Asymmetry Evidences

Early studies have shown that gene expression in the human neocortex was globally symmetric [4, 5]. Later, a functional gene cluster was found in the upper part of the human temporal cortex, having differential gene expression between hemispheres [6]. The epigenetic mechanisms of asymmetric brain maturation in the early stages of human development, including faster maturation of the right hemisphere cortex, were investigated in detail [7, 8]. Comparative transcriptomic analysis of unilateral left or right human BA10 identified more than 60 differentially expressed genes [9]. Moreover, 24 differentially expressed miRNAs were found in the same samples [10].

Thus, the question, if the interhemispheric asymmetry of the gene expression can be revealed between bilateral BA10 regions of the same brains, remains to be unexplored, and the functional significance of asymmetric gene expression is an unresolved problem.

Here, in bilateral BA10 samples, we found differential expression of FOS, PDK4, CD44, and AQP1 genes, and demonstrated the decrease of this asymmetry in schizophrenia patients. Expression of Aqp1 in human-specific cell type, and advanced functional asymmetry in human brain suggests the disruption of an evolutionarily novel mechanisms in neuropsychiatric diseases.

2 Methods

2.1 Ethics Statement

The experimental design was approved by the Independent Multidisciplinary Committee on Ethical Review of Clinical Trials (protocol №4 from 15.03.2019), Moscow, Russia.

2.2 Samples

Three healthy control and four schizophrenia adult human bilateral Brodmann area 10 (BA10) samples were used in the experiment. Two BA10 samples were dissected from each brain: one BA10 sample from the left hemisphere and a second BA10 sample from the right hemisphere of the same donor. The Atlas of the Human Brain [11] were used to locate regions in the human brains. All individuals were Caucasians who died of natural causes. Healthy control donors (HC) had no history of neurological or psychiatric illness. Schizophrenia (SZ) patients had a history of observation and confirmed schizophrenia diagnosis at Mental-health Clinic №1 named after N.A. Alexeev, Moscow, Russia. All subjects suffered sudden deaths with no prolonged agonal state. Mean age of HC and SZ donors did not differ (52 ± 14.22 vs 57.25 ± 15.86, Mean ± SD). Mean postmortal intervals between HC and SZ did not differ (28 ± 3.45 vs 29.50 ± 13.00). Detailed information on human brain samples given in the Appendix, Table 1. The healthy control BA10 samples were obtained from the Anatomic Pathology Department of I.M. Sechenov First Moscow State Medical University, Moscow, Russia. The schizophrenia BA10 samples were obtained from the Mental-health Clinic №1 named after N.A. Alexeev.

2.3 RT-qPCR

RNA was extracted from human BA10 brain regions with PureLink RNA Mini kit (Ambion) according to the manufacturer's recommendations. The quality of purified RNA was examined with a Nanodrop spectrophotometer and 1 g of RNA was taken for DNase I (Thermo Scientific) treatment conducted according to the manufacturer's recommendations. DNA-free RNA was subsequently transcribed into cDNA for RT-qPCR procedure using Maxima First Strand cDNA Synthesis kit (Thermo Scientific). Quantitative PCR was performed using QuantStudio 3 Real-Time PCR System (Applied Biosystems) in duplicates for each sample. The protocol used SsoAdvanced Universal SYBR Green Supermix (Bio-Rad) according to the manufacturer's recommendations.

ZBTB20, ATF5, FOS, PDK4, GADD45G, CD44, and AQP1 genes were chosen for investigation as they demonstrated differential expression in right and left BA10 during transcriptomic analysis of unilateral samples previously [4]. Primer sequences used for ZBTB20, ATF5, FOS, PDK4, GADD45G, CD44, AQP1, and GAPDH provided in Appendix, Table 2. The relative expression levels of ZBTB20, ATF5, FOS, PDK4, GADD45G, CD44, and AQP1 mRNA were normalized by the geometric mean of GAPDH mRNA expression.

2.4 Immunohistochemistry

Multiple immunofluorescent histochemistry was performed as described previously [12, 13]. Shortly, 20 μm thick cryosections were cut from BA10 samples from three HC and four SZ (Appendix, Table 1). All samples were previously frozen in liquid nitrogen vapor and stored at −80 °C until experiment. Sections were thaw-mounted onto microscope slides and fixed with 4% paraformaldehyde solution for 7 min followed by washing in phosphate-buffered saline 0.1 M PBS (pH 7.4) three times for 5 min. Then sections were preincubated in PBST (0.5% Triton X-100 in PBS) with 5% normal donkey serum (NDS) and 5% normal horse serum (NHS) for 1 h. The mixture of primary antibodies – mouse anti-AQP1 (sc-55466, Santa Cruz, 1:250) and goat anti-GFAP (PA5-18598, Thermo Fisher Scientific, 1:1000) in the blocking buffer (2.5% NDS and 2.5% NHS in PBST) was applied to the sections for 24 h at 4 °C in Shandon coverplates. Then sections were washed and incubated with biotinylated horse anti-mouse IgG (BA-2000, Vector Laboratories, 1:200) in the blocking buffer for 2 h at room temperature. After rinses in PBST, sections were incubated in a mixture of donkey anti-goat Alexa Fluor 488 (A-11055, Thermo Fisher Scientific, 1:500) and streptavidin-Alexa Fluor 568 conjugate (S-11226 Thermo Fisher Scientific, 1:500) for 2 h. After several washes in PBST, sections were stained in 1% Sudan black B solution in 70% ethanol for 30 min to block lipofuscin autofluorescence. Then they were washed in PBS, mounted with aqueous mounting medium (Fluoromount, Sigma-Aldrich, with DAPI) under coverslips, and sealed with transparent nail polish. No staining was seen in control sections processed without the primary antibody.

2.5 Imaging

Images were obtained via an Olympus FluoView FV10i confocal laser scanning microscope with UPLSAPO 60 ×/1.20-W objective. Image reconstructions were performed in Imaris v7.2.3 (Bitplane). Three images were obtained from each section. One section was processed per individual in each BA10. All individuals yielded reproducible results.

2.6 Statistics

Statistical processing of the RT-qPCR data was performed using QuantStudio design and analysis software v.1.5.1 (ThermoFisher Scientific). Differences were considered to be statistically significant at $p < 0.05$. Graphs were made by GraphPad Prism 6.0 software.

3 Results

3.1 Interhemispheric Asymmetry

FOS, PDK4, CD44, and AQP1 genes had differential expression in the right and left BA10 in HC as revealed by RT-qPCR (Fig. 1a, c). No change in ZBTB20, GADD45G, and ATF5 expression asymmetry was detected in HC (Fig. 1b). In SZ FOS gene showed differential expression only (Fig. 1c). Interhemispheric asymmetry of FOS, PDK4, CD44, and AQP1 gene expression in human BA10 significantly decreased in schizophrenia (Fig. 1d-f). A tendency for the increase of expression asymmetry in SZ for ZBTB20 gene was observed (Fig. 1g). No SZ associated changes in GADD45G and ATF5 gene expression asymmetry were detected (Fig. 1h-i).

3.2 Cell Phenotyping

Immunohistochemistry with antibodies against Aqp1 revealed its colocalization with GFAP-immunopositive astrocytes in the infragranular layers of the human BA10 cortex (Fig. 2). Close proximity of AQP1-positive astrocytic endfeets to the cerebral vessels was observed. Membrane-bound Aqp1 expression clearly marked long-range vesicular astrocytic processes.

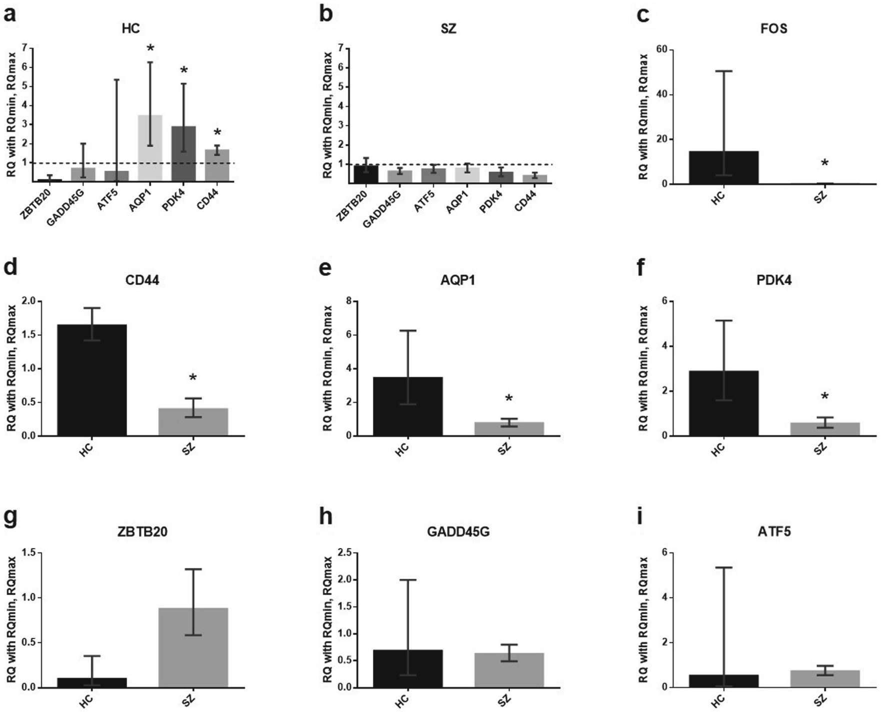

Fig. 1. Interhemispheric asymmetry of gene expression in human BA10: a – in healthy control (HC), b – in schizophrenia (SZ), c-f – significant decrease in FOS, CD44, AQP1 and PDK4 gene expression asymmetry in SZ, g – a tendency for the increase in ZBTB20 gene expression asymmetry in SZ, and h-i – no change in GADD45G and ATF5 gene expression asymmetry.

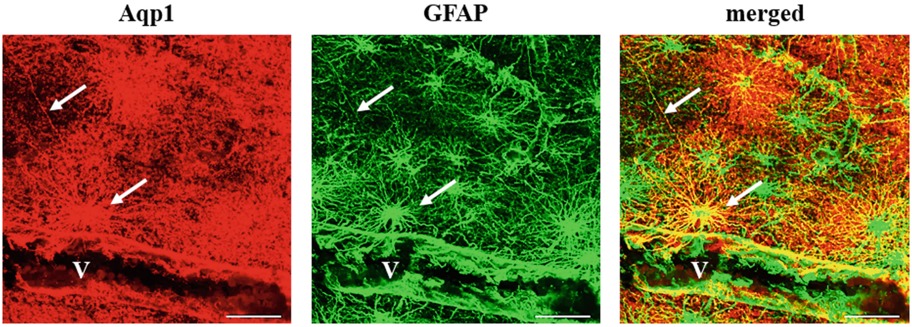

Fig. 2. AQP1 expression colocalized with astrocytic marker GFAP in the infragranular layers of the human BA10 cortex. Note the closeness of AQP1-positive astrocytic endfeets to the vessel (V). Note the AQP1 expression in long-range vesicular astrocytic process (arrows). Aqp1 (red), GFAP (green), merged (AQP1 with GFAP colocalization). Scale 50 µm.

4 Discussion

4.1 Interhemispheric Asymmetry

We demonstrated that FOS, PDK4, CD44, and AQP1 genes had differential expression in bilateral BA10 regions of the same healthy control brains. These results are in concordance with previously published data obtained from the left and right BA10 regions of the different brains [9]. No change in ZBTB20, GADD45G, and ATF5 expression asymmetry was detected in contrast to [9]. Further investigations are required with an extended number of bilateral donors.

4.2 Cell Phenotyping

Immunohistochemistry revealed that Aqp1 localized in the GFAP-positive astrocytes of the infragranular cortical layers. Close proximity of AQP1-positive astrocytic endfeets to the cerebral vessels implies that they participate in neurovascular coupling. Aqp1 expression in long-range vesicular astrocytic processes is remarkable as such processes known to be a hallmark of human-unique astrocytic subtype [16].

In addition, we detected concordant changes in AQP1 and CD44 expression asymmetry in BA10, in agreement with the fact, that AQP1 and CD44 expression colocalized in projection vesicular astrocytes [16]. Recent single-cell-resolution transcriptome analysis also showed that AQP1 and CD44 expression had human-specific expression in astrocytes compared to primates [13]. Thus, our results are in good agreement with the hypothesis that evolutionarily novel mechanisms of brain functioning are disrupted in neuropsychiatric diseases [17].

5 Conclusions

In conclusion, we would like to emphasize that a decrease of interhemispheric asymmetry of FOS, PDK4, CD44, and AQP1 gene expression in BA10 of schizophrenia patients was found. We propose that it might play a key role in the cognitive and social maladaptation. This assumption is supported by a decrease in the functional asymmetry of the brain connectome in schizophrenia [14] and in normal aging [15]. Revealed gene expression asymmetry may reflect the advanced functional interhemispheric laterality considered to be a unique feature of the human brain [1–3].

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix

Table 1. Sample information

№	Donor ID	Psychiatric diagnosis	Sex	Age	PMI	Cause of death
1	HC1	Healthy	M	59	24	Hypovolemic shock
2	HC2	Healthy	F	62	30	Peritonitis
3	HC3	Healthy	F	36	30	Hepatocellular failure
4	SZ1	Schizophrenia	M	35	24	Coronary heart disease
5	SZ2	Schizophrenia	M	74	48	Coronary heart disease
6	SZ3	Schizophrenia	F	57	28	Coronary heart disease
7	SZ5	Schizophrenia	M	62	18	Suicide

Table 2. Primer sequences for RT-qPCR

Gene name	Primer direction	Sequence	Length
Homo sapiens zinc finger and BTB domain containing 20 (ZBTB20)	Forward	5´-CAGCACTGTTATCACTGTCA-3´	118
	Reverse	5´-TTCTGTCTGGCGTAAGTAGA-3´	
Homo sapiens activating transcription factor 5 (ATF5)	Forward	5´-AGTCAGGGCGGGCTTTG-3´	81
	Reverse	5´-CCTTAGCGTAGTGTCCCAAGGT-3´	
Homo sapiens Fos proto-oncogene, AP-1 transcription factor subunit (FOS)	Forward	5´-GAGAGCTGGTAGTTAGTAGCAT-GTTGA-3´	112
	Reverse	5´-AATTCCAATAATGAACCCAATA-GATTAGTTA-3´	
Homo sapiens pyruvate dehydrogenase kinase 4 (PDK4)	Forward	5´-CCCCGAGAGGTGGAGCAT-3´	83
	Reverse	5´-GCATTTTCTGAACCAAAGTCCAG-TA-3´	
Homo sapiens growth arrest and DNA damage inducible gamma (GADD45G)	Forward	5´-TACGCTGATCCAGGCTTTCT-3´	133
	Reverse	5´-AATGAGGATGCAGTGCAGGT-3´	
Homo sapiens CD44 molecule (Indian blood group) (CD44)	Forward	5´-TGCCGCTTTGCAGGTGTAT-3´	66
	Reverse	5´-GGCCTCCGTCCGAGAGA-3´	
Homo sapiens aquaporin 1 (Colton blood group) (AQP1)	Forward	5´-TGGCTGTGGGATTAACCCTG-3´	65
	Reverse	5´-GGTTGCTGAAGTTGTGTGTGATC-3´	
Homo sapiens glyceraldehyde-3-phosphate dehydrogenase (GAPDH)	Forward	5´-TGCACCACCAACTGCTTAGC-3´	87
	Reverse	5´-GGCATGGACTGTGGTCATGAG-3´	

References

1. Xiang, L., Crow, T., Roberts, N.: Cerebral torque is human specific and unrelated to brain size. Brain Struct. Funct. **224**(3), 1141–1150 (2019). https://doi.org/10.1007/s00429-018-01818-0
2. Corballis, M.C.: Evolution of cerebral asymmetry. Prog. Brain Res. **250**, 153–178 (2019). https://doi.org/10.1016/bs.pbr.2019.04.041
3. Neubauer, S., Gunz, P., Scott, N.A., Hublin, J.J., Mitteroecker, P.: Evolution of brain lateralization: a shared hominid pattern of endocranial asymmetry is much more variable in humans than in great apes. Sci. Adv. **6**(7), eaax9935 (2020). https://doi.org/10.1007/s00429-017-1401-7
4. Hawrylycz, M.J., Lein, E.S., Guillozet-Bongaarts, A.L., Shen, E.H., Ng, L., Miller, J.A., et al.: An anatomically comprehensive atlas of the adult human brain transcriptome. Nature **489**(7416), 391–399 (2012). https://doi.org/10.1038/nature11405
5. Pletikos, M., Sousa, A.M., Sedmak, G., Meyer, K.A., Zhu, Y., Cheng, F., et al.: Temporal specification and bilaterality of human neocortical topographic gene expression. Neuron **81**(2), 321–332 (2014). https://doi.org/10.1016/j.neuron.2013.11.018
6. Muntané, G., Santpere, G., Verendeev, A., Seeley, W.W., Jacobs, B., Hopkins, W.D., Navarro, A., Sherwood, C.C.: Interhemispheric gene expression differences in the cerebral cortex of humans and macaque monkeys. Brain Struct. Funct. **222**(7), 3241–3254 (2017). https://doi.org/10.1007/s00429-017-1433-z
7. de Kovel, C.G.F., Lisgo, S.N., Fisher, S.E., Francks, C.: Subtle left-right asymmetry of gene expression profiles in embryonic and foetal human brains. Sci. Rep. **8**, 12606 (2018). https://doi.org/10.1038/s41598-018-29496-2
8. Schmitz, J., Güntürkün, O., Ocklenburg, S.: Building an asymmetrical brain: the molecular perspective. Front. Psychol. **10**, 982 (2019). https://doi.org/10.3389/fpsyg.2019.00982
9. Dolina, I.A., Efimova, O.I., Kildyushov, E.M., Sokolov, A.S., Khaitovich, P.E., Nedoluzhko, A.V., Sharko, F.S., Velichkovsky, B.M.: Exploring terra incognita of cognitive science: lateralization of gene expression at the frontal pole of the human brain. Psychol. Russ. **10**(3), 231–247 (2017). https://doi.org/10.11621/pir.2017.0316
10. Velichkovsky, B.M., Nedoluzhko, A.V., Goldberg, E., Korosteleva, A.N., Efimova, O.I., Sharaev, M.G., Ushakov, V.L.: New insights into the human brain's cognitive organization: views from the top, from the bottom, from the left and particularly, from the right. Procedia Comp. Sci. **169**, 547–557 (2020). https://doi.org/10.1016/j.procs.2020.02.211
11. Mai, J.K., Majtanik, M., Paxinos, G.: Atlas of the Human Brain, 4th edn. Academic Press, Elsevier (2016). eBook ISBN: 9780128028018
12. He, Z., Han, D., Efimova, O., Guijarro, P., Yu, Q., Oleksiak, A., Jiang, S., Anokhin, K., Velichkovsky, B., Grünewald, S., Khaitovich, P.: Comprehensive transcriptome analysis of neocortical layers in humans, chimpanzees and macaques. Nat. Neurosci. **20**(6), 886–895 (2017). https://doi.org/10.1038/nn.4548
13. Khrameeva, E., Kurochkin, I., Han, D., Guijarro, P., Kanton, S., Santel, M., Qian, Z., Rong, S., Mazin, P., Sabirov, M., Bulat, M., Efimova, O., Tkachev, A., Guo, S., Sherwood, C.C., Camp, J.G., Pääbo, S., Treutlein, B., Khaitovich, P.: Single-cell-resolution transcriptome map of human, chimpanzee, bonobo, and macaque brains. Genome Res. **30**(5), 776–789 (2020). https://doi.org/10.1101/gr.256958.119
14. Sun, Y., Chen, Y., Collinson, S.L., Bezerianos, A., Sim, K.: Reduced hemispheric asymmetry of brain anatomical networks is linked to schizophrenia: a connectome study. Cereb. Cortex **27**, 602–615 (2017). https://doi.org/10.1093/cercor/bhv255
15. Dolcos, F., Rice, H.J., Cabeza, R.: Hemispheric asymmetry and aging: right hemisphere decline or asymmetry reduction. Neurosci. Biobehav. Rev. **26**(7), 819–25 (2002). https://doi.org/10.1016/s0149-7634(02)00068-4

16. Sosunov, A.A., Wu, X., Tsankova, N.M., Guilfoyle, E., McKhann 2nd, G.M., Goldman, J.E.: Phenotypic heterogeneity and plasticity of isocortical and hippocampal astrocytes in the human brain. J. Neurosci. **34**(6), 2285–98 (2014). https://doi.org/10.1523/JNEUROSCI.4037-13.2014
17. Liu, X., Han, D., Somel, M., Jiang, X., Hu, H., Guijarro, P., Zhang, N., Mitchell, A., Halene, T., Ely, J.J., Sherwood, C.C., Hof, P.R., Qiu, Z., Pääbo, S., Akbarian, S., Khaitovich, P.: Disruption of an evolutionarily novel synaptic expression pattern in autism. PLoS Biol. **14**(9), e1002558 (2016). https://doi.org/10.1371/journal.pbio.1002558

Lipidomic Uniqueness of the Human Cerebellum White Matter

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Abstract. Lipidomics is the omics technology aimed to detect and quantify the complete diversity of lipids (lipidome) in the specific sample. Despite numerous reports confirming the crucial role of lipids in the brain functions, studies of brain lipid composition are sparse and incomplete in contrast to genome and transcriptome data. Cerebellum recently emerged as a potent modulating center of neuronal plasticity of the forebrain. Moreover, cerebellum has undergone great changes during human brain evolution. Here, we studied the spatial distribution in thousands of lipid species, marking different functional hubs in cerebellar microcircuits in evolutionary lineage - macaque, chimpanzee and human. MALDI mass-spectrometry imaging demonstrated that molecular and granular layers as well as white matter of the cerebellum had unique lipid profiles. Lipidome-based hierarchical clustering of different cerebellar hubs revealed significant evolutionary differences. Remarkably, the greatest evolutionary distance in humans compared to primates was observed in the white matter lipid profile. This fact completely agrees with the significant changes in oligodendrogenesis and myelination during human brain evolution.

Keywords: Human · Brain · Lipidomics · Evolution

1 Introduction

Lipids make up half of the brain's dry weight, and play an important role in structural and functional brain organisation [1]. For a long time the lipid significance was limited to cell membrane and energy storage. According to the modern view, lipids are considered to be the key regulators of synaptic plasticity [2, 3]. Evidence shows that lipids affect the activity of membrane-bound and unbound proteins that specifically interact with definite lipid species [4]. Lipids affect fusion and formation of synaptic vesicles, ion flow through membrane channels, and lateral diffusion of membrane receptors by regulating chemical and mechanical properties of the membranes [5–7].

Information on lipid spatial distribution and its evolution in primate cerebellum are very scarce. A comparative study of human, chimpanzee, macaque and mouse lipidomes in a range of organs showed that brain lipid composition evolved faster than lipid composition of other organs. Some human-specific brain lipidome features were identified

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in this study of tissue extracts, including cerebellum [8]. To our knowledge, no study has addressed the lipidome evolution of cerebellar structures with spatial resolution.

The actively developing method for spatial mass-spectrometry of low molecular weight metabolites, MALDI imaging (Matrix Assisted Laser Desorption/Ionization) measures the intensity of thousands of lipid ions on fresh frozen tissue sections with spatial resolution up to 10 μ. This approach is a powerful tool to study such a heterogeneous tissue as a brain.

In the present study, we have established that patterns of lipid distribution in primate cerebellum follow the cytoarchitecture of the main hub layers: white matter, granule and molecular layers, and have species-specific features.

2 Materials and Methods

2.1 Samples

We measured nine cerebellum samples: human (n = 3), chimpanzee (n = 3) and macaque (n = 3). Human and macaque brain samples were obtained from Shanghai Brain Biobank, chimpanzee brain samples - from the Leipzig Max Planck Institute of Evolutionary Anthropology. Donors had no known history of neurological disease. Detailed information on the samples can be found in the Appendix (Table 1).

Samples were dissected from cerebellum region, frozen in liquid nitrogen vapors and stored at −80 °C until used. Cerebellum samples were atemperated to −20 °C prior to dissection, placed on a metal board, and cubic pieces 5–7 mm (LxWxH) were cut out from the lateral area for the analysis. The frozen brain samples were mounted onto the sample holders by O.C.T. compound (Sakura, Japan) from the underlying side, exclusively. The brain samples were cut into sections 20 μm thick by cryomicrotome (CM 1950, Leica Microsystems, Germany), and thaw-mounted onto the ITO slides (15Ω, HST, US). For MALDI, sections were dried in the vacuum chamber, and matrix was applied by spraying. CHCA (α-Cyano-4-hydroxycinnamic acid) in 70% acetonitrile and 0.1% trifluoroacetic acid was used as MALDI matrix. Neighboring sections were mounted on SuperFrost slides (Thermo Scientific, US) for subsequent immunohistochemistry, and stored at −80 °C until processing.

2.2 MALDI Imaging

MALDI imaging was performed by a modified MALDI-Orbitrap mass-spectrometer [9] (ThermoScientific Q-Exactive orbitrap with MALDI/ESI Injector from Spectroglyph, LLC) equipped with an 355 nm Nd:YAG Laser Garnet (Laser-export. Co. Ltd, Moscow, Russia). For positive ion induction laser power was set to 20 J repetition rate to 1.7 kHz. The distance between the sample on a coordinate table and ion funnel was 5 cm. Produced ions were captured by ion funnel and transferred to QExactive Orbitrap mass spectrometer (Thermo). Mass-spectra were obtained in a mass range of m/z 500–1000, and a mass resolution was 140,000. The tissue region to be imaged and the raster step size were controlled using the Spectroglyph MALDI Injector Software. The spectra were collected at 35 μm intervals in both the x and y dimensions across the surface of the sample [9]. Ion images were generated from raw files (obtained from Orbitrap tunesoftware) and coordinate files (obtained from MALDI Injector Software) by Image Insight software from Spectroglyph LLC (www.spectroglyph.com).

2.3 Immunohistochemistry

To identify cerebellar layers, sections were stained with anti-NeuN antibodies. NeuN is localized in the nuclei and perinuclear cytoplasm of all types of neurons in the mammalian brain, except for the Purkinje cells [8]. Antibodies to NeuN have been widely used to detect neuronal bodies in neuroscience, developmental biology, and stem cell research as well as diagnostic histopathology [10]. Neighboring sections, adjacent for those, taken for MALDI, were dried at +37 °C for 40 min, then fixed in 10% neutral buffered formalin (HEM, Russia) for 7 min and rinsed in PBS (PBS, Sigma Aldrich, USA) 3 times × 5 min. Then slides with sections were placed onto Shandon Cover plate disposable immunostaining chambers and inserted into Shandon Sequenza racks (Thermo Scientific, US). Non-specific binding was blocked by 5% normal donkey serum (Sigma) in PBS with 0.5% Triton X-100 (PBS-T) for 1 h at room temperature. Then sections were incubated with mouse anti-NeuN monoclonal antibody (Millipore, MAB377) diluted at 1:250 in PBS-T with 2.5% normal donkey serum and 0.01% NaN_3 at +4 °C overnight. After that, samples were thoroughly rinsed in PBS and incubated with 1:500 Alexa Fluor 488 donkey-anti mouse IgG (Invitrogen, ThermoFisher Scientific, US) for 2 h at room temperature. Then samples were rinsed in PBS and coverslipped with mounting medium (FluoroMount, Sigma, USA). Omission of primary antibodies was used as IHC negative control.

2.4 Imaging

Panoramic imaging of immunofluorescent cerebellum sections was performed using Zeiss LSM 800 confocal system with ZEN Pro 2.3 software (Carl Zeiss Microscopy GMBH, Jena, Germany). Cerebellar white matter, granule and molecular layers were identified based on NeuN staining.

2.5 Data Analysis

MALDI raw mass spectra were converted to *.ibd and *.imzML formats using Spectroglyph software (https://spectroglyph.com/). All further processing was done in Cardinal 2.0 and R package designed for mass spectrometry imaging data analysis [8]. Imported datasets were cropped to remove the uninformative parts of the spectra. Data was then normalized to total ion current, and duplicated coordinates were removed. Peak picking on the basis of signal to noise ratio of 3 was done to select peak centers for further analysis. Signal to noise ratio was calculated based on the difference between mean peak height in a pre-defined size window and the height of a relatively flat part of the spectrum [8]. Spatial Shrunken Centroids algorithm was used for spatial clustering of pixels with similar spectra.

The resulting cluster boundaries were compared with the structure boundaries on histology images in order to assign every cluster to a specific cerebellar structure. Spectral features, specific for every cluster, were extracted from each dataset using the top labels method of top-rank feature retrieval. Out of the top ranked features, only those that had mean intensity > 1 in only one of the clusters, were analyzed. From all the m/z values, typical for each structure, only values that were shared for all donors of the same species were selected for the further analysis.

3 Results

We analyzed 1733 ions in every cerebellum sample. An example of ion spatial distribution (**A**), clusterization (**B**) and anti-NeuN IHC image (**C**) of the *Macaca mulatta* cerebellum is shown in Fig. 1. Similar results were obtained in all cerebellum samples for m/z 748.6025 ions.

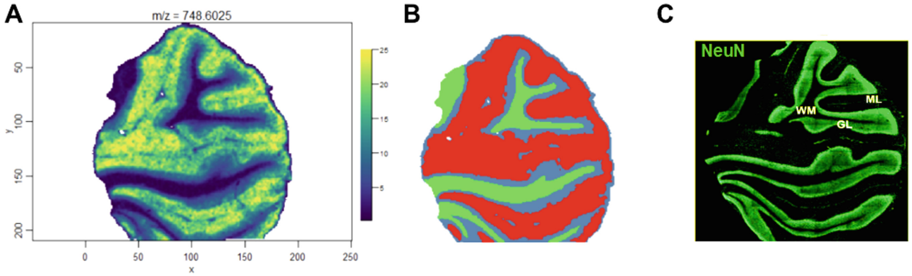

Fig. 1. Differential lipid distribution in *Macaca mulatta* cerebellum: **A -** an ion, detected exclusively in the molecular layer; **B** - spatial clustering of all ions, detected in a cerebellum; **C -** NeuN, a neuronal marker, IHC staining of neighbouring section: WM - white matter, GL - granule layer, ML - molecular layer.

To go deeper, we studied the evolutionary distances as well as correlation between lipid profiles of each cerebellum layer in the human, chimp and macaque cerebellum, using a subset of ions, demonstrating layer-specific distribution. The result can be seen in Fig. 2. Lipidome composition of the cerebellum appeared to have a high correlation (Fig. 1A) inside individuals of the same species. Evolutionary differences between the layers were found (Fig. 1B).

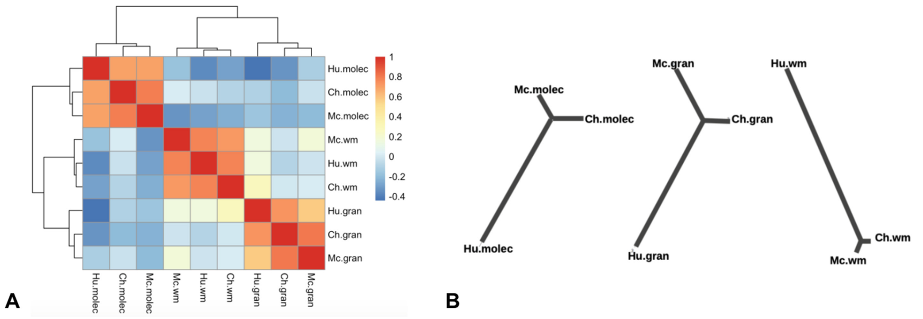

Fig. 2. Cerebellar brain lipidome evolution: **A** - heatmap based on 279 peaks, showing layer-specific distribution in at least one species. Colour represents Spearman correlation coefficient; **B** - evolutionary distances between cerebellar structures of human, chimp and macaque. Abbreviations: Hu - human, Ch - chimpanzee, Mc - macaque; wm - white matter, gran - granule layer, molec - molecular layer of cerebellum.

4 Discussion

Spatial distribution of 1733 ions was influenced by cerebellum cytoarchitecture in human, chimpanzee and macaque. We demonstrated that white matter, granule and molecular layers had distinct lipid profiles, and human white matter lipids had unique features compared to chimpanzees and macaques.

Lipidome composition of cerebellum layers was generally conserved inside one species, but differed among primates. The distance between structures was in good accordance with the genetic distances between chosen primate species. Our results were also consistent with the data from human and primate brain lipids measurement of tissue homogenates [8].

Analysis of evolutionary differences between the cerebellum layers revealed several unexpected results. Only a minor distance was observed between lipid profiles of the white matter in chimpanzees and macaques, in contrast to a significant distance seen between these two species and the human in the white matter. This fact completely agrees with the significant changes in oligodendrogenesis and myelination during human brain evolution [11]. The largest difference between chimp and macaque was demonstrated in the lipidome of the cerebellar granule layer. The evolutionary distances between granular and molecular layers' lipid profiles in human and nonhuman primates were similar.

Thus, the primate cerebellum has undergone heterogeneous changes in the course of evolution on the level of lipid composition. Lipid annotation would shed more light on the functional significance of the revealed lipidome changes.

Appendix

Table 1. Sample information

№	Sample ID	Species	Sex	Age
1	HG	*Homo sapiens*	m	54
2	HA	*Homo sapiens*	m	62
3	HF	*Homo sapiens*	f	63
4	Reba	*Pan troglodytes*	f	45
5	Japie	*Pan troglodytes*	m	12
6	Herman	*Pan troglodytes*	f	12
7	90049	*Macaca mulatta*	m	17
8	88099	*Macaca mulatta*	m	26
9	89321	*Macaca mulatta*	m	25

References

1. Piomelli, D., Astarita, G., Rapaka, R.: A neuroscientist's guide to lipidomics. Nat. Rev. Neurosci. **8**(10), 743–54 (2007). https://doi.org/10.1038/nrn2233
2. Bray, N.: Cerebellum: the little learning brain. Nat. Rev. Neurosci. **18**, 263 (2017). https://doi.org/10.1038/nrn.2017.47
3. Keefe, M., Nowakowski, T.: Evolutionary expansion of human cerebellar germinal zones. Trends Neurosci. **43**, 75–77 (2020). https://doi.org/10.1016/j.tins.2019.12.005
4. Harayama, T., Riezman, H.: Understanding the diversity of membrane lipid composition. Nat. Rev. Mol. Cell Biol. **19**, 281–296 (2018). https://doi.org/10.1038/nrm.2017.138
5. Rohrbough, J., Broadie, K.: Lipid regulation of the synaptic vesicle cycle. Nat. Rev. Neurosci. **6**(2), 139–50 (2005). https://doi.org/10.1038/nrn1608
6. van Deijk, A., Camargo, N., Timmerman, J., Heistek, T., Brouwers, J., Mogavero, F., Mansvelder, H., Smit, A., Verheijen, M.: Astrocyte lipid metabolism is critical for synapse development and function in vivo. Glia **654**, 670–682 (2017). https://doi.org/10.1002/glia.23120
7. Moine, H., Vitale, N.: Of local translation control and lipid signaling in neurons. Adv. Biol. Regu. **71**, 194–205 (2019). https://doi.org/10.1016/j.jbior.2018.09.005

8. Bozek, L., Wei, Y., Yan, Z., Liu, X., Xiong, J., Sugimoto, M., Tomita, M., Pääbo, S., Sherwood, C., Hof, P.: Organization and evolution of brain lipidome revealed by large-scale analysis of human, chimpanzee, macaque, and mouse tissues. Neuron **85**, 695–702 (2015). https://doi.org/10.1016/j.neuron.2015.01.003
9. Belov, M., Ellis, S., Dilillo, M., Paine, M., Danielson, W., Anderson, G., de Graaf, E., Eijkel, G., Heeren, R., McDonnell, L.: Design and performance of a novel interface for combined matrix-assisted laser desorption ionization at elevated pressure and electrospray ionization with orbitrap mass spectrometry. Anal. Chem. **89**, 7493–7501 (2017). https://doi.org/10.1021/acs.analchem.7b01168
10. Kim, K., Adelstein, R., Kawamoto, S.: Identification of neuronal nuclei(neun) as fox-3, a new member of the fox-1 gene family of splicing factors. J. Biol. Chem. **284**, 31052–31061 (2008). https://doi.org/10.1074/jbc.M109.052969
11. Sherman, D., Peter, J.: Mechanisms of axon ensheathment and myelin growth. Nat. Rev. Neurosci. **6**, 683–690 (2015). https://doi.org/10.1038/nrn1743

Brown Rats May Learn Awareness of Their Body Weight When Interacting with Environmental Objects

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Abstract. Studies of the ability of animals to take into account the limits of their bodies when penetrating into various holes and openings are a well-developed direction of research in body awareness. Here we studied the ability of brown rats (*Rattus norvegicus*) to take into account their body weight. To solve the experimental problem, the animals had to correlate their body weight with the strength of the support along which they moved. It was found that 8 out of 25 rats were able to solve this problem. During the experiment, the rodents demonstrated characteristic "testing movements", during which, we believe, they correlated their own weight with the characteristics of external objects. We consider these results to be a demonstration of the awareness of their weight in rats as one of the body-awareness modules.

Keywords: Brown rats · Self-awareness · Body-awareness · Body weight awareness · Mirror self-recognition

1 Introduction

1.1 Body-Awareness Studies

The study of the evolutionary prerequisites for self-awareness (discriminating between the self as a subject and the environment) is one among the main directions of modern comparative psychology and cognitive ethology based on several methodological approaches simultaneously [1]. At the moment, the point of view is being developed, according to which self-awareness is a modular phenomenon, and each module develops independently in phylogeny [2].

One of the essential components of self-awareness is body-awareness, the ability of animals to take into account the physical parameters of their body in relation to environmental objects [3–6]. In recent years, this phenomenon has been actively explored as an alternative to classical mirror self-recognition [7].

In a 2017 study [8], Asian elephants *Elephas maximus* were to step on a mat and pick up a stick attached to it with a rope, and then pass the stick over to the experimenter. To do this, the elephants had to recognize their body as an obstacle to successful action

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and first step off the mat before trying to pass over the stick. The testing elephants left the mat significantly more often than in the control group, where it was unnecessary to step off the mat.

A similar study was conducted on children aged 18 to 24 months [3]. The authors used several techniques to study the children's awareness of their bodies. One problem was when the child had to choose the right one of two holes in the door (penetrable and impenetrable for his body) in order to reach the parent on the other side. Another was a problem with a stroller, when the child had to realize that his own body standing on a rug was an obstacle to the movement of the stroller, to which the rug was attached. In the third task, the child had to get off the rug in order to hand it over to the experimenter. On average, children of different ages made 2.5 mistakes while solving these problems.

1.2 Awareness of Body Limits as a Manifestation of Body-Awareness

Since 2004 we have been studying body-awareness in various animal species [5]. In the experimental setup, the animals solved the problem that required correlating the limits of their body with the size of the holes to penetrate into the goal compartment. The independent variables in the experiments were the limits of the body and the limits of environmental objects (the diameter of the holes in the walls of compartments). The body limits of animals were enlarged in several ways. In snakes, this was achieved by letting them swallow food items of various sizes [5]. In other animals, this was achieved by attaching various objects to their bodies by gluing (e.g. cockroaches) [9], or by putting on a blanket (toads) [10], or by mounting an object on the skull (rats) [11]. Experimental results show that animals of all studied species were able to form the skill of taking into account both natural and enlarged limits of their body, but differ in the speed of formation of this skill and the flexibility of its transformation.

1.3 Awareness of Body Weight as a Manifestation of Body-Awareness

Thus, most studies of the phenomenon of body-awareness conducted in recent years on animals and humans focus on studying the ability of subjects to take into account the physical limits of their bodies. In the recent study, we attempted to explore one other aspect of body-awareness, i.e. the awareness of the body weight.

The aim of this study was the ability of brown rats to take into account their body weight to assess the strength of a support along which they moved. In this case, we consider the awareness of the animal's weight as one of the modules of the complex phenomenon of body-awareness, necessary for the coordination of their interaction with environmental objects. Thus, we investigated the same phenomenon that was studied earlier on elephants, although we used a different technique.

2 Method

2.1 Ethic Statement

All procedures performed in this study were conducted in compliance with the approval of the Ethics Committee of the Moscow Institute of Psychoanalysis, No. 2, September 25, 2019.

2.2 Experimental Design

The experimental setup was a glass box without a ceiling (1000 × 950 mm^2, height 500 mm). Inside the box, on its opposite sides, parallel to the bottom at a height of 300 mm, there were two shelves occupying the entire width of the box and each 320 mm long. The shelves were connected with three parallel bridges (50 mm wide each). Two bridges were located along the sides, 200 mm off the walls of the box, the central one 200 mm from each of the side bridges (see Fig. 1). The bridges were attached to a single metal rod, located exactly in the mid-length, and could be fixed in different positions:

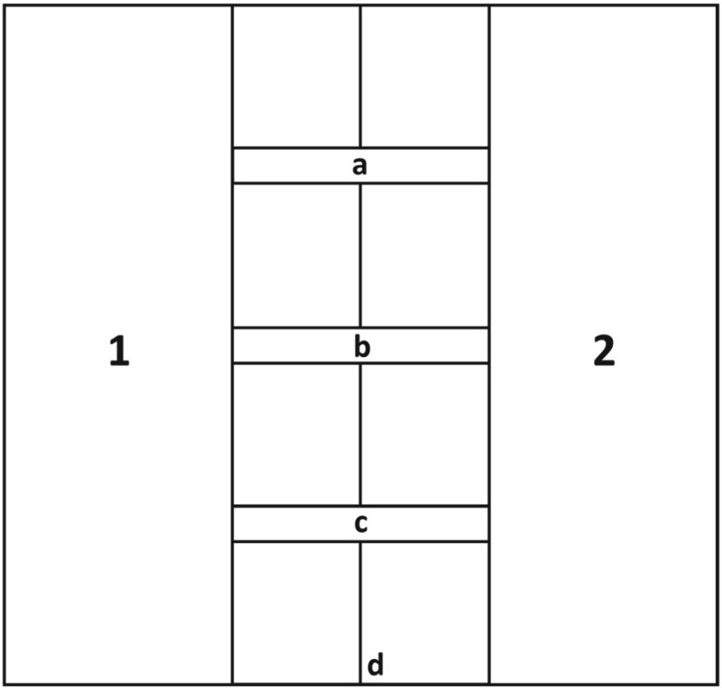

Fig. 1. Experimental setup (top view): 1 - shelf no.1; 2 - shelf no.2; a, b, c – bridges; d - bridge fastening rod.

- Loose position: The bridges, when balanced, were parallel to the bottom, connecting both shelves, so that light pressure on one edge made the bridge move vertically.
- Fixed position: the bridges were additionally attached to the shelves with latches so that pressing them did not entail displacement.

The experiment comprised two series: introductory and experimental. At the beginning of each testing, the rat was placed in the center of one of the shelves inside the experimental setup (shelf no.1). In the center of the opposite shelf (shelf no.2) there was a bait (cheese). The testing was considered completed either after the rat, having passed one of the bridges to shelf no.2, reached the bait, or when the rat fell from the bridge, which was in a loose position, or if the rat did not attempt to pass over any bridges. Trials of all series were carried out sequentially with each animal. The time interval between the trials was 5 min.

The introductory series consisted of 27 trials. All bridges were in a fixed position. Objectives were to form the skill of reaching the bait and to reveal individual preferences of a certain bridge.

The experimental series. In each trial, only 1 of 3 bridges was in a fixed position; the location of this bridge varied quasi-randomly. The objective of this series was to form the skill of choosing a suitable bridge for passing the rats. The series continued either until the rat reached the learning criterion, 9 successful passes in a row without falling ($p < 0.001$, binomial testing), or after a total of 36 trials.

Indicators:

- Number of successful passes over the fixed bridge from shelf no.1 to shelf no.2.
- Number of falls from fixed bridges.
- Number of testing movements. By “testing movements” we understood the behavior of a rat when it placed all 4 paws on shelf no.1 and directed the muzzle toward the bridge, sniffing it and feeling it with vibrissae, then pressed the bridge with one of the front paws and acted depending on the result. If the bridge was fixed, the rat crossed it to shelf no.2. If the bridge was not fixed, the testing movements led to some displacement of the bridge under the pressure of the paw. Then the rat moved to another bridge and also examined it until it found a fixed one. The described testing movements were discovered in some rats, starting from the second trial of the experimental series.

2.3 Subjects

25 naive male rats *Rattus norvegicus* aged 2 to 6 months. From the beginning to the end of the experiment the animals were kept in individual cages.

2.4 Data Processing and Analysis

The behavior of rats in the experimental set up was registered using a Panasonic HC-VX980 video camera.

Statistical analysis was performed using Pearson’s chi-squared test (χ^2) (StatSoft© Statistica 8).

3 Results

The introductory series. All rats successfully reached the bait going from shelf no.1 to shelf no.2, in all trials. All rats showed an individual preference for the central bridge (27 trials each), the χ^2 testing ($df = 2$, $p < 0.01$). In total, the rats crossed one side bridge 77 times, another side bridge 89, the central bridge 509 times ($\chi^2 = 241.3$; $df = 2$; $p < 0.001$).

According to the results of the series, the rats split into 3 groups.

- Group 1: 8 individuals reached the training criterion. The rats allowed 2 to 5 falls ($S = 3.5$; $SD = 0.9$). These rats demonstrated testing movements after several falls, starting from the 2nd trial. On average, each rat performed from 1 to 3 testing movements per trial.
- Group 2: 5 individuals that did not reach the training criterion after 36 trials. The rats allowed 13 to 19 falls ($S = 16.2$; $SD = 2.6$). On average, a rat fell every second or third trial. No testing movements were observed in this group.
- Group 3: 12 individuals that after 2 to 3 falls ($S = 2.3$; $SD = 0.5$) did not attempt to cross the bridge and stayed on shelf no.1. After the falls, being placed in subsequent trials on shelf no.1, the rats either did not approach the bridges, or approached them, made testing movements, but did not go further.

In total, for all trials of the experimental series, the group 1 rats allowed 26 falls and made 137 testing movements; the group 2 rats allowed 81 falls and performed no testing movements. Thus, rats from group 1 made significantly fewer falls and significantly more testing movements ($\chi^2 = 155.2$; $df = 1$; $p < 0.001$).

4 Discussion

We believe that in the introductory series, the preference of all rats for the central bridge is explained by the fact that it allowed the shortest path to the bait. This factor is secondary; however, it was excluded by the quasi-random position of the fixed bridge in the second series. For the animals of the third group, the falls were most likely a strong distress, and therefore they did not dare to make further attempts to cross the bridges. This is probably a specific feature of their nervous system. Meanwhile, basing on the results of 8 individuals (group 1) we can state that the brown rat is able to take into account its body weight when interacting with environmental objects. We believe that it was in the course of the revealed “testing movements” that the rats carried out a comparison of their own body weight with the strength of the support (fixed or non-fixed bridge). The fact that the group 1 rats performing the testing movements made significantly fewer falls than the group 2 rats, which did not perform such movements, testifies to the effectiveness of this way of correlating the weight with the strength of the support.

At the same time, for the group 1 rats in this study their body was at first an obstacle to solving the problem (same as in early experiments with elephants [8], rats [11] and children [3]), but then they began to use it in as a prototype tool for the selection of a suitable bridge. Thus, we think, we have demonstrated a possibility of experimental revealing the awareness of their weight in rats, which can be considered as one of the modules of body-awareness and self-awareness [1, 2].

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Gallup Jr., G.G., Anderson, J.R.: Self-recognition in animals: where do we stand 50 years later? Lessons from cleaner wrasse and other species. Psychol. Conscious. Theor. Res. Pract. **7**(1), 46–58 (2020)
2. De Waal, F.B.M.: Fish, mirrors, and a gradualist perspective on self-awareness. PLoS Biol. **17**(2), e3000112 (2019). https://doi.org/10.1371/journal.pbio.3000112
3. Brownell, C.F., Zerwas, S., Ramani, G.B.: "So Big": the development of body self-awareness in toddlers. Child Dev. **78**(5), 1426–1440 (2007)
4. Maeda, T., Fujita, K.: Do dogs (*Canis familiaris*) recognize their own body size? In: Proceedings of the 2nd Canine Science Forum, Vienna, Austria, pp. 25–28, July 2010
5. Khvatov, I.A., Sokolov, A.Yu., Kharitonov, A.N.: Snakes elaphe radiata may acquire awareness of their body limits when trying to hide in a shelter. Behav. Sci. **9**, 67 (2019). https://doi.org/10.3390/bs9070067
6. Lenkei, R., Faragó, T., Kovács, D., Zsilák, B., Pongrácz, P.: That dog won't fit: body size awareness in dogs. Anim. Cognition. **23**, 337–350 (2020)
7. Gallup Jr., G.G.: Chimpanzees: self recognition. Science **167**(3914), 86–87 (1970). https://doi.org/10.1126/science.167.3914.86
8. Dale, R., Plotnik, J.M.: Elephants know when their bodies are obstacles to success in a novel transfer task. Sci. Rep. **7**, 46309 (2017)
9. Khvatov, I.A.: Spetsifika samootrazheniya u vida Periplaneta americana. (Specificity of self-reflection in the species Periplaneta americana). Eksperimental'naya Psikhologiya **4**(1), 28–39 (2011)
10. Khvatov, I.A., Zhelankin, R.V.: Osobennosti naucheniya zhab Bufo viridis v povedenii, trebuyushchem ucheta granits sobstvennogo tela (Features of learning toad Bufo viridis in behavior that requires consideration of the limits of their own body). Eksperimental'naya Psikhologiya **11**(4), 5–16 (2018). https://doi.org/10.17759/exppsy.2018110401
11. Khvatov, I.A., Sokolov, A.Yu., Kharitonov, A.N., Kulichenkova, K.N.: Skhema sobstvennogo tela u gryzunov (na primere krys Rattus norvegicus) (Scheme of own body in rodents (on the example of rats Rattus norvegicus)). Eksperimental'naya Psikhologiya **9**(1), 112–130 (2016). https://doi.org/10.17759/exppsy.2016090109

Effects of Perineural Stem Cell Implantation on Motor Activity and Content of NO and Copper in the Olfactory System After Brain Ischemia

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Abstract. It was shown by electron paramagnetic resonance (EPR) spectroscopy that one day after bilateral occlusion of the common carotid arteries (to simulate ischemia) in Wistar rats (group 1, $n = 15$) under ketamine-xylazine-acepromazine anesthesia (55.6, 5.5, 1.1 mg/kg, respectively, intraperitoneally), the content of nitric monoxide (NO) in the olfactory bulbs decreased, and recovered after two days. A similar trend was observed in Wistar rats (group 2, $n = 15$), which, simultaneously with ischemia modeling, were implanted intranasally with mesenchymal stem cells (MSCs). An intact group of rats (group 3, $n = 15$) was kept in the usual conditions of the vivarium and did not undergo surgical interventions. The content of copper in the olfactory bulbs of rats (for assessing the activity of superoxide dismutases 1 and 3) after ischemia modeling (group 1) tended to increase and maintain the increase for two days of observation. Intranasal administration of MSCs during the ischemia modeling was accompanied by a more significant increase in copper content on the first day after brain ischemia modeling, but after two days, a tendency towards restoration of the initial copper level was noted.

Intranasal administrating of MSC simultaneously with ischemia modeling (group 2) was accompanied by a more rapid recovery of orientational-motor activity in experimental animals compared to rats in which only modeling of ischemic stroke was performed (group 1).

Keywords: Ischemic stroke · Nitric oxide · Copper · Electron paramagnetic resonance · Mesenchymal stem cells · Olfactory bulb

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1 Introduction

The pathogenesis of cerebral ischemia is constantly being supplemented by new hypotheses [1–3], including the rationale for the choice of clinical tactics in violation of cerebral blood supply in patients with COVID-19 [4]. These hypotheses concern problems of metabolism and imbalance of neurotransmitters, active transport of ions across membranes and an increase in the level of ionized calcium in neurons. The mechanisms of neuronal damage are diverse and are caused, including paradoxically, by the neurotoxicity of the signaling molecule glutamate, in the development of which nitric monoxide (NO) plays a key role [5–7]. NO is a highly chemically reactive free radical, which can act as an oxidizing agent as well as a reducing agent [8]. The regulatory role of NO has been shown in the nervous, cardiovascular, and other systems [6, 9–11]. The main components of the NO cycle are NO-synthase and nitrite reductase enzymatic systems [7, 9, 10, 12, 13]. During hypoxia as a result of the activation of the enzymatic and non-enzymatic systems participating in the formation of NO from NO_2 ions, the NO cycle is activated and NO is produced from L-arginine. Mild and moderate hypoxia are factors that drive metabolic and reparative processes in the body [7, 12–14]. In this case, the NO cycle is activated, followed by an increase in the NO content and the activation of many bodily enzyme systems that are involved in the synthesis of ATP and other intra- and extracellular processes [7, 12, 13, 15]. This positive phenomenon at the pheno- and genotypic level has been studied in detail when observing long-livers in mountainous regions.

In the neurodestructive processes of various etiologies, including severe cerebral ischemia, deficiency of regulatory neurotransmitter mechanisms is revealed. It is important that in addition to neurotransmitter mechanisms, endogenous stem cells (SCs) of the brain are activated [15–17]. SCs are grouped mainly in three areas of the brain—the olfactory bulb, hippocampus, and the lateral ventricle region of the brain [15–17]. Unfortunately, clinical practice demonstrates insufficient effectiveness of endogenous preventive and reparative processes in the brain during the development of cerebral ischemia of various etiologies. In this regard, attempts are systematically made to decipher the complex features of the recovery processes in the brain when modeling ischemia.

Until now, research work has not yet proposed radical therapeutic technologies that significantly improve the classical methods of treating patients with cerebral ischemia [18]. This situation was one of the incentives for the study, the results of which are presented in this article. Thus, the aim of the study was to clarify the reparative potential of perineurally administered MSCs to activate recovery processes in ischemic brain regions, as well as to specify, under these conditions, the functional interaction of MSCs with NO-synthase and nitrite reductase enzymatic systems of the brain in the process of optimizing the synthesis of ATP and other intra- and extracellular processes during hypoxia.

2 Materials and Methods

2.1 Experimental Animals and Behavioral Experiments

In male Wistar rats weighing 240–260 g (group 1, n = 15), ligation of common carotid arteries was performed using sterile silk thread under ketamine-xylazine-acepromazine anesthesia (55.6, 5.5, 1.1 mg/kg, respectively, intraperitoneally). The technique is distinguished by high demonstrativeness and reliability (data were selected at $p \leq 0.01$) and is widely used for modeling cerebral ischemia [19–21]. In the second group ($n = 15$), mesenchymal stem cells (MSCs) were implanted intranasally in male Wistar rats weighing 240–260 g simultaneously with bilateral occlusion of the common carotid arteries under anesthesia. An intact group of rats (group 3, $n = 15$) was kept in the usual conditions of the vivarium and did not undergo surgical interventions. Parameters of orientational motor activity of all rats were assessed within five minutes in an elevated cruciform maze before ligation and in the first, second, and seventh days after surgery. Using a Logitech Webcam 905 video camera (Logitech, China), the average movement speed, general mobility, and motor activity of rats in the open and closed sections of the maze, verticalization, and grooming were recorded. The data obtained were evaluated using the ANY-Maze software package. Program version 4.82, serial number: DBUT-VNJJ-JD8S-SFGU; license number: PK8W-NBWV-HTHT-BYHB dated 02.28.2013 (Stoelting Inc., USA).

2.2 Formation of a NO Complex with a Spin Trap

For the quantitative determination of NO and Cu in the brain, we used the method of electron paramagnetic resonance - EPR [6, 22]. This method is based on the reaction of a radical (in this case, NO) with a spin trap, which is the Fe^{2+} complex with diethyldithiocarbamate (DETC), which captures NO to form a stable ternary complex $(DETC)_2$-Fe^{2+}-NO in various animal tissues. These complexes are characterized by an easily recognizable EPR spectrum with a g-factor $g = 2.035$–2.040 and a triplet hyperfine structure. The EPR spectra were measured using the spin trap technique [23, 24]. Spin trap components: DETC-Na were injected intraperitoneally and a mixture of solutions (iron sulfate and sodium citrate) prepared immediately before administration, was injected subcutaneously into three points - the right and left thighs and the rostral part of the interscapular region [25]. Iron citrate is formed in a mixture of iron sulfate and sodium citrate. DETC-Na and iron citrate are distributed throughout the body and upon interaction form a water-insoluble DETC-Fe^{2+} complex, that is capable of interacting with NO to form a stable radical $(DETC)_2$-Fe^{2+}-NO, which can be detected by EPR spectroscopy. The complex of spin trap with NO $(DETC)_2$-Fe^{2+}-NO is characterized by an easily recognizable EPR spectrum with a g-factor $g = 2.038$ and a triplet hyperfine structure. In addition, the spin trap interacts with Cu, forming the Cu $(DETC)_2$ complex, which can also be detected by EPR spectroscopy [26].

2.3 Measurements of NO and Cu

EPR measurements were carried out using a Brucker EMX/plus EPR spectrometer in the X range (9.50 GHz) with a magnetic field modulation of 100 kHz, a modulation amplitude of 2 Gs, a microwave power of 30 mW, a time constant of 200 ms, and a temperature of 77 K in a Brucker finger Dewar. Tissue samples were delivered from Minsk to Kazan in a container with dry ice after freezing in liquid nitrogen. The sample weight was 100 mg. The amplitude of the EPR spectra was always normalized in proportion to the mass of the sample and the amplitude of the EPR signal of the reference sample [6].

2.4 Data Analyses

The results are shown as mean ± SEM. The paired and unpaired Student's t-test and Signed Rank test were used for comparison within each experimental group. The statistical software SigmaStat32 was used. The statistical significance criterion was $p < 0.05$.

3 Results

3.1 Behavior of Rats After Brain Ischemia

It was found that on the second day after the occlusion of the common carotid arteries (modeling of cerebral ischemia), in comparison with the initial values in the rats of group 1, which were not injected with MSCs, decreases in the total distance traveled (three times), distance covered in a closed area (twice), number of episodes of mobility (twice), number and duration of acts of verticalization (twice), total distance covered in the closed area (twice), average speed of movement in the closed area (twice), and total time of mobility in the closed area (three times) were observed. Also, there were no visits to the open areas of the labyrinth. A similar picture in the animals of group 1 was also observed on the seventh day after surgery. This pattern of animal behavior reflects a decrease in orientational motor activity in laboratory animals after the modeling of cerebral ischemia in comparison with the preoperative period and animals of group 3 (intact). These changes persist both during the initial observation period after modeling of cerebral ischemia (first-second days) and during a more distant period (until the seventh day) after modeling ischemic stroke.

3.2 Behavior of Rats After Brain Ischemia and Administration of MSCs

A different pattern of behavior was observed in the group of animals that underwent modeling of cerebral ischemia and received MSCs intranasally (group 2). On the second and seventh days after modeling of cerebral ischemia and intranasal administration of MSCs in the animals of group 2, in comparison with the initial values and with the data of group 3, no significant differences were observed in the pattern of orientational motor activity in the elevated cruciform maze. Thus, the administration of MSCs in the acute period after the modeling of cerebral ischemia is accompanied by a more rapid recovery of orientational-motor activity in the experimental animals. The data obtained are an additional argument in favor of the experimental substantiation of the use of cellular technologies during the rehabilitation period in patients after ischemic stroke.

3.3 Migration of MSCs After Its Intranasal Perineural Administration

The next stage of the study was to investigate the features of migration of MSCs after 24 h, two and seven days after the intranasal perineural administration of MSCs to the experimental rats. The migration of MSCs in the brain after 24 h was studied using the specific marker MSCs CD90 and FITC, while the specific marker MSCs CD90 + PKH67 were used after two and seven days after modeling the brain ischemia. Horizontal sections of the brain (thickness 8 μm) for microscopic examination were obtained using a Microm HM525 cryostat (Microm International GmbH, Germany). The preparations were immediately examined after their preparation using a fluorescence microscope at the B.I. Stepanov Institute of Physics of the National Academy of Sciences of Belarus (Zeiss AxioVert 200M inverted research, camera: Zeiss AxioCam HRm, lens: Plan-Neofluar 40x/0.75, Plan-Neofluar 20x/0.75 or Plan-Neofluar 10x/0.75). In the rats of the first and second groups, migration of MSCs labeled with a fluorescent dye into the cerebral cortex and subcortical regions of the brain was observed. The brainstem contained single fluorescent MSC, which presumably reflects the fact that blood flow is preserved in the vertebrobasilar region of the vascular bed due to intact vertebral arteries. Preservation of blood supply to the brainstem structures under model experimental conditions is a condition for the functioning of the neural and glial structures of the brainstem. It has been demonstrated [27] that MSCs migrate mainly to damaged areas of the nervous tissue and, therefore, the main migration of stem cells is directed to the cortical regions of the brain, which are supplied with blood from the region of clipped carotid arteries.

3.4 NO and Cu Content After Brain Ischemia and MSCs Intranasal Perineural Administration

Measurements of the intensity of NO production by EPR spectroscopy were performed using the spin trap technique [6, 22]. The components of the spin trap were injected 30 min before the extraction of the studied tissues. As a result, the complex DETC-Fe^{2+} is formed, which forms a stable radical $(DETC)_2$-Fe^{2+}-NO with NO (Fig. 1). This $(DETC)_2$-Fe^{2+}-NO complex is characterized by an easily recognizable EPR spectrum with a g-factor $g = 2.038$ and a triplet hyperfine structure. Moreover, the spin trap interacts with Cu, forming the Cu $(DETC)_2$- complex, which can also be detected by EPR spectroscopy. Decreased content of NO in the olfactory bulb of the rat brain was found one and two days after the modeling of ischemia caused by the occlusion of the common carotid arteries. The level of NO production in rats, in which ischemia was simulated along with simultaneous intranasal administration of MSCs, was also reduced after one and two days of simulating ischemia compared with group No. 3 of intact animals (Fig. 2). There was no significant difference in the content of NO in rats, in which ischemia was simulated with simultaneous intranasal administration of MSCs, relative to ischemic rats.

The signals from the olfactory bulb.

The temperature is 77 °K. The rats were injected with (DETC)-Fe^{2+} - citrate. $g_{cp} = 2.038$.

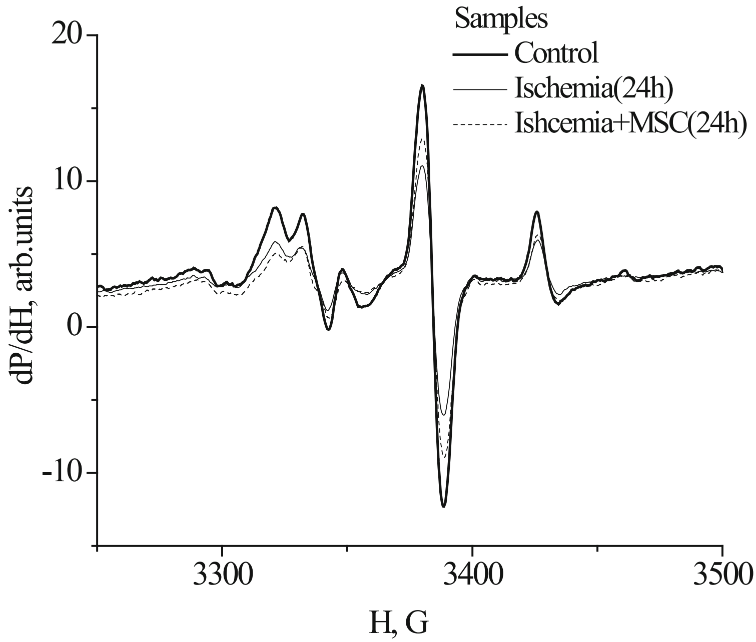

Fig. 1. EPR spectra of olfactory bulb: a) of healthy rat, b) of rat after modeling of ischemia, c) of rat after modeling of ischemia with simultaneously intranasal administration of MSC.

The signals from complex $(DETC)_2$-Fe^{2+}-NO.

The temperature is 77 °K. The rats were injected with (DETC)-Fe^{2+} - citrate. $g_{cp} = 2.038$.

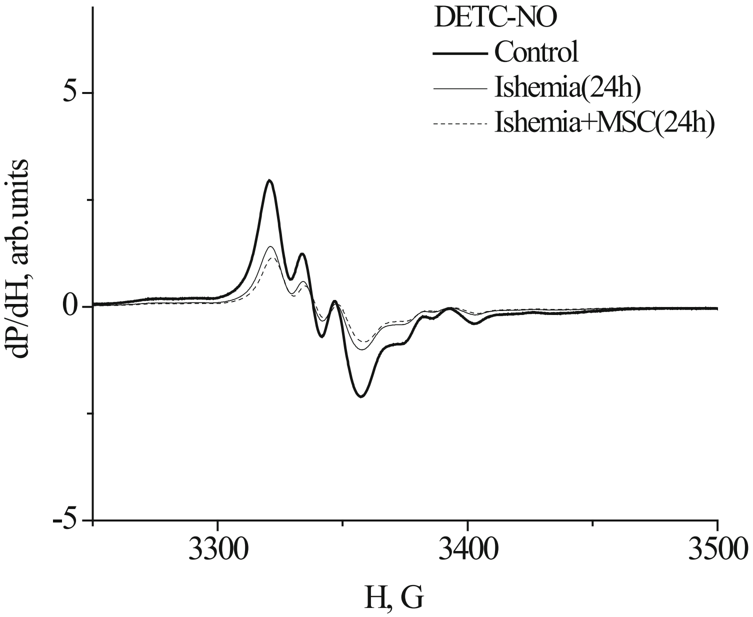

Fig. 2. EPR spectra of olfactory bulb: a) of healthy rat, b) of rat after modeling of ischemia, c) of rat after modeling of ischemia with simultaneously intranasal administration of MSC.

The signals from complex $Cu(DETC)_2$.

The temperature is 77 °K. The rats were injected with $(DETC)\text{-}Fe^{2+}$ - citrate. $g_{cp} = 2.038$.

The copper content, which corresponds to the level of superoxide dismutases 1 and 3, in the olfactory bulb of the rat tended to increase after simulating ischemia by ligation of the carotid arteries and persisted for two days of observation. Intranasal administration of MSCs was accompanied by a significant increase in the Cu content one day after modeling ischemia, and by a decrease in its content two days later (Fig. 3).

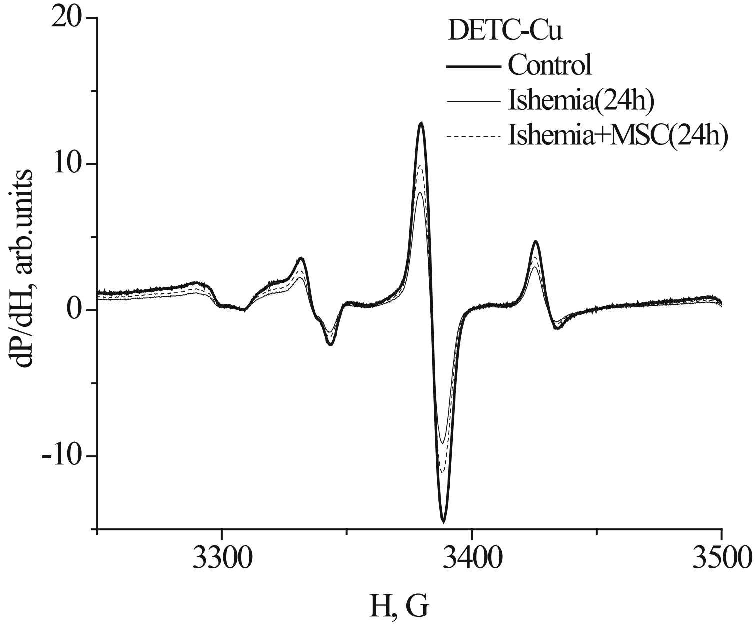

Fig. 3. EPR spectra of olfactory bulb: a) of healthy rat, b) of rat after modeling of ischemia, c) of rat after modeling of ischemia with simultaneously intranasal administration of MSC.

4 Discussion

The data obtained reflect to a certain extent the known fact about the dependence of NO mechanisms of action on the amount of this neurotransmitter in ischemic tissues. In relatively small amounts, NO plays a regulatory role, whereas in excess amounts it has dysregulatory function and may even exhibit toxic effects. Under these circumstance, optimal conditions are formed for the manifestation of the reparative effects of MSCs.

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Conflicts of Interest. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Foreman, B.: The pathophysiology of delayed cerebral ischemia. J. Clin. Neurophysiol. **33**(3), 174–182 (2016). https://doi.org/10.1097/WNP.0000000000000273
2. Campbell, B.C.V., Khatri, P.: Stroke. Lancet **396**(10244), 129–142 (2020). https://doi.org/10.1016/S0140-6736(20)31179-X
3. Jensen, M., Thomalla, G.: Causes and secondary prevention of acute ischemic stroke in adults. Hamostaseologie **40**(1), 22–30 (2020). https://doi.org/10.1055/s-0039-1700502
4. Koralnik, I.J., Tyler, K.L.: COVID-19: a global threat to the nervous system. Ann. Neurol. **88**(1), 1–11 (2020). https://doi.org/10.1002/ana.25807
5. Wu, W.C., Chai, C.Y.: Nitric oxide release in the nucleus tractus solitarius during and after bilateral common carotid artery occlusion. Clin. Exp. Pharmacol. Physiol. **31**(3), 152–158 (2004). https://doi.org/10.1111/j.1440-1681.2004.03967.x
6. Gainutdinov, K., Gavrilova, S.A., Iyudin, V.S., Golubeva, A.V., Davydova, M.P., Jafarova, G.G., Andrianov, V.V., Koshelev, V.B.: EPR study of the intensity of the nitric oxide production in rat brain after ischemic stroke. Appl. Magn. Reson. **40**, 267–278 (2011)
7. Terpolilli, N.A., Moskowitz, M.A., Plesnila, N.: Nitric oxide: considerations for the treatment of ischemic stroke. J. Cereb. Blood Flow Metab. **32**, 1332–1346 (2012). https://doi.org/10.1038/jcbfm.2012.12
8. Vanin, A.F.: Dinitrosyl iron complexes with thiol-containing ligands as a “working form” of endogenous nitric oxide. Nitric Oxide **54**, 15–29 (2016). https://doi.org/10.1016/j.niox.2016.01.006
9. Steinert, J.R., Chernova, T., Forsythe, I.D.: Nitric oxide signaling in brain function, dysfunction, and dementia. Neuroscientist **16**, 435–452 (2010). https://doi.org/10.1177/1073858410366481
10. Reutov, V.P., Okhotin, V.E., Shuklin, A.V., Sorokina, E.G., Kosicin, N.S., Gurin, V.N.: Nitric oxide and cycle in miocarde: molecular, biochemical and physiological aspects. Uspehi fiziologicheskih nauk **38**, 39–58 (2007). (in Russian)
11. Deryagin, O.G., Gavrilova, S.A., Gainutdinov, K., Golubeva, A.V., Andrianov, V.V., Yafarova, G.G., Buravkov, S.V., Koshelev, V.B.: Molecular bases of brain preconditioning. Front. Neurosci. **11**, 427 (2017). https://doi.org/10.3389/fnins.2017.00427
12. D’yakonova, T.L., Reutov, V.P.: The effects of nitrite on the excitability of brain neurons in the common snail. Neurosci. Behav. Physiol. **30**(2), 179–186 (2000). https://doi.org/10.1007/BF02463156
13. Bolanos, J.P., Almeida, A.: Roles of nitric oxide in brain hypoxia-ischemia. Biochim. Biophys. Acta. **1411**, 415–436 (1999)
14. Manukhina, E.B., Malyshev, I.Y., Smirin, B.V., Mashina, S.Y., Saltykova, V.A., Vanin, A.F.: Production and storage of nitric oxide in adaptation to hypoxia. Nitric Oxide **3**, 393–401 (1999). https://doi.org/10.1006/niox.1999.0244
15. Barthels, D., Das, H.: Current advances in ischemic stroke research and therapies. Biochim Biophys. Acta Mol. Basis Dis. **1866**(4), 165260 (2020). https://doi.org/10.1016/j.bbadis.2018.09.012
16. Li, C., Fei, K., Tian, F., Gao, C., Yang, S.: Adipose-derived mesenchymal stem cells attenuate ischemic brain injuries in rats by modulating miR-21-3p/MAT2B signaling transduction. Croat. Med. J. **60**(5), 439–448 (2019). https://doi.org/10.3325/cmj.2019.60.439
17. Sakai, S., Shichita, T.: Inflammation and neural repair after ischemic brain injury. Neurochem. Int. **130**, 104316 (2019). https://doi.org/10.1016/j.neuint.2018.10.013

18. Lapergue, B., Labreuche, J., Blanc, R., Barreau, X., Berge, J., Consoli, A., Rodesch, G., Saleme, S., Costalat, V., Bracard, S., Desal, H., Duhamel, A., Baffert, S., Mazighi, M., Gory, B., Turjman, F., Piotin, M.: First-line use of contact aspiration for thrombectomy versus a stent retriever for recanalization in acute cerebral infarction: the randomized ASTER study protocol. Int. J. Stroke **13**(1), 87–95 (2018). https://doi.org/10.1177/1747493017711948
19. Huang, Y., Fan, S., Li, J., Wang, Y.-L.: Bilateral common carotid artery occlusion in the rat as a model of retinal ischaemia. Neuroophthalmology **38**(4), 180–188 (2014). https://doi.org/10.3109/01658107.2014.908928
20. Farkas, E., Luiten, P.G.M., Bari, F.: Permanent, bilateral common carotid artery occlusion in the rat: a model for chronic cerebral hypoperfusion-related neurodegenerative diseases. Brain Res. Rev. **54**(1), 162–180 (2007). https://doi.org/10.1016/j.brainresrev.2007.01.003
21. De la Torre, J.C., Aliev, G.: Inhibition of vascular nitric oxide after rat chronic brain hypoperfusion: spatial memory and immunocytochemical changes. J. Cereb. Blood Flow Metab. **25**(6), 663–672 (2005). https://doi.org/10.1038/sj.jcbfm.9600057
22. Vanin, A.F., Huisman, A., Van Faassen, E.E.: Iron dithiocarbamate as spin trap for nitric oxide detection: pitfalls and successes. Meth. Enzymol. **359**, 27–42 (2003). https://doi.org/10.1016/S0076-6879(02)59169-2
23. Mikoyan, V.D., Kubrina, L.N., Serezhenkov, V.A., Stukan, R.A., Vanin, A.F.: Complexes of Fe2+ with diethyldithiocarbamate or N-methyl-D-glucamine dithiocarbamate as traps of nitric oxide in animal tissues. Biochim. Biophys. Acta. **1336**, 225–234 (1997). https://doi.org/10.1016/S0304-4165(97)00032-9
24. Ismailova, A.I., Gnezdilov, O.I., Muranova, L.N., Obynochny, A.A., Andrianov, V.V., Gainutdinov, K., Nasyrova, A.G., Nigmatullina, R.R., Rahmatullina, F.F., Zefirov, A.L.: ESR study of the nitric oxide production in tissues of animals under the external influence on the functioning of the cardiovascular and nervous systems. Appl. Magn. Reson. **28**, 421–430 (2005)
25. Gainutdinov, K.L., Andrianov, V.V., Iyudin, V.S., Yurtaeva, S.V., Jafarova, G.G., Faisullina, R.I., Sitdikov, F.G.: EPR study of nitric oxide production in rat tissues under hypokinesia. Biophysics **58**, 203–205 (2013)
26. Van Faassen, E.E., Koeners, M.P., Joles, J.A., Vanin, A.F.: Detection of basal NO production in rat tissues using iron–dithiocarbamate complexes. Nitric Oxide **18**, 279–286 (2008). https://doi.org/10.1016/j.niox.2008.02.003
27. Stukach, Y., Gainutdinov, K.L., Dosina, M., Pashkevich, S., Andrianov, V., Denisov, A., Bogodvid, T., Yafarova, G., Bushuk, S., Kuznetsova, T., Kulchitsky, V.: Migration of neural stem cells in hippocampal slices in hypoxia modeling. J. Stem Cells Regenerative Ther. **1**(1), 1–8 (2016). Article 15

Wild Animals as the Model Subjects to Study the Hippocampal Formation, Spatial Navigation and Memory

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Abstract. In this brief review the role of the hippocampal formation in the processes of navigation, orientation and spatial memory in wild animals is discussed. Studies in bats revealed previously unknown types of spatial neurons associated with three-dimensional navigation and their new properties. The involvement of the hippocampal formation in the processes of long-distance flights of birds during migration and homing is considered. The available data on the difference in hippocampal morphology in relative species (or subspecies) of mammals and birds that differ in their food-caching ability, foraging types, and the size of the home range should be supplemented analysis brain functions with utilizing modern technologies. The results of research on wild species are significant for both zoologists and neuroscientists and should be developed into interdisciplinary frameworks.

Keyword: Hippocampus · Hippocampal formation · Spatial navigation · Spatial memory · Ecology · Environment · Bats · Birds · Rodents · Wild animal models

At the present time there is significant progress in the experimental study of the hippocampal formation functions in control of various aspects of spatial behavior (exploration, cognitive mapping, spatial memory and navigation), while in more often studies were carried out on laboratory rodents using the small laboratory apparatus (arenas, mazes). Substantial advance in modern research of the hippocampus was connected with the obtaining of numerous evidence of the functional heterogeneity of the hippocampus along its septotemporal axis.

Multiple scales of spatial representation, a gradient of representational granularity was found along this axis both in rodents and humans [1–3]. The spatial selectivity of place cells decreases from the septal to temporal pole, the size of firing fields increases along the hippocampal septotemporal axis. Using an 18-m-long linear track allowed detecting place cells with large firing field (10 m) in temporal subregion of rat hippocampus [4]. It has been suggested that the large-scale mapping process may be important for the formation of representations in the natural environment, for example within wild rodent home range. Mechanisms such as the dynamic scaling of place fields in response to the environment size and level of details may play a role in producing efficient representations of space [2, 4]. These and other findings led to an understanding of the limitations of the standard laboratory approaches in the study of the spatial cognition. They should

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be augmented with the research of the hippocampal formation in wild animals [2, 5]. It is obvious that model subjects should not be merely laboratory rodents artificially selected for a long time. The diverse species of animals are adopted to the complex environment in a wild, they fit to the specific ecological niche. It provides opportunities to adequately study natural functional systems and their neurological basis. It is known that significant differences exist between laboratory mice and rats in spatial cognition. The considerable difficulties of spatial learning noted in many mouse strains and there is clear strain differences of the spatial behavior and morphology of the hippocampus in laboratory rodents [6–9]. This undoubtedly makes it difficult to objectively assess the function of the hippocampus, which may significantly differ from those of wild species of rats and mice.

Spatial behavior plays a key role in the survival of animals in the natural environment; this is the exploration of an unknown area and control of changes occurring there, optimal movement when searching for food, shelter, mates, avoiding dangerous places, controlling the boundaries of the home range, etc. In wild, animals move around the territory, the size of which significantly exceeds the size of laboratory apparatus. Animal species differ in ecology, sensory capabilities, specified complexity of spatial behavior, and spatial memory requirements. There are only few comparative studies on wild animals because of the extremely limited or simple lack of data on the brain morphology of the most species. Moreover, there are objective difficulties in applying many laboratory procedures in the field conditions. The research of the complex interrelation between the ecological specifics of wild animals (the size of home range, the load on spatial memory in food-storing birds, the distinct type of foraging, etc.) and the comparative morphology of the hippocampus began long ago, but there are only few studies in this field [10, 11]. The significant role of ecological context in the specificity of hippocampal morphology and function has been revealed in studies by Lipp and his colleagues [6, 12–15]. Recent studies of the hippocampal formation in different species have confirmed the perspectives of this approach. Substantial progress has been achieved in the study of the hippocampal formation in flying animals (bats) moving in 3D space that requires appropriate mechanisms for 3D mapping the environment, orientation and navigation. Unique properties of neurons in the hippocampal formation were discovered, which differ remarkably from those observed in laboratory rats [16]. Spatial specific neurons (place cells) with large 3D place fields were recorded from hippocampal CA1 subfield of flying Egyptian fruit bats (*Rousettus aegyptiacus*). It was demonstrated that bat hippocampus represents 3D volumetric space by a uniform and nearly isotropic rate code [17] and this result was confirmed with other bats species, big brown bat (*Eptesicus fuscus*) [18]. These findings have stimulated interest in a detailed study of the neurophysiological basis of spatial orientation and navigation to understand how representation of 3D space forms in other animals. Recently neuronal activity of the hippocampal place cells and grid cells (in the medial entorhinal cortex) were studied in rats in the apparatus with wire horizontal and vertical surfaces [19]. When rats explored vertical surfaces, the hippocampal place fields were sparser, but their size and shape were similar in vertical and horizontal plans. Additionally, grid fire fields on the wall were fewer and field size was larger than on the floor. Thus, the spatial firing patterns of grid and place cells were altered on a vertical plane. Authors suggested that the 3D metrics of the cognitive map were determined by an interaction between egocentric information (the body plane) and allocentric information (the gravity axis). It was assumed that an altered or absent odometric (distance-measuring) process in rats move on a vertical surface. Recent experiments with Egyptian fruit bat flying towards a spatial goal led to the discovery (in CA1 subfield) of subpopulation of neurons unusual for the hippocampus of other species [20]. The neurons with angular tuning to the goal direction were found, they were tuned to the egocentric direction and distance to the goal. Authors supposed that the goal direction and goal-distance signals made up a vectorial representation of spatial goals; therefore, a previously unrecognized neuronal mechanism for goal-directed navigation was revealed. Commenting on this study, de Cothi and Spiers [21] noted that the discovery of these cells fills a missing piece in the puzzle regarding how the brain supports spatial navigation. These findings explain the results of human functional magnetic resonance imaging (fMRI) during navigation in virtual environments. It was observed that activity in the hippocampus/subiculum correlates with the distance to the goal during navigation [e.g. 22].

Perfect navigation of bats is also ensured by 3D head direction (HD) system. Unlike rats [23], directionally specific cells were found in the presubiculum of bats that selectively responded not only to the position of the head in the horizontal plane (tuning to azimuth) but also provided pitch and roll tuning. 3D HD cells tuned to both azimuth and pitch, which provided a global 3D compass that encoded the direction of the heading vector in 3D [16, 24]. The discovery of a 3D compass in bats undoubtedly intensified the research and led to revision of previous data on the functioning of the HD system in laboratory rodents. It was demonstrated that head-direction cells in the mouse thalamus and retrosplenial cortex were tuned to the combinations of an azimuth and tilt [25]. However, the results of the rats studies using another method were somewhat different [26]. It was concluded that that information from a horizontal canal is primarily use for the brain representation of the directional heading and that a 3D gravity-referenced HD signal anchored to a direction in the horizontal plane. The possible interpretation of the data obtained by these two groups remains a subject of discussion [27, 28]. There are a few data to compare spatial neurons (place cells, grid cells and others) of the hippocampal formation in birds and mammals. Spatial specificity of neurons was found in the hippocampal formation of freely moving homing pigeons. However, spatial specific single-unit activity was less robust than in rats [29, 30]. It has been suggested that the spatial ecology and evolutionary history of various species may be a critical factors shaping spatial-specific activity of hippocampal neurons. The HD system in the brain of birds has not been found yet, although one can assume, that birds have such a functional and necessary analogue for controlling and maintaining direction in flight. The search of brain regions in birds, functional analogs or homologous of the mammalian HD system is difficult because of differences in cellular organization of the telencephalon. In contrast to mammals most of the avian pallium consists of nuclear subdivisions [31]. The problem of homology of hippocampal subfields in birds and mammals is not quite clear, the concepts are being refined [32–34].

In a comparative study of the brain in animals capable of homing or migrating it is an important both to assess the functioning of the hippocampal formation during navigation in a complex and extensive environment, and to correctly identify brain structures involved in the realization of long-distance movement. Insufficient data are present on mammals, no difference was found in relative hippocampus volume between migratory and sedentary species of bats [35]. Most of the comparative studies were carried out on homing pigeons and migratory bird species. Increased relative hippocampal volume, number and a higher density of hippocampal neurons were revealed in garden warblers (*Sylvia borin*) with migratory experience as compared to juvenile birds without such experience [36]. An intraspecific comparison of the hippocampus of migratory (*Zonotrichia leucophrys gambelii*) and non-migratory (*Z. leucophrys nuttalli*) subspecies of white-crowned sparrows also revealed increased relative size of the hippocampus and more neurons in the right hippocampus in adult birds of migratory subspecies [37]. In addition, enlarged hippocampus was in homing pigeon with homing experience [38]. Homing experiments utilizing GPS data-loggers to uncover the entire flight paths of the pigeons prior to and after bilateral lesions of hippocampal formation showed important results [32,39,40]. Impaired navigational performance in lesioned birds was over the familiar space near the home loft, whereas the specific direction of the flight home from the unfamiliar release location was correct. In addition, the lesioned pigeons as compared to intact birds flew a straighter path home over a space they had never explored before. The authors suggested that hippocampal lesion resulted in a perceptual neglect of environmental stimuli in homing pigeon. These experiments showed that navigation from distant, unfamiliar locations was independent of hippocampal formation in homing pigeons. The reason for the increased size of the hippocampal formation in birds with experience of migration and homing remains unclear. It is possible the hippocampus is involved in other processes that are not related to navigation per se, in processes accompanying flights over unfamiliar territories (memorizing landmarks, spatial behavior during stopover phase, etc.) [41]. However, researchers of the neural basis of long-distance navigation in migratory birds do not exclude the participation of the hippocampus in information processing during celestial orientation (compass), the functioning of navigational olfactory maps, as well as in the storage, integration and retrieval of information about maps and compasses [42].

Comparative study of related species (or subspecies), differing in the load on spatial memory, in the intensity and complexity of movement across the extensive territory represents a promising way to study the hippocampus. Notable differences in the size, morphology and the number of neurons of the hippocampus were found in food-caching birds and those that do not [43, 44] and in rodents, differing in the size of home range and the characteristics of foraging. The bannertail kangaroo rat (*Dipodomys spectabilis*) hoards seeds in its burrow and cache retrieval in this manner requires no specialized spatial memory. Merriam's kangaroo rat (*D. merriami*), in contrast, hoards food in scattered locations and uses spatial memory to find its caches. Hippocampus size, relative to brain size, was significantly larger in the scatter-hoarding species Merriam's kangaroo rat than in the bannertail kangaroo rat [10]. Species-specific differences in the size of intra/infra pyramidal mossy fiber projection were found in two vole species (*Clethrionomys glareolus* and *Microtus oeconomus*) differed in ecology, a specific type of foraging, the size of home range and success in spatial learning in water maze [12].

One of the intriguing directions is the study of the hippocampus in animals at various of the life circle stages, when there is a change in interaction with the environment (departure from the nest of young individuals, the formation of home range in adults and sex specific spatial traits, seasonal factors). Descriptions of these processes, for example, in shrews and voles are available in zoological works. However, there are few studies about the effects of these factors on the hippocampus [10, 11, 45, 46]. Many findings discovered long time ago need to be studied using modern laboratory technologies. Research of the morphology and functions of the hippocampus in wild animals are of interest to both zoologists and neuroscientists. These studies should be developed in the framework of interdisciplinary projects (e.g., [46]). The use of valid animal models will significantly expand knowledge about the neurobiological mechanisms of spatial behavior. The study of real navigation will be undoubtedly complementary to investigation of human spatial navigation in virtual reality set-ups combined with fMRI.

References

1. Strange, B.A., Witter, M.P., Lein, E.S., Moser, E.I.: Functional organization of the hippocampal longitudinal axis. Nat. Rev. Neurosci. **15**, 655–669 (2014). https://doi.org/10.1038/nrn3785
2. Harland, B., Contreras, M., Fellous, J.-M.: A role for the longitudinal axis of the hippocampus in multiscale representations of large and complex spatial environments and mnemonic hierarchies. In: Stuchlik, A. (ed.) The Hippocampus - Plasticity and Functions, pp. 67–104 (2017). https://doi.org/10.5772/intechopen.71165
3. Brunec, I.K., Bellana, B., Ozubko, J.D., Man, V., Robin, J., Liu, Z.X., Grady, C., Shayna Rosenbaum, R., Winocur, G., Barense, M.D., Moscovitch, M.: Multiple scales of representation along the hippocampal anteroposterior axis in humans. Curr. Biol **28**, 2129.e6-2135.e6 (2018). https://doi.org/10.1016/j.cub.2018.05.016
4. Kjelstrup, K.B., Solstad, T., Brun, V.H., Hafting, T., Leutgeb, S., Witter, M.P., Moser, E.I., Moser, M.B.: Finite scale of spatial representation in the hippocampus. Science **321**(5885), 140–143 (2008). https://doi.org/10.1126/science.1157086
5. Jacobs, L.F., Menzel, R.: Navigation outside of the box: what the lab can learn from the field and what the field can learn from the lab. Mov. Ecol. **2**, 3 (2014). https://doi.org/10.1186/2051-3933-2-3
6. Lipp, H.P., Wolfer, D.P.: New paths towards old dreams: microphrenology or the study of intact brains in intact worlds. In: Alleva, E., Fasolo, A., Lipp, H.P., Nadel, L., Ricceri, L. (eds.) Behavioural Brain Research in Naturalistic and Semi-Naturalistic Settings: Possibilities and Perspectives, pp. 1–39. Kluwer, Dordrecht, The Netherlands (1995)
7. Wolfer, D.P., Lipp, H.P.: Dissecting the behaviour of transgenic mice: is it the mutation, the genetic background, or the environment? Exp. Physiol. **85**, 627–634 (2000)
8. Crusio, W.E., Schwegler, H.: Learning spatial orientation tasks in the radial-maze and structural variation in the hippocampus in inbred mice. Behav. Brain Funct. **1**, 3 (2005). https://doi.org/10.1186/1744-9081-1-3
9. Hok, V., Poucet, B., Duvelle, É., Save, É., Sargolini, F.: Spatial cognition in mice and rats: similarities and differences in brain and behavior. Wiley Interdiscip. Rev. Cogn. Sci. **7**, 406–421 (2016). https://doi.org/10.1002/wcs.1411

10. Sherry, D.F., Jacobs, L.F., Gaulin, S.J.: Spatial memory and adaptive specialization of the hippocampus. Trends Neurosci. **15**, 298–303 (1992)
11. Jacobs, L.F.: The ecology of spatial cognition. Adaptive patterns of space use and hippocampal size in wild rodents. In: Alleva, E., Fasolo, A., Lipp, H.P., Nadel, L., Ricceri, L. (eds.) Behavioural Brain Research in Naturalistic and Semi-naturalistic Settings: Possibilities and Perspectives, pp. 301–322. Kluwer, Dordrecht (1995)
12. Pleskacheva, M.G., Wolfer, D.P., Kupriyanova, I.F., Nikolenko, D.L., Scheffrahn, H., Dell'Omo, G., Lipp, H.P.: Hippocampal mossy fibers and swimming navigation learning in two vole species occupying different habitats. Hippocampus **10**, 17–30 (2000). https://doi.org/10.1002/(sici)1098-1063(2000)10:1%3c17::aid-hipo2%3e3.0.co;2-o
13. Poletaeva, I.I., Pleskacheva, M.G., Markina, N.V., Perepelkina, O.V., Shefferan, H., Wolfer, D.P., Lipp, H.P.: Survival under conditions of environmental stress: variability of brain morphology and behavior in the house mouse. Russ. J. Ecol. **32**, 211–215 (2001). https://doi.org/10.1023/a:1011322513788
14. Amrein, I., Dechmann, D.K., Winter, Y., Lipp, H.P.: Absent or low rate of adult neurogenesis in the hippocampus of bats (Chiroptera). PLoS ONE **2**, e455 (2007). https://doi.org/10.1371/journal.pone.0000455
15. Amrein, I., Slomianka, L., Poletaeva, I.I., Bologova, N.V., Lipp, H.P.: Marked species and age-dependent differences in cell proliferation and neurogenesis in the hippocampus of wild-living rodents. Hippocampus **14**, 1000–1010 (2004). https://doi.org/10.1002/hipo.20018
16. Finkelstein, A., Las, L., Ulanovsky, N.: 3-D maps and compasses in the brain. Annu. Rev. Neurosci. **39**, 171–196 (2016). https://doi.org/10.1146/annurev-neuro-070815-013831
17. Yartsev, M.M., Ulanovsky, N.: Representation of three-dimensional space in the hippocampus of flying bats. Science **340**(6130), 367–372 (2013). https://doi.org/10.1126/science.1235338
18. Wohlgemuth, M.J., Yu, C., Moss, C.F.: 3D hippocampal place field dynamics in free-flying echolocating bats. Front. Cell Neurosci. **12**, 270 (2018). https://doi.org/10.3389/fncel.2018.00270
19. Casali, G., Bush, D., Jeffery, K.: Altered neural odometry in the vertical dimension. Proc. Natl. Acad. Sci. USA **116**, 4631–4636 (2019). https://doi.org/10.1073/pnas.1811867116
20. Sarel, A., Finkelstein, A., Las, L., Ulanovsky, N.: Vectorial representation of spatial goals in the hippocampus of bats. Science **355**(6321), 176–180 (2017). https://doi.org/10.1126/science.aak9589
21. de Cothi, W., Spiers, H.J.: Spatial cognition: goal-vector cells in the bat hippocampus. Curr. Biol. **27**, R239–R241 (2017). https://doi.org/10.1016/j.cub.2017.01.061
22. Howard, L.R., Javadi, A.H., Yu, Y., Mill, R.D., Morrison, L.C., Knight, R., Loftus, M.M., Staskute, L., Spiers, H.J.: The hippocampus and entorhinal cortex encode the path and Euclidean distances to goals during navigation. Curr. Biol. **24**, 1331–1340 (2014). https://doi.org/10.1016/j.cub.2014.05.001
23. Taube, J.S.: The head direction signal: origins and sensory-motor integration. Annu. Rev. Neurosci. **30**, 181–207 (2007). https://doi.org/10.1146/annurev.neuro.29.051605.112854
24. Finkelstein, A., Derdikman, D., Rubin, A., Foerster, J.N., Las, L., Ulanovsky, N.: Three-dimensional head-direction coding in the bat brain. Nature **517**(7533), 159–164 (2015). https://doi.org/10.1038/nature14031
25. Angelaki, D.E., Ng, J., Abrego, A.M., Cham, H.X., Asprodini, E.K., Dickman, J.D., Laurens, J.: A gravity-based three-dimensional compass in the mouse brain. Nat. Commun. **11**, 1855 (2020). https://doi.org/10.1038/s41467-020-15566-5
26. Shinder, M.E., Taube, J.S.: Three-dimensional tuning of head direction cells in rats. J Neurophysiol. **121**, 4–37 (2019). https://doi.org/10.1152/jn.00880.2017
27. Laurens, J., Angelaki, D.E.: A model-based reassessment of the three-dimensional tuning of head direction cells in rats. J. Neurophysiol. **122**, 1274–1287 (2019). https://doi.org/10.1152/jn.00136.2019

28. Taube, J.S.: Reply to Laurens and Angelaki: a model-based reassessment of the three-dimensional tuning of head direction cells in rats. J. Neurophysiol. **122**, 1288–1289 (2019). https://doi.org/10.1152/jn.00525.2019
29. Siegel, J.J., Nitz, D., Bingman, V.P.: Spatial-specificity of single-units in the hippocampal formation of freely moving homing pigeons. Hippocampus **15**, 26–40 (2005). https://doi.org/10.1002/hipo.20025
30. Siegel, J.J., Nitz, D., Bingman, V.P.: Lateralized functional components of spatial cognition in the avian hippocampal formation: evidence from single-unit recordings in freely moving homing pigeons. Hippocampus **16**, 125–140 (2006)
31. Jarvis, E. D., Yu, J., Rivas, M. V., Horita, H., Feenders, G., Whitney, O., Jarvis, S.C., Jarvis, E.R., Kubikova, L., Puck, A.E., Siang-Bakshi, C., Martin, S., McElroy, M., Hara, E., Howard, J.,Pfenning, A., Mouritsen, H., Chen, C.C., Wada, K.: Global view of the functional molecular organization of the avian cerebrum: mirror images and functional columns. J. Comp. Neurol. **521**, 3614-3665 (2013). https://doi.org/10.1002/cne.23404
32. Herold, C., Coppola, V.J., Bingman, V.P.: The maturation of research into the avian hippocampal formation: recent discoveries from one of the nature's foremost navigators. Hippocampus **25**, 1193–1211 (2015). https://doi.org/10.1002/hipo.22463
33. Herold, C., Schlömer, P., Mafoppa-Fomat, I., Mehlhorn, J., Amunts, K., Axer, M.: The hippocampus of birds in a view of evolutionary connectomics. Cortex **118**, 165–187 (2019). https://doi.org/10.1016/j.cortex.2018.09.025
34. Atoji, Y., Sarkar, S., Wild, J.M.: Proposed homology of the dorsomedial subdivision and V-shaped layer of the avian hippocampus to Ammon's horn and dentate gyrus, respectively. Hippocampus **26**, 1608–1617 (2016). https://doi.org/10.1002/hipo.22660
35. McGuire, L.P., Ratcliffe, J.M.: Light enough to travel: migratory bats have smaller brains, but not larger hippocampi, than sedentary species. Biol. Lett. **7**, 233–236 (2011). https://doi.org/10.1098/rsbl.2010.0744
36. Healy, S.D., Gwinner, E., Krebs, J.R.: Hippocampal volume in migratory and non-migratory warblers: effects of age and experience. Behav. Brain Res. **81**, 61–68 (1996)
37. Pravosudov, V.V., Kitaysky, A.S., Omanska, A.: The relationship between migratory behavior, memory and the hippocampus: an intraspecific comparison. Proc. Biol. Sci. **273**(1601), 2641–2649 (2006). https://doi.org/10.1098/rspb.2006.3624
38. Cnotka, J., Mohle, M., Rehkamper, G.: Navigational experience affects hippocampus size in homing pigeons. Brain Behav. Evol. **72**, 233–238 (2008). https://doi.org/10.1159/000165102
39. Gagliardo, A., Pollonara, E., Coppola, V.J., Santos, C.D., Wikelski, M., Bingman, V.P.: Evidence for perceptual neglect of environmental features in hippocampal-lesioned pigeons during homing. Eur. J. Neurosci. **40**, 3102–3110 (2014). https://doi.org/10.1111/ejn.12680
40. Bingman, V.P., MacDougall-Shackleton, S.A.: The avian hippocampus and the hypothetical maps used by navigating migratory birds (with some reflection on compasses and migratory restlessness). J. Comp. Physiol. A Neuroethol. Sens. Neural Behav. Physiol. **203**, 465–474 (2017). https://doi.org/10.1007/s00359-017-1161-0
41. Diniz, C.G., Magalhães, N.G., Sousa, A.A., Santos Filho, C., Diniz, D.G., Lima, C.M., Oliveira, M.A., Paulo, D.C., Pereira, P.D., Sherry, D.F., Picanço-Diniz, C. W.: Microglia and neurons in the hippocampus of migratory sandpipers. Braz. J. Med. Biol. Res. **49**, e5005 (2016). https://doi.org/10.1590/1414-431X20155005
42. Mouritsen, H., Heyers, D., Güntürkün, O.: The neural basis of long-distance navigation in birds. Annu. Rev. Physiol. **78**, 133–154 (2016). https://doi.org/10.1146/annurev-physiol-021115-105054
43. Smulders, T.V.: A multi-disciplinary approach to understanding hippocampal function in food-hoarding birds. Rev. Neurosci. **17**, 53–69 (2006)

44. Pravosudov, V.V., Roth II, T.C., LaDage, L.D., Freas, C.A.: Environmental influences on spatial memory and the hippocampus in food-caching chickadees. Comp. Cogn. Behav. Rev. **10**, 25–43 (2015). https://doi.org/10.3819/ccbr.2015.100002
45. Yaskin, V.A.: Seasonal changes in hippocampus size and spatial behaviour in mammals and birds Zhurn. Obchs. Biol. (J. Gener. Biol.) **72**, 27–39 (2011). (in Russian)
46. Lazaro, J., Hertel, M., Sherwood, C.C., Muturi, M., Dechmann, D.K.N.: Profound seasonal changes in brain size and architecture in the common shrew. Brain Struct. Funct. **223**, 2823–2840 (2018). https://doi.org/10.1007/s00429-018-1666-5

Reconsolidation and Cognitive Novelty

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Abstract. In order to investigate activity correspondence between brain components with different phylogenetic age during learning processes we analyzed neuronal activations of the retrosplenial disgranular (RSD) cortex along rostrocaudal axis. This cortex was chosen due to its structural organization which suggest that it includes neurons of different phylogenetic affiliation. The RSD cortex is known to be the region of interest for the studies of memory acquisition, memory consolidation and memory reconsolidation. In our experiments we trained animals different instrumental food-acquisition tasks and analysed gene expression changes in neurons by Fos-mapping (transcription factor Fos is a product of *c-fos* gene expression) on brain slices. The experimental groups differed by novelty degree, i.e. the degree of mismatch between the recent experience and the experience previously formed in the experiment, namely the difference was in the number of new key elements in the experimental chamber which animals had to interact with to get food during the last session. We found uneven activation of the RSD cortex along rostro-caudal axis and significant differences in this cortical activity patterns between the “high novelty” group and the “low novelty” group. The “low novelty” group animals showed significantly fewer Fos-positive neurons in the caudal part of the RSD than the “high novelty” group animals. There were no differences found in the rostral part of the RSD. It might be assumed that in the caudal part of the cortex, neurons are specialized relative to the systems of “older” low-differentiated experience. While the younger part of the cortex contains neurons belonging to a highly differentiated newer experience. The obtained data also indicate that Fos mapping of brain activity reflects the processes of accommodation reconsolidation of earlier acquired memory and marks differences in individual experience.

Keywords: Learning · Reconsolidation · Novelty · Phylogenesis · Differentiation · RSD · Rostro-caudal axis · c-Fos

1 Introduction

The acquisition of new experience (learning) is considered as the formation of a new system aimed at achieving a useful adaptive result. At the neural level it is underlied by the acquisition of neuronal specializations, identified though specific activations during a corresponding behavioral act, such as pedal pressing [1, 2] or being at a specific location

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(place cells) [3]. c-Fos protein synthesis, a product of expression of the immediate early gene *c-fos*, is a necessary step for long-term memory consolidation that induces a cascade of molecular changes in neurons and is related specialization processes [4, 5]. The expression of the early genes is induced by the mismatch within the individual's experience and is determined by the factor of subjective novelty of this event [6, 7].

Previously, a relationship was shown between the number of pre-training stages and the number of neurons expressing the *c-fos* gene in the rat cortex after learning a new instrumental food-acquisition skill [8]. It was concluded that varying the history of skill acquisition, for example, learning in one or several stages, leads to differences in the structure of individual experience and, therefore, to differences in its re-organization in the process of re-learning, which is manifested by differences in the number of neurons that change their genetic activity.

In order to investigate activity correspondence between brain components with different phylogenetic age during learning processes we analyzed neuronal activations of the retrosplenial disgranular (RSD) cortex along rostro-caudal axis. This part of the cortex was chosen because the change in the activity of its neurons is clearly associated with the learning processes, and it is a zone of interest in experiments with recording neuronal activity, in which these processes are studied [9–12].

The structural organization of this cortex suggests that it includes neurons of different phylogenetic affiliation because its rostral part merges into the forebrain structures (in particular, the cingulate cortex) and is closely related to them, and its caudal part – into the zones of the hippocampus [13–16].

2 Materials and Methods

Subjects and Behavioral Task. Mature long-Evans rats (200–350 g) were trained three consecutive food-acquisition skills in an experimental chamber (Fig. 1A) equipped with automatic feeders that triggered when a corresponding lever is pressed.

The experimental design is illustrated in Fig. 1B. Animals were trained to trigger the first feeder (f1) using one lever (i1), then trained to use another lever (i2) to activate the same feeder, and use the third lever (i3) to trigger a new feeder (f2). Only one lever was effective at the corresponding training stage. The third lever was introduced during the last session, on the same day the animal brains were extracted for immunohistochemical analysis (IHC).

Before any lever is introduced, animals were familiarized with the first feeder. After that all animals were divided into two groups, which differed in familiarity with the second feeder:

"Low novelty" group (Gr.1) – after familiarization with the first feeder were trained to obtain food from the second feeder, thereby during the last session the animals were trained to use a new lever to activate a familiar feeder.

"High novelty" group (Gr.2) – continued to receive food from the first feeder, so during the last session they learned both a new lever and a new feeder. That is, the novelty regarding the previously acquired experience in animals of the second group is higher.

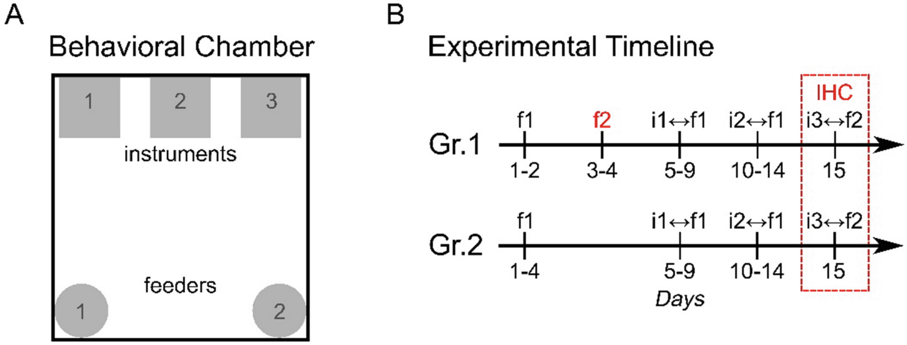

Fig. 1. (A) Behavioral chamber. Numbered instruments (levers) and feeders. (B) Experimental timeline. f – feeder; i – instrument; i ↔ f - behavioral cycle: press the instrument, then take food from the feeder; IHC – immunohistochemistry. Gr. 1 - “low novelty” group; Gr. 2 - “high novelty” group.

Immunohistochemistry. After the last experimental session, the animals were returned to their home cages for 75 min, then put to sleep under inhalation anesthesia and decapitated. The marker of neuronal gene expression changes, the c-Fos protein, was detected on cryogenic brain sections by immunohistochemical method (antibodies by Santa Cruz, USA). Each brain was sliced at four levels (see Fig. 2A): from 4.20 to 3.00 mm from bregma (forebrain); from −1.72 to −2.52 mm (rostral); from −2.76 to −3.24 mm; from −4.44 to −5.04 mm (caudal). All together 32 brain slices were taken according to the sixth edition of rat brain atlas [17].

Statistical Analysis. Data were analyzed using Statistica 6.0 (StatSoft Inc., USA). The nonparametric Mann-Whitney test was used to assess the statistical significance of differences in the number of Fos-positive neurons in brain structures in animals of different groups. Differences were considered to be significant if $p \leq 0.05$.

3 Results

The “low novelty” group animals showed significantly fewer Fos-positive neurons in the caudal part of the RSD than the “high novelty” group animals. There were no differences between the groups found in the rostral part of the RSD (Fig. 2B). The differences reached the level of significance at the coordinate −2.76 mm from bregma. No significant difference was found when we compared the averaged density for all brain slices between the two groups (Mann-Whitney test, $Z = -1.67$, $p = 0.094$). Thus, uneven activation of this cortical region along its rostro-caudal axis was revealed. We also found significant differences in the activation pattern between two conditions: “low novelty” and “high novelty”.

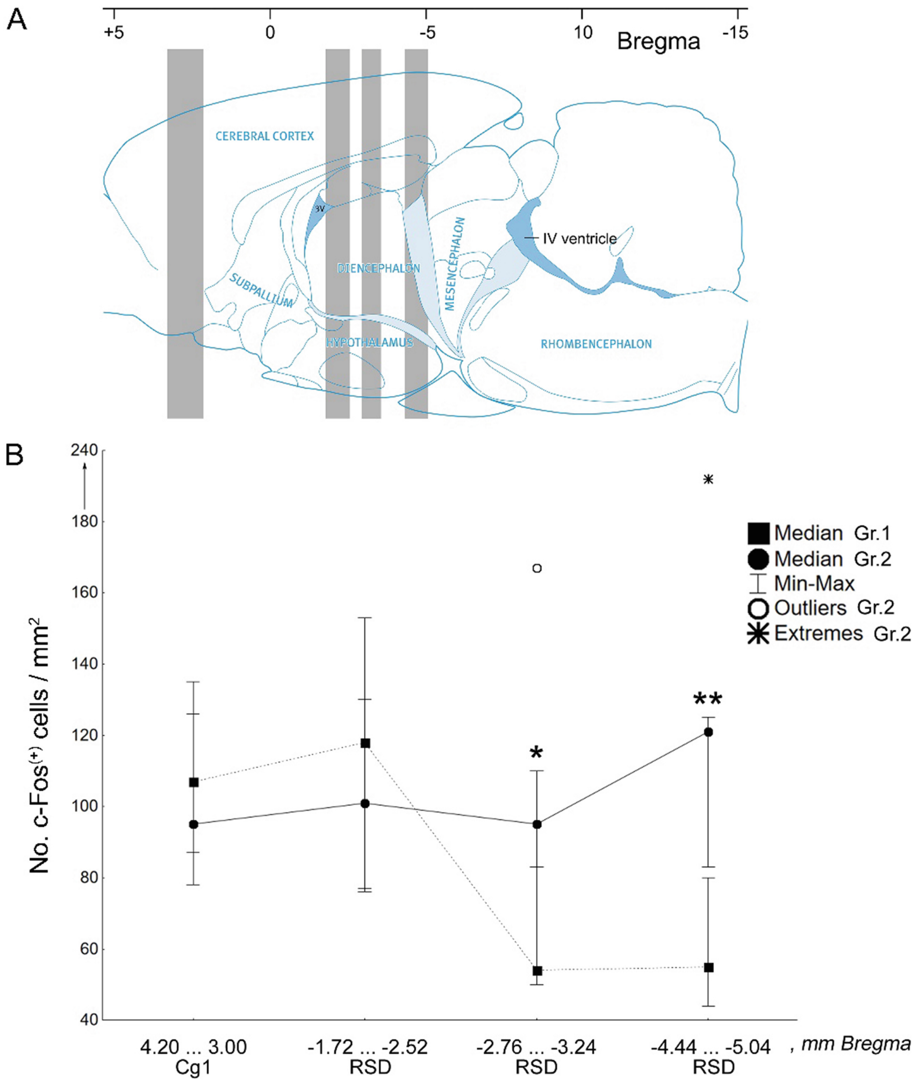

Fig. 2. (A) Schematic diagram of the rat brain, sagittal plane (Watson and Paxinos et al. [17]). Grey color marks areas of brain sections. (B) Density of c-Fos-positive neurons in cingulate (Cg1) and retrosplenial (RSD) cortex at different brain coordinates after last skill acquisition. Gr. 1 – "low novelty" group, N = 5; Gr. 2 – "high novelty" group, N = 5. Mann-Whitney test, *Z = −2.4, p = 0.015; ** Z = −2.5, p = 0.012.

4 Discussion

As it was noted earlier [18] neurons are specialized in relation to acquired behavior at every stage of learning. Then it might be suggested that "low novelty" animals already formed at the previous learning stages neuronal groups specialized in relation to the second feeder. Another possible example of such specializations is “place neurons” (place cells). “High novelty” animals form such specializations during the last session which might be reflected in a higher number of Fos-positive neurons in the caudal part of RSD cortex necessary for the following selection for the specialized neurons. Thus the results may support the assumption that the caudal part of the cortex is dominated by specialized neurons relative to older, low-differentiated systems (related to spatial localization, locomotor activity, etc.). While the phylogenetically younger structural part (rostral) of the cortex includes neurons related to highly differentiated newer experiences, including those that characterize the specifics of the selected behavioral alternatives. Perhaps, in this behavioral task related to the need to find a new effective tool for achieving the goal (food), such a parameter as novelty in the place where the result is obtained is not significant for the subject, which explains the lack of differences in the degree of activation in the rostral part of the cortex.

The resulting overt behavior of animals of both groups (the third skill) is similar and does not demonstrate significant differences in behavioral indicators (such as the number of effective and ineffective cycles), but there are differences in Fos expression, which supports the assumption that mapping brain activity by Fos-expressing neurons reflects the processes of accommodative reconsolidation [19, 20] and marks differences in individual experience.

5 Conclusion

RSD activation along the rostro-caudal axis is uneven during learning.

Significant differences were found in the rostrocaudal pattern of RSD activation with different degrees of mismatch.

It is necessary to take into account possible differences in the degree of RSD activation along the rostro-caudal axis in order to select certain coordinates when planning studies.

Fos-mapping of brain activity reflects the processes of accommodation reconsolidation and marks differences in individual experience.

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References

1. Shvyrkov, V.B.: Behavioral specialization of neurons and the system-selection hypothesis of learning. In: Klix, F., Hagendorf, H. (eds.) Human Memory and Cognitive Capabilities: Mechanisms and Performances, pp. 599–611. Elsevier Science Publishers BV, North-Holland (1986)
2. Aleksandrov, Y.I., Grechenko, T.N., Gavrilov, V.V., Gorkin, A.G., Shevchenko, D.G., Grinchenko, Y.V.: Formation and realization of individual experience. Neurosci. Behav. Physiol. **27**, 441–454 (1997). https://doi.org/10.1007/BF02462946
3. O’Keefe, J, Dostrovsky, J.: The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat. Brain Res. **34**, 171–175 (1971). https://doi.org/10.1016/0006-8993(71)90358-1

4. Anokhin, K.V., Rose, S.P.R.: Learning-induced increase of immediate early gene messenger RNA in the chick forebrain. Eur. J. Neurosci. **3**, 162–167 (1991). https://doi.org/10.1111/j.1460-9568.1991.tb00076.x
5. Svarnik, O.E., Alexandrov, Y.I., Gavrilov, V.V., Grinchenko, Y.V., Anokhin, K.V.: Fos expression and task-related neuronal activity in rat cerebral cortex after instrumental learning. Neuroscience **136**(1), 33–42 (2005). https://doi.org/10.1016/j.neuroscience.2005.07.038
6. Anokhin, K.V., Sudakov, K.V.: The systems organization of behavior: novelty as the leading factor in the expression of early genes in the brain during learning. Usp. Fiziol. Nauk **24**(3), 53–70 (1993)
7. Anokhin, K.V., Sudakov, K.Y.: Genome of brain neurons in organization of systemic mechanisms of behavior. Bull. Exp. Biol. Med. **135**, 107–113 (2003). https://doi.org/10.1023/A:1023843125404
8. Svarnik, O.E., Bulava, A.I., Alexandrov, Y.I.: Expression of c-Fos in the rat retrosplenial cortex during instrumental re-learning depends on the number of stages of previous training. Front. Behav. Neurosci. **7**, 78 (2013). https://doi.org/10.3389/fnbeh.2013.00078
9. Vann, S.D., Aggleton, J.P., Maguire, E.A.: What does the retrosplenial cortex do? Nat. Rev. Neurosci. **10**(11), 792–802 (2009). https://doi.org/10.1038/nrn2733
10. Sozinov, A.A., Grinchenko, Y.V., Alexandrov, Y.I.: Switch of multitrial tasks is accompanied by dissimilar activity changes in anterior (ACC) and posterior (PCC) cingulate cortex neurons. FENS Abstracts. No. 3750 (2016)
11. Alexandrov, Y.I., Sozinov, A.A., Svarnik, O.E., Gorkin, A.G., Kuzina, E.A., Gavrilov, V.V.: Neuronal bases of systemic organization of behavior. In: Yu, A. (ed.) Advances in Neurobiology. Systems Neuroscience, pp. 1–33. Springer (2018). https://doi.org/10.1007/978-3-319-94593-4_1
12. Mineeva, O.A., Bezryadnov, D.V., Chekhov, S.A., Svarnik, O.E., Anokhin, K.V.: Integrative functions of retrosplenial cortex: anatomy, connectomics, and cellular electrophysiology in rats. Ann. Clin. Exp. Neurol. **13**(1), 47–54 (2019). https://doi.org/10.25692/ACEN.2019.1.6
13. Vogt, B.A., Finch, D.M., Olson, C.R.: Functional heterogeneity in cingulate cortex: the anterior executive and posterior evaluative regions. Cereb. Cortex **2**(6), 435–443 (1992). https://doi.org/10.1093/cercor/2.6.435-a
14. Wyass, J.M., Van Groen, T.: Connections between the retrosplenial cortex and the hippocampal formation in the rat: a review. Hippocampus **2**(1), 1–11 (1992). https://doi.org/10.1002/hipo.450020102
15. Albasser, M.M., Poirier, G.L., Warburton, E.C., Aggleton, J.P.: Hippocampal lesions halve immediate–early gene protein counts in retrosplenial cortex: distal dysfunctions in a spatial memory system. Eur. J. Neurosci. **26**(5), 1254–1266 (2007). https://doi.org/10.1111/j.1460-9568.2007.05753.x
16. Alexander, A.S., Rangel, L.M., Tingley, D., Nitz, D.A.: Neurophysiological signatures of temporal coordination between retrosplenial cortex and the hippocampal formation. Behav. Neurosci. **132**(5), 453 (2018). https://doi.org/10.1037/bne0000254
17. Paxinos, G., Watson, C., Carrive, P., Kirkcaldie, M.T.K., Ashwell, K.: Chemoarchitectonic Atlas of the Rat Brain, p. 375. Elsevier, USA (2009). (Authored Research Book). ISBN 978-0-12-374237-7
18. Gorkin, A.G., Shevchenko, D.G.: Distinctions of the neuronal activity of the rabbit limbic cortex under different training strategies. Neurosci. Behav. Physiol. **26**, 103–121 (1996). https://doi.org/10.1007/BF02359413
19. Alexandrov, Y.I., Grinchenko, Y.V., Shevchenko, D.G., Averkin, R.G., Maz, V.N., Laukka, S., Korpusova, A.V.: A subset of cingulate cortical neurones is specifically activated during alcohol-acquisition behaviour. Acta Physiol. Scand. **171**, 87–97 (2001). https://doi.org/10.1046/j.1365-201X.2001.00787.x
20. Alexandrov, Y.I.: Learning and memory: traditional and systems approaches. Neurosci. Behav. Physiol. **36**, 969–985 (2006). https://doi.org/10.1007/s11055-006-0133-6

Sensory Inflow from Whiskers Modulates Development of Absence Epilepsy in WAG/Rij Rats

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Abstract. Whisker sensory system plays crucial role in development of brain functions in rats. In WAG/Rij rats with genetic predisposition to absence epilepsy, the area of whiskers' projection in the somatosensory cortex (barrelfield) is known to contain hyperexcitable neurons which form epileptic focus. Neonatal period of development (PN1–8) is critical for development of whisker sensory system. Whisker deafferentaion during this period causes irreversible plastic changes that considerably impact brain functions in adulthood. Bilateral trimming of all whiskers in WAG/Rij rats during PN1–8 affected seizure activity between 5 and 9 months of age. First, it prevented age-related increase in the number of seizures, suggesting consistency of epileptic activity in the cortical focal zone; second, it prevented age-related increase in seizure duration, suggesting consistency of thalamo-cortical synchronization. Unilateral whisker trimming on PN1–8 increased excitability of pyramidal cells in the intact barrelfild mediated by HCN-related processes.

Keywords: Genetic model of epilepsy · Spike-wave discharges · Somatosensory cortex · Excitability · Whiskers · Barrelfield

1 Introduction

Whiskers in rodents' snout are the part of a unique sensory organ. During explorative behavior, adult rats and mice move their facial whiskers rhythmically in order to obtain tactile information about the closest environment. This "whisking" behavior requires specific mechanism of sensorimotor integration. It is known that the maturation of "whisking" associates with functional integration of sensory and motor parts of the whisker system [1–3]. During the neonatal period between PN1–8, rat pups could not move their whiskers, but obtain whisker-related information passively could be considered as the "passive touch" period of early ontogenesis [4–6]. The first regular movements of whiskers in rats, i.e., bilaterally synchronous protraction followed rapidly by retraction of whiskers, could be found on PN11, and they are engaged in the "whisking" behavior on PN13 [3]. Furthermore, bilateral movements of whiskers co-occur with the animal's ability to support its head and to locomote in a forward direction. Integration of sensory and motor information during active whisker sensation occurs prominently in the neocortex [3, 7].

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The first postnatal weeks is the period when somatosensory and motor areas of the neocortex are rapidly developed and actively controlled by the sensory information from whiskers [8–11]. Classical studies indicated that complete denervation of the whisker pad via section of the sensory nerve or cauterization of follicles during the "passive touch" period prevented patterning of the whisker-related neuronal circuits, including the area of whisker's projections in the somatosensory cortex (so-called barrelfield) [12, reviewed by 9]. Another technique used for mild deafferentaion via trimming/clipping of whiskers is noninvasive and reversible. Whiskers are known to grow back after trimming with a speed of 1.5 mm per day [13], and whisking activity restores as soon as whiskers grow back. Remarkably is that whisker trimming during the "passive touch" period does not alter whisker-specific patterning along the trigeminal pathway, but affects receptive fields of cortical neurons in the projection area of whiskers (so-called barrel cortex) mainly throughout a decrease of inhibitory interactions [e.g. 14,15; reviewed by 16]. In general, the "passive touch" period can be considered as the critical period for development of neuronal properties in the whisker-related area of the somatosensory cortex, such as (1) inhibitory control of receptive fields; (2) excitation-inhibition balance; (3) ion mechanisms of membrane excitability.

It is well known that somatosensory cortex in rats with genetic predisposition to absence epilepsy (i.e., GAERS and WAG/Rij rats) play a key role in initiation of paroxysmal spike-wave discharges (i.e., electroencephalographic hallmarks of absence epilepsy) [17–19]. This 'focal zone' of absence seizures in genetically prone rats characterized by an increased neuronal excitability [20,21; reviewed by 18]. An increased excitability is associated with an increased ability to produce regular bursts (i.e., peacemaking functions) of cortical neurons, which is related to hyperpolarization-activated cyclic nucleotide-gated channels (HCN) [22]. The role of HCN channels in controlling neuronal excitability and pacemaker functions has been well described in the literature [23–26]. It is important that functional properties of HCN channels can be modified by changing of early sensory experience. For example, Ulrich Schridde and coauthors indicated [27] that neonatal handling, maternal deprivation in WAG/Rij rats lead to an increase of Ih and HCN1 associated with a reduction of absence seizures. Therefore, a restriction of sensory inflow during the "passive" touch (the critical period of whisker system) might promote absence epilepsy via an increase cortical excitability mediated by HCN-related processes. This hypothesis was examined in WAG/Rij rats with a genetic predisposition to absence epilepsy. Sensory experience was restricted by unilateral and bilateral whisker trimming during PN 1–8. Electrocoticographic seizure activity was examined at the age of 5, 7 and 9 months (considering that the fully blown seizures appeared approx. at the age of 7 months [28]). Membrane properties and impulse activity the somatosensory cortex were examined using patch clamp recordings at the age of PN 40–52.

2 Method

2.1 Electroencephalographic Study

This part of the study was performed in WAG/Rij rats that were bred and maintained at Institute of Higher Nervous Activity and Neurophysiology RAS (Moscow, Russia). The experiments were approved by the animal ethics committee of our Institute. Rats were kept in environmentally controlled conditions with a 12:12 h light:dark cycle (light on at 08.00) at a temperature of 21 ± 1 °C, appropriate humidity with constant airing. Food and water were provided ad libitum.

The progeny was obtained from 8 primiparous female WAG/Rij rats at the age of 4–6 months. The day of delivery was defined as P0. On the next day after birth, the number of pups per litter was reduced to 7–9 with the equal number of males and females (or set to equal as close as possible). Gender of pups was determined by measuring of urogenital distance which was greater in males than in females. Litters were randomly assigned to the trimmed and control groups. In the trimmed group, all whiskers were trimmed daily directly at the skin surface on the both sides of the snout from PN1 to PN8. In the control groups, trimming was imitated by means of gentle mechanic stimulation of the whisker pad skin with scissors. Immediately prior to trimming/sham trimming (approximately 10–20 s per pup), dams were removed from the home cage.

At the age of 4.5 m, male rats were equipped with screw electrodes for recording of electrocorticograms (ECoG). Stereotactic surgery was performed under chloralhydrate anesthesia (i.p. injections 325 mg/kg, 4% solution in 0.9% NaCl). Electrodes were secured to the skull using stainless steel screws (shaft length = 2.0 mm, head diameter = 2.0 mm, shaft diameter = 0.8 mm). Active electrodes were placed epidurally over the left and right sides of frontal cortex (AP 2; L ±2.5). All coordinates are given in mm relative to the bregma. Reference electrode was placed over the cerebellum. Electrodes were permanently fixed to the skull with methyl methacrylate monomer together with two additional anchoring screws. After a recovery period, rats were used to record electrical cortical activity in free behavior under 12:12 h light:dark cycle (light on at 8 a.m.). Signals were recorded continuously during the entire day (around 24 h), fed into a multi-channel amplifier (PowerLab 4/35, ADInstruments) via a swivel contact, band-pass filtered between 0.5–200 Hz, digitized with 400 samples/second/per channel and stored in hard disk.

The first ECoG examination was performed at the age of 5 months and repeated at the age of 7 and 9 months. In total, 14 control and 14 trimmed rats underwent ECoG analysis. In the control group, 4 subjects did not develop epilepsy and were excluded from analysis. In the trimmed group, 5 subjects were non-epileptics and were excluded from analysis. Statistical data shown here were obtained in 10 control 'epileptic' rats and 9 trimmed 'epileptic' rats.

2.2 Patch-Clamp Study

This part of the study was done at Institute of Physiology I, University of North Rhine-Westphalia (Münster, Germany) in 2019. Experiments were approved by the ethical committee of this institution. Male and female WAG/Rij rats were used (n = 15 rats). In the experimental group (n = 9), unilateral whisker trimming was performed on the right side of the snout every day during PN 1–8. The left side of the snot was intact. The control group (n = 6) underwent sham trimming on the right side. At the age PN 40–52, animals were sacrificed under general isoflurane anesthesia, their brains were quickly removed and brain slices were performed for patch-clamp recording.

Details of the current-clamp protocol described in [29,30]. Cortical sections of 250 mm thick were made in ice-cooled oxygenated solution with pH 7.35. The sections were transferred to artificial cerebrospinal fluid (ACSF) chamber at 33 C and held for 30 min. The pH was adjusted to 7.35 by passing a gas mixture (95% O2 and 5% CO2). Registration was carried out in the external solution (in bath) containing (in mmole): NaCl - 125; KCl - 2.5; NaH_2PO_4 - 1.25; HEPES - 30; $MgSO_4$ - 2; $CaCl_2$ - 2; Glucose - 10; $BaCl_2$ - 0.5–1, pH = 7.35 at 30 ± 1° C.

In the trimmed group, 25 neurons were recorded in the left somatosensory cortex (contralateral to the trimmed side) and 16 neurons in the right (contralateral to the intact side). In the control group - 9 neurons in the left cortex and 3 neurons - in the right cortex.

3 Results

3.1 Effect of Bilateral Whisker Trimming (PN1–8) on the Age-Related Dynamics of Spike-Wave Seizures

Spike-wave discharges (SWD) in the ECoG (hallmark of absence epilepsy) in WAG/Rij rats were recognized as hypersynchronous repetitive high-voltage discharges with a frequency of 8–10 Hz [31]. SWD were detected automatically in the full length EEG at the frontal right channel using the custom software using detection algorithm based on the continuous wavelet transform (see [32] for technical details). We measured the number of SWD and duration of SWD over ~ 24 h period of time and averaged them per

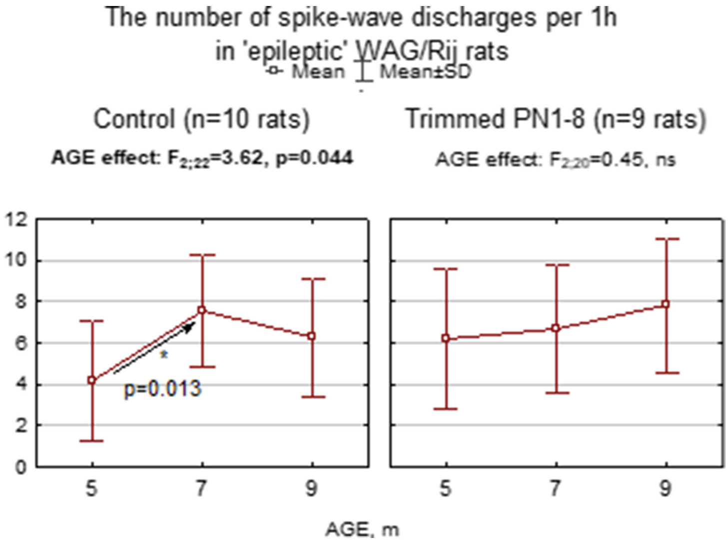

Fig. 1. The effect of bilateral whisker trimming during PN1–8 on the age-related dynamics in number of spike-wave discharges as measured in ECoG in freely moving WAG/Rij rats during late ontogenesis. The effect of AGE is shown as ANOVA and asterisk indicates significant differences according to LSD post-hoc test.

h. Inasmuch as the number of SWD reflects the process of initiation within the epileptic focal zone in the somatosensory cortex (i.e., excitability of epileptic focus), and duration of SWD—the process of seizure maintenance in the thalamocortical network.

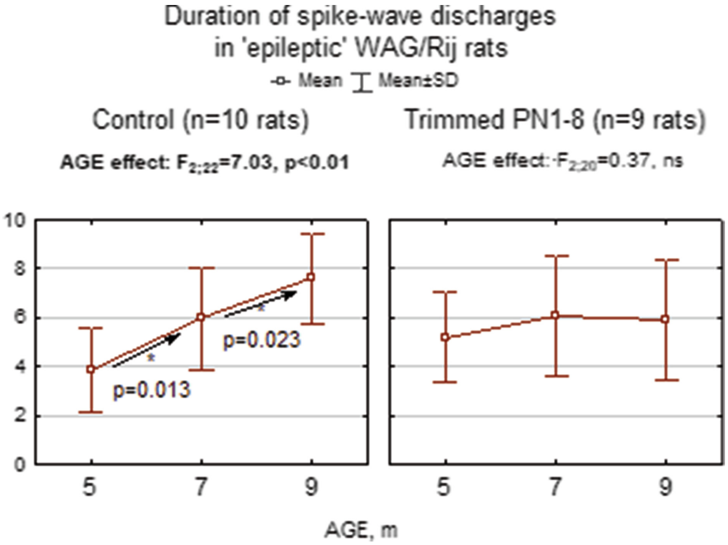

Fig. 2. The effect of bilateral whisker trimming during PN1–8 on duration of spike-wave discharges as measured in ECoG in freely moving rats during late ontogenesis. Labels are similar to that in Fig. 1.

In the control group, the number and mean duration of SWD were minimal at the age of 5 m as compared to other ages (Fig. 1 and 2). The number of epileptic discharges gradually increased between the age of 5 to 7 months (Fig. 1) suggesting an increased epileptogenic activity in the somatosensory cortex. Duration of epileptic discharges gradually increased during the period from 5 to 9 months and this may be accounted for age-related increase of synchronization within the thalamo-cortical network.

In the bilaterally trimmed rats, epileptic activity did not change between 5 and 9 months of age (Fig. 1 and 2). Therefore, whisker trimming on PN1–8 (1) prevented age-related increase of epileptogenic cortical epileptic zone during late ontogenesis as suggested by the number of seizures, and (2) abolished age-related increase of thalamo-cortical synchronization, as suggested by seizure duration.

3.2 Effect of Unilateral Neonatal Whisker Trimming (PN1–8) on the Excitability of Cortical Neurons in the Somatosensory Cortex

Voltage-clamp protocol was used to examine membrane properties of pyramid neurons in layer 5a of the somatosensory cortex. In the control group, no differences were found between the threshold of action potentials obtained in neurons from the left and right hemispheres. See Fig. 3a where blue columns display recorded at the "intact" hemisphere and pink columns – at the “sham trimmed” hemisphere. In contrast, in the trimmed animals, threshold of action potentials in pyramidal neurons located in the intact (right) hemisphere was lower than in the deprived (left) hemisphere (Fig. 3a).

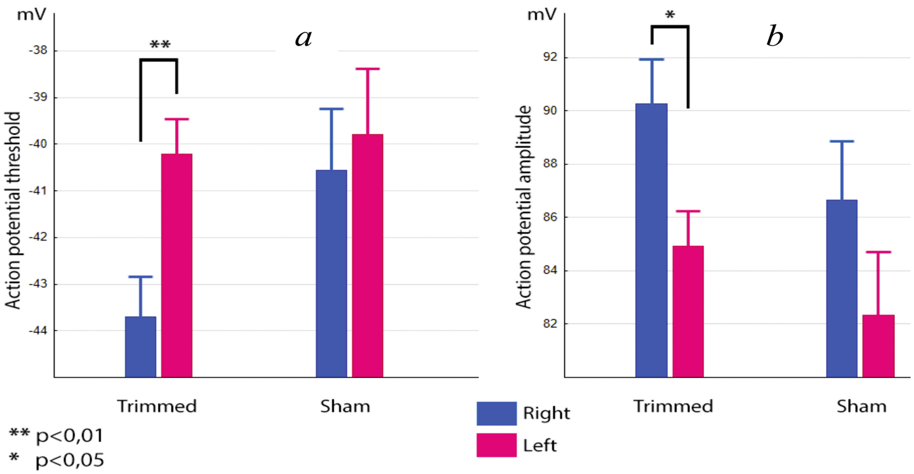

Fig. 3. The effect of unilateral whisker trimming (PN1–8) on parameters of action potentials obtained in pyramidal neurons from layer 5a of the whisker area in the somatosensory cortex (=barrelfield) as recorded on PN40–52. In “trimmed” group n = 9 rats, in control “Sham” group n = 6 rats. Blue columns - right side (intact); pink columns - left side (trimmed/sham trimmed). Asterisked are significant differences according to Mann-Whitney criterion.

In the control group, no differences were found between the amplitude of action potential obtained in the right and left hemispheres (“Sham” in Fig. 3b). In the “trimmed” group, neurons in the intact (right) hemisphere showed higher amplitude of action potential as compared to that on the left (deprived) side.

Furthermore, gradual increase in the depolarization current caused gradual increase in number of action potentials (Fig. 4). In the control group, pyramidal neurons in the right and left hemispheres showed similar current-dependent increase in number of action potentials (Fig. 4b). In the “trimmed” group (Fig. 4a), differences between the right and left sides were significant. When depolarization current exceeded 120 pA, neurons on the right (intact) side showed more action potentials than neurons in the left (trimmed) side.

The current clamp protocol was used to investigate the properties of Ih-current mediated by HCN channels. Hyperpolarizing and depolarizing currents of 200 to 500 pA with 20 pA increment were injected in respect to the resting potential. Each pulse lasted 1 s. Neuronal membrane resting potential was measured with the zero current injection. In this experimental paradigm, the activation of HCN channels caused the so-called “sagging” of voltage (“voltage sag,” Fig. 5a). Sag amplitude directly related to HCN channel activity and used to estimate membrane current Ih [29, 30].

In the control group, sag amplitude in the right and left sides was similar (Fig. 5c). In the “trimmed” group (Fig. 3b), sag amplitude in pyramidal neurons in the right (intact)

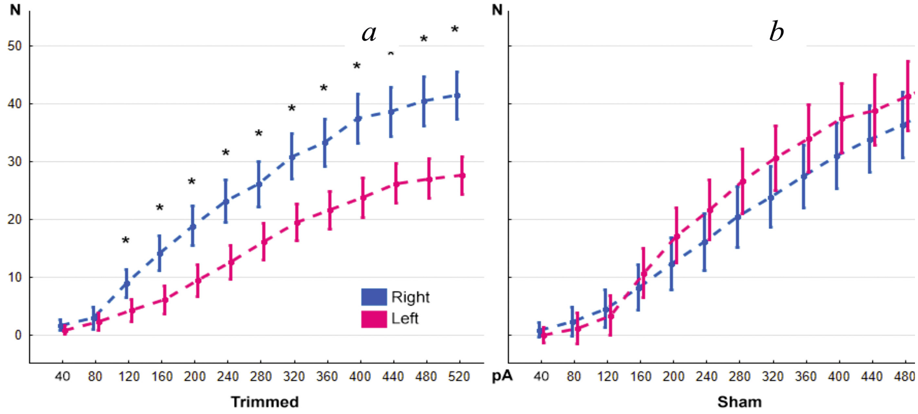

Fig. 4. The number of action potentials elicited by increase of depolarizing current in pyramid neurons of layer 5a in the whisker area in the somatosensory cortex (=barrelfield) as recorded on PN40–52. In "trimmed" group n = 9 rats, in control "Sham" group n = 6 rats. Blue columns - right side (intact); pink columns - left side (trimmed/sham trimmed). Asterisked are significant differences according to Mann-Whitney criterion ($p < 0.05$).

side was lower than in the left (trimmed) side. This suggests lower activity of HCN channels in pyramidal neurons at the intact area of whisker projections as compared to the sensory-deprived area.

In the unilaterally trimmed rats, whiskers on the trimmed side were re-grown at the age of recording, but neuronal properties in the intact and deprived barrelfield were significantly different. It is assumed that the intact barrelfield might be overloaded therefore their excitability increased (action potentials, Figs. 1 and 2). Considering an asymmetry of activity of Ih-current mediated by HCN channels (Fig. 3), lower activity of HCN channels at the intact barrelfield might contribute to higher excitability of pyramidal neurons.

4 Discussion

The "critical (sensitive) period" in functional maturation is restricted period of time when structural and functional properties of the nervous system are changed rapidly and crucially depended on sensory experience. This is the turning point of an alternative choice between two (or more) possible ways of development [33]. Pathological processes in the nervous system may also have a "critical period". We associate the "critical period" in the development of absence epilepsy with the ontogenesis of the somatosensory cortex. In our understanding, the critical period in the development of absence epilepsy is a "time window" when plasticity of the nervous system is the highest, and sensory experience during this period may predetermine the clinical manifestations of the disease in the distant future.

Giblin and Blumenfeld [34] assumed that the "critical period" of the development of absence epilepsy in WAG/Rij rats is the age of 2 to 4 months, since the first epileptic discharges in electroencephalogram appear during this period as well as upregulation

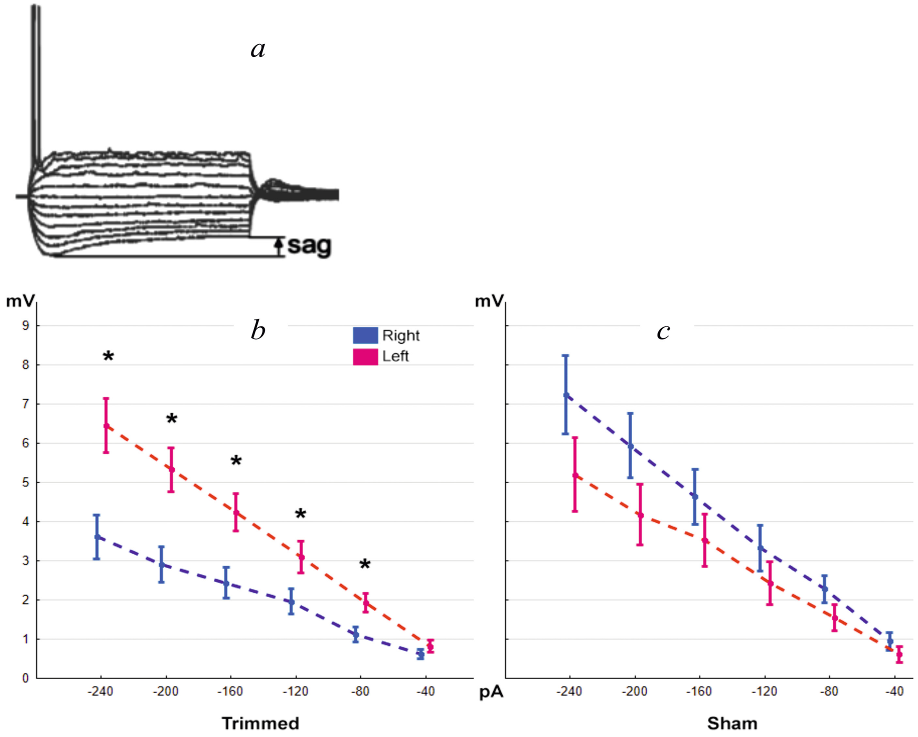

Fig. 5. Sag amplitude as measured in pyramid neurons of layer 5a in the whisker area in the somatosensory cortex (=barrelfield) as recorded on PN40–52. Blue columns - right side (intact); pink columns - left side (trimmed/sham trimmed). Asterisks indicate significant differences in sag amplitude according to Mann-Whitney criterion ($p < 0.05$). In “trimmed” group $n = 9$ rats, in control “Sham” group $n = 6$ rats. Blue columns - right side (intact); pink columns - left side (trimmed/sham trimmed).

of voltage-gated sodium channels Nav 1.1 and 1.6 in the somatosensory cortex. Here we found that neonatal sensory experience significantly impact development of absence epilepsy in WAG/Rij rat model, suggesting that the “critical period” of this disease may be shifted to earlier stages of development and it may related to disfunctioning of cortical HCN-channels.

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References

1. Landers, M., Philip Zeigler, H.: Development of rodent whisking: trigeminal input and central pattern generation. Somatosens Mot. Res. **23**(1–2), 1–0 (2006)
2. Grant, R.A., Mitchinson, B., Prescott, T.J.: The development of whisker control in rats in relation to locomotion. Dev. Psychobiol. **54**(2), 151–168 (2012). https://doi.org/10.1002/dev.20591

3. Feldmeyer, D., Brecht, M., Helmchen, F., Petersen, C.C., Poulet, J.F., Staiger, J.F., Luhmann, H.J., Schwarz, C.: Barrel cortex function. Prog. Neurobiol. **103**, 3–27 (2013). https://doi.org/10.1016/j.pneurobio.2012.11.002
4. Sullivan, R.M., Landers, M.S., Flemming, J., Vaught, C., Young, T.A., Polan, H.J.: Characterizing the functional significance of the neonatal rat vibrissae prior to the onset of whisking. Somatosens. Mot. Res. **20**(2), 157–162 (2003). https://doi.org/10.1016/j.brainres.2005.12.100
5. Mosconi, T., Woolsey, T.A., Jacquin, M.F.: Passive vs. active touch-induced activity in the developing whisker pathway. Eur. J. Neurosci. **32**(8), 1354–1363 (2010). https://doi.org/10.1111/j.1460-9568.2010.07396.x
6. Akhmetshina, D., Nasretdinov, A., Zakharov, A., Valeeva, G., Khazipov, R.: The nature of the sensory input to the neonatal rat barrel cortex. J. Neurosci. **36**(38), 9922–9932 (2016). https://doi.org/10.1523/JNEUROSCI.1781-16.2016
7. Diamond, M.E., Arabzadeh, E.: Whisker sensory system - from receptor to decision. Prog. Neurobiol. **103**, 28–40 (2013). https://doi.org/10.1016/j.pneurobio.2012.05.013
8. Inan, M., Crair, M.C.: Development of cortical maps: perspectives from the barrel cortex. Neuroscientist **13**(1), 49–61 (2007). https://doi.org/10.1177/1073858406296257
9. Erzurumlu, R.S., Gaspar, P.: Development and critical period plasticity of the barrel cortex. Eur. J. Neurosci. **35**(10), 1540–1553 (2012). https://doi.org/10.1111/j.1460-9568.2012.08075.x
10. Yang, J.W., Kilb, W., Kirischuk, S., Unichenko, P., Stüttgen, M.C., Luhmann, H.J.: Development of the whisker-to-barrel cortex system. Curr. Opin. Neurobiol. **53**, 29–34 (2018). https://doi.org/10.1016/j.conb.2018.04.023
11. Khazipov, R., Milh, M.: Early patterns of activity in the developing cortex: focus on the sensorimotor system. Semin. Cell Dev. Biol. **76**, 120–129 (2018). https://doi.org/10.1016/j.semcdb.2017.09.014
12. Belford, G.R., Killackey, H.P.: The sensitive period in the development of the trigeminal system of the neonatal rat. J. Comp. Neurol. **193**(2), 335–350 (1980)
13. Ibrahim, L., Wright, E.A.: The growth of rats and mice vibrissae under normal and some abnormal conditions. J. Embryol. Exp. Morphol. **33**(4), 831–844 (1975)
14. Simons, D.J., Land, P.W.: Early experience of tactile stimulation influences organization of somatic sensory cortex. Nature **326**, 694–697 (1987)
15. Fox, K.: A critical period for experience-dependent synaptic plasticity in rat barrel cortex. J. Neurosci. **12**(5), 1826–1838 (1992). https://doi.org/10.1523/JNEUROSCI.12-05-01826.1992
16. Erzurumlu, R.S.: Critical period for the whisker-barrel system. Exp. Neurol. **222**(1), 10–12 (2010). https://doi.org/10.1016/j.expneurol.2009.12.025
17. Meeren, H.K.M., Pijn, J.P.M., Van Luijtelaar, E.L.J.M., Coenen, A.M.L., Lopes da Silva, F.H.: Cortical focus drives widespread corticothalamic networks during spontaneous absence seizures in rats. J. Neurosci. **22**, 1480–1495 (2002)
18. van Luijtelaar, G., Sitnikova, E.: Global and focal aspects of absence epilepsy: the contribution of genetic models. Neurosci. Biobehav. Rev. **30**, 983–1003 (2006). https://doi.org/10.1016/j.neubiorev.2006.03.002
19. Depaulis, A., Charpier, S.: Pathophysiology of absence epilepsy: insights from genetic models. Neurosci. Lett. **667**, 53–65 (2018). https://doi.org/10.1016/j.neulet.2017.02.035
20. Manning, J.P., Richards, D.A., Leresche, N., Crunelli, V., Bowery, N.G.: Cortical-area specific block of genetically determined absence seizures by ethosuximide. Neuroscience **123**, 5–9 (2004)
21. Polack, P.-O., Guillemain, I., Hu, E., Deransart, C., Depaulis, A., Charpier, S.: Deep layer somatosensory cortical neurons initiate spike-and-wave discharges in a genetic model of absence seizures. J. Neurosci. **27**, 6590–6599 (2007). https://doi.org/10.1523/JNEUROSCI.0753-07.2007

22. Strauss, U., Kole, M.H., Brauer, A.U., Pahnke, J., Bajorat, R., Rolfs, A., Nitsch, R., Deisz, R.A.: An impaired neocortical Ih is associated with enhanced excitability and absence epilepsy. Eur. J. Neurosci. **19**, 3048–3058 (2004)
23. Ludwig, A., Zong, X., Jeglitsch, M., Hofmann, F., Biel, M.: A family of hyperpolarization-activated mammalian cation channels. Nature **393**, 587–591 (1998)
24. Kaupp, U.B., Seifert, R.: Molecular diversity of pacemaker ion channels. Ann. Rev. Physiol. **63**, 235–257 (2001)
25. Robinson, R.B., Siegelbaum, S.A.: Hyperpolarization-activated cation currents: from molecules to physiological function. Ann. Rev. Physiol. **65**, 453–480 (2003)
26. Biel, M., Wahl-Schott, C., Michalakis, S., Zong, X.: Hyperpolarization-activated cation channels: from genes to function. Physiol. Rev. **89**, 847–885 (2009)
27. Schridde, U., Strauss, U., Bräuer, A.U., van Luijtelaar, G.: Environmental manipulations early in development alter seizure activity, Ih and HCN1 protein expression later in life. Eur. J. Neurosci. **23**, 3346–3358 (2006)
28. Coenen, A.M.L., van Luijtelaar, E.L.J.M.: The WAG/Rij rat model for absence epilepsy: age and sex factors. Epilepsy Res. **1**, 297–301 (1987). https://doi.org/10.1016/0920-1211(87)90005-2
29. Kanyshkova, T., Meuth, P., Bista, P., Liu, Z., Ehling, P., Caputi, L., Doengi, M., Chetkovich, D.M., Pape, H.C., Budde, T.: Differential regulation of HCN channel isoform expression in thalamic neurons of epileptic and non-epileptic rat strains. Neurobiol. Dis. **45**, 450–461 (2012). https://doi.org/10.1016/j.nbd.2011.08.032
30. Zobeiri, M., Chaudhary, R., Datunashvili, M., Heuermann, R.J., Lüttjohann, A., Narayanan, V., Balfanz, S., Meuth, P., Chetkovich, D.M., Pape, H.C., Baumann, A., van Luijtelaar, G., Budde, T.: Modulation of thalamocortical oscillations by TRIP8b, an auxiliary subunit for HCN channels. Brain Struct. Funct. **223**(3), 1537–1564 (2018). https://doi.org/10.1007/s00429-017-1559-z
31. Coenen, A.M.L., van Luijtelaar, E.L.J.M.: Genetic animal models for absence epilepsy: a review of the WAG/Rij strain of rats. Behav. Genet. **33**, 635–655 (2003). https://doi.org/10.1023/A:1026179013847
32. Sitnikova, E., Hramov, A.E., Koronovskii, A.A., van Luijtelaar, G.: Sleep spindles and spike-wave discharges in EEG: their generic features, similarities and distinctions disclosed with Fourier transform and continuous wavelet analysis. J. Neurosci. Meth. **180**, 304–316 (2009). https://doi.org/10.1016/j.jneumeth.2009.04.006
33. Raevsky, V.V.: Reorganization of functional systems during ontogenesis. J. Evol. Biochem. Physiol. **38**(5), 502–506 (2002)
34. Giblin, K.A., Blumenfeld, H.: Is epilepsy a preventable disorder? New evidence from animal models. Neuroscientist **16**(3), 253–275 (2010). https://doi.org/10.1177/1073858409354385

Medical Applications

Study of Chronic Post-Comatose States: On the Way to Understanding the Phenomenon of Consciousness

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Abstract. Chronic disorders of consciousness (DOC; i.e., vegetative state and minimally consciousness state) develop in patients surviving coma after severe brain damage. Characteristic clinical feature of these syndromes is the dissociation between preserved wakefulness and complete or almost complete absence of awareness. Advanced diagnostic technologies provide us with valuable insights into the pathophysiology of chronic DOC, and structural and/or functional disconnection of elements of brain networks that are essential for information processing is believed to be its major underlying cause. Depending on the study modality, findings may include global or more localized decrease of cortical metabolism on PET scanning, or abnormal structural or functional connectivity on DTI or fMRI, as well as low-differentiated/disintegrated TMS-EEG responses, etc. Understanding the mechanisms of chronic DOC leads us to deeper knowledge about the phenomenon of human consciousness.

Keywords: Chronic disorders of consciousness · Vegetative state · Minimally consciousness state · PET · TMS-EEG · FMRI

1 Introduction

Understanding the neuronal architectures that give rise to conscious experience is one of the central unsolved problems of today's neuroscience. In the context of clinical medicine, researchers deal with a variety of severe conditions associated with the acute or prolonged loss of consciousness resulting from brain injury, hypoxia, cerebral ischemia or haemorrhage, infection, intoxication, etc. Unravelling mechanisms underlying these disorders may not only pave the way to the development of effective rehabilitation

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techniques but also create an approach to the understanding of the phenomenon of consciousness.

Prolonged disorders of consciousness (DOC) represent a spectrum of conditions that develop in patients surviving coma beyond 4 weeks after brain injury [1, 2]. Their characteristic feature is the dissociation between preserved wakefulness and complete or partial absence of awareness [3]. Indeed, typical clinical presentation of a vegetative state (VS) patient includes spontaneous eye-opening (that differentiates this condition from coma), restored sleep-wake cycle and completely of partially spared brainstem reflexes and functioning of the autonomic nervous system, while no apparent signs of purposeful behaviour and voluntary reactions can be seen [4, 5].

The degree to which the patient is able to demonstrate non-reflexive response to external stimuli determines clinical syndrome within the spectrum of DOC. The complete absence of behavioural signs of awareness along with preserved arousal indicates VS, or unresponsive wakefulness syndrome (UWS), that is a synonym replacing a “VS” term due to ethical considerations [2, 5, 6]. To cross the borderline between UWS/VS and minimally consciousness state (MCS) the patient must be capable to reflect his interaction with the environment. This may be low-level behavioural activity, such as visual pursuit, localization of noxious stimuli or appropriate emotional reaction, or more complex responses, e.g., command following, intelligible verbalization or discernible attempts to communicate. Depending on the complexity of this non-reflexive acts MCS is divided into the subcategories MCS “minus” and MCS “plus” [7]. The next level of recovery, denoted as an emergence from MCS, is achieved when the patient regains the ability to use the objects or communicate in a functional way [8]. Chances for recovery in DOC decrease after first 2 years post-injury and may be higher in traumatic brain injury and in patients who gain command following in early stages, with up to 35% patients achieving independence after 10 years [9, 10]. Therefore, as DOC patients generally maintain vital functions, their condition may remain unimproved for years and even decades.

Recent development of research techniques and theoretical constructs, such as global neuronal workspace theory and the integrated information theory, significantly promoted the studies of DOC [11–15]. Exploring mechanisms of DOC led to several advances in our understanding of neural correlates of consciousness, i.e., “the minimal set of neuronal events that gives rise to a specific aspect of a conscious percept” [16].

2 Anatomical Abnormalities in Chronic DOC

Even early morphological studies of DOC established widespread lesions in the cerebral hemispheres along with relatively spared brainstem structures as characteristic features of UWS/VS [17]. While in traumatic brain injury typical pattern includes diffuse axonal damage and ischaemic thalamic lesions [18, 19], in non-traumatic DOC diffuse cortical laminar necrosis and multifocal cortical infarctions were often found [17, 20]. These findings support the widely accepted view that content of consciousness is determined by the function of the thalamocortical system, while arousal is controlled by the ascending reticular activating system and forebrain [21, 22]. Therefore, dysfunction or disconnection between these structures underlies clinical presentation of chronic DOC. Of note, the pattern of abnormalities is less severe in MCS patients than in UWS/VS [23].

Standard MRI data seen in prolonged DOC are also consistent with more significant burden of abnormalities in UWS/VS than in MCS. T1-weighted MRI demonstrated that DOC states are characterized by severe atrophy of the thalamus, basal ganglia, hippocampus and basal frontal lobes, with clinical measures of awareness and wakefulness associated with the degree of tissue atrophy within thalamic and basal ganglia nuclei, respectively [24]. Typical patterns of MRI lesions (i.e., diffuse cortical atrophy, ventricular enlargement, leukoaraiosis, degenerative lesions in the thalamus and brainstem) were presented as a scale that allows classifying UWS/VS and MCS patients [25].

In a study exploiting brain volumetry DOC patients were characterized by smaller regional brain volumes than healthy subjects, with atrophy of grey matter occurred faster in UWS/VS compared to MCS [26]. White matter integrity studies using diffusion MRI approaches (i.e., diffusion tensor imaging, DTI) demonstrated that in traumatic brain injury corpus callosum lesions, namely fractional anisotropy measure, may reflect levels of consciousness [27]. Post-anoxic DOC patients are characterized by more distributed white matter changes [28]. Levels of consciousness correlated with the integrity of pathways between regions comprising default mode network (DMN; see below) and the thalamus [29]. DTI results discriminated MCS and VS patients by abnormalities in subcortical white matter and thalamic regions and successfully predicted clinical scores; of note, no differences between VS and MCS were seen considering brainstem changes [30]. Another diffusion MRI-based approach to measuring structural integrity, diffusional kurtosis imaging, also demonstrated its utility in the assessment of microstructural changes in both white and grey brain matter in DOC [31, 32]. Novel approaches to data analysis, such as machine learning, may increase the accuracy of classification across various levels of consciousness (UWS/VS, MCS “minus”, and MCS “plus”) using thalamocortical connectivity up to 84% [33].

3 Functional Neuroimaging in Chronic DOC

Functional neuroimaging methods rely on the assessment of brain activity via determining cerebral blood flow or cerebral metabolism. Positron emission tomography (PET) uses radioactively-labelled molecules of ^{18}F-fluorodeoxyglucose (FDG) to estimate glucose uptake, that indirectly represents neural activity, or $H2^{15}O$ to assess regional cerebral flow. PET-FDG studies demonstrated a reduction of global metabolism in UWS/VS patients to 40%–50% compared to healthy and awake volunteers [34, 35]. In MCS patients global metabolism level was significantly higher than in VS (55% vs. 42% of normal values), that allowed differentiating between these two conditions [36]. However, recovery of consciousness was not necessarily associated with the restoration of global metabolic activity [37]. Therefore, maintaining the global cerebral metabolism at a certain level may be necessary but insufficient for the recovery of consciousness, and restoration of awareness may be related to the level of global metabolism in a nonlinear fashion. Studies of regional metabolism in UWS/VS patients indicated decreased glucose uptake in a large-scale frontoparietal network [38], including the medial association cortex (i.e., anterior cingulate/medial prefrontal cortex and posterior cingulate/precuneus cortex) and the lateral association cortex (prefrontal and posterolateral cortex) that are the components of DMN [38–40]. In MCS patients the frontoparietal network metabolism might be partially preserved, while in UWS/VS more homogeneous decrease in cortical metabolism was demonstrated [36]. Recovery of consciousness was shown to be accompanied by an increase of metabolism in the corresponding cortical areas [37] and restoration of thalamocortical connectivity [41]. Therefore, preservation of the widespread frontoparietal neural network and its connections to thalamic nuclei is an essential prerequisite for consciousness.

Functional MRI (fMRI) assesses brain activity by measuring BOLD signal oscillations in response to a stimulus or in resting state. The latter approach has advantages when applied in DOC patients as it does not require interaction, and allows to estimate functional connectivity between brain regions [42]. Impairment of the connectivity within several large-scale brain networks has been identified in DOC patients, with abnormalities being more severe in UWS/VS than in MCS [43–46]. Specifically, the role of DMN connectivity changes ni DOC has been studied extensively, as it is the most robust and widely reproduced finding [46]. It has been established that abnormalities of connectivity within the DMN are associated with the degree of clinical impairment [47] and predict the outcome [48] in DOC. Whole-brain connectivity patterns have also been used to estimate the degree of connectome disruption in UWS/VS and MCS [49, 50].

Activation fMRI studies using the auditory, visual or somatosensory paradigm are aimed at detecting cortical responses to specific stimuli or instructions. In response to auditory or noxious stimuli, UWS/VS patients demonstrated activation only at the level of primary cortical areas, without the involvement of associative zones, in contrast to high-level cortical activation, seen in MCS [51, 52]. Higher-level activation was also associated with a greater chance of recovery at long-term follow-up [53]. Experiments using cognitive fMRI paradigms, when the patient is instructed to imagine some action, led to a discovery of the phenomenon of cognitive-motor dissociation, or "covert consciousness", i.e., near-normal fMRI activation pattern in patients lacking any behavioural signs of purposeful motor activity [54–56]. A recent meta-analysis indicated that the prevalence of cognitive-motor dissociation among DOC patients may approach 15% depending on the modality and paradigm used for testing [57]. Of note, recent guidelines on the diagnosis of coma and prolonged DOC considered several functional imaging techniques (PET, resting-state fMRI and active fMRI paradigms) as a part of multimodal assessment in unresponsive patients [58].

4 Electrophysiological Studies in Chronic DOC

EEG and event-related potentials (ERP) are valuable tools for clinical and research purpose in DOC. From the perspective of medical care, EEG plays a crucial role in the detection of epileptiform activity that may be seen in the absence of seizures. Visual analysis of standard EEG, sleep EEG, quantitative analysis of high-density EEG and cognitive ERP (P300) were also included in the recent diagnostic guidelines [58]. Detection of reactivity to stimuli and the presence of elements of sleep on EEG may indicate a higher level of awareness and better prognosis. Spectral analysis of high-density EEG, assessment of functional and effective connectivity may show differences between UWS/VS and MCS patients [59], with machine learning algorithms for analysis seem promising for this task [60, 61]. Furthermore, active EEG paradigms allow for the identification of cognitive-motor dissociation. P300, that is thought to be caused by activation of attention and working memory, may discriminate UWS/VS and MCS; however, the sensitivity of this method is low [62].

Recently, a theoretically based electrophysiological measure of consciousness, a perturbational complexity index (PCI), was introduced [63]. PCI is derived from the EEG response to transcranial magnetic stimulation (TMS) and measures the complexity of the spatiotemporal pattern of TMS-triggered cortical activation. This approach allows to assess functional differentiation and functional integration of thalamocortical networks, that is considered to be an essential prerequisite for consciousness within the framework of the integrated information theory [13, 64]. PCI is expected to be low when there is the loss of integration between cortical areas or when the differentiation of responses is low (i.e., perturbation elicit a stereotypic reaction in most areas). Conversely, PCI is high if many integrated areas are affected with the perturbation and they produce differentiated responses. PCI provided reproducible values when tested in healthy subjects during wakefulness, dreaming, non-rapid eye movement sleep, and different levels of pharmacological sedation [63]. An empirical threshold value of 0.31 was suggested to discriminate between conscious and unconscious states, that was later confirmed in the setting of chronic DOC, with the sensitivity of 94.7% in detecting MCS [65]. Considering its relevance at the individual subject level, TMS-EEG was acknowledged as a part of a multimodal assessment of chronic DOC patients, according to recent diagnostic guideline [58]. Several studies demonstrated congruence between the distribution of PCI values and patterns of structural [66, 67] and metabolic [68] abnormalities in DOC subjects, paving the way to more detailed the stratification of this category of patients.

5 Conclusion

Novel research methods applied to chronic DOC patients indicate structural and/or functional disintegration of groups of neurons and neural networks, which blocks information processing at the local level and interaction with network components. This manifests as impaired cortical metabolism, disturbed structural and functional connectivity, and poorly differentiated/disintegrated neuronal responses to external stimuli. It allows us to characterize the state of conscious wakefulness as a complex, differentiated and highly energy-consuming activity of neural networks in the thalamocortical system, supported by the activating effects of parts of the brainstem and basal frontal lobe. This activity is realized through dynamic neural ensembles and large-scale neural networks including neurons of the prefrontal, parietal and cingulate cortex, and results in the processing of incoming and existing information, and the formation of conscious perception.

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References

1. Giacino, J.T., Katz, D.I., Schiff, N.D., Whyte, J., Ashman, E.J., Ashwal, S., Barbano, R., Hammond, F.M., Laureys, S., Ling, G.S.F., Nakase-Richardson, R., Seel, R.T., Yablon, S., Getchius, T.S.D., Gronseth, G.S., Armstrong, M.J.: Practice guideline update recommendations summary: disorders of consciousness. Neurology **91**, 450–460 (2018). https://doi.org/10.1212/WNL.0000000000005926
2. Giacino, J.T., Katz, D.I., Schiff, N.D., Whyte, J., Ashman, E.J., Ashwal, S., Barbano, R., Hammond, F.M., Laureys, S., Ling, G.S.F.F., Nakase-Richardson, R., Seel, R.T., Yablon, S., Getchius, T.S.D.D., Gronseth, G.S., Armstrong, M.J.: Comprehensive systematic review update summary: disorders of consciousness: report of the guideline development, dissemination, and implementation subcommittee of the American Academy of Neurology; the American Congress of Rehabilitation Medicine; and the National Institute on Disability, Independent Living, and Rehabilitation Research. Neurology **91**, 461–470 (2018). https://doi.org/10.1212/WNL.0000000000005928
3. Giacino, J.T., Schnakers, C., Rodriguez-Moreno, D., Kalmar, K., Schiff, N., Hirsch, J.: Behavioral assessment in patients with disorders of consciousness: gold standard or fool's gold? In: Progress in Brain Research, pp. 33–48. Elsevier (2009)
4. Schnakers, C.: Update on diagnosis in disorders of consciousness. Exp. Rev. Neurother. **20**, 997–1004 (2020). https://doi.org/10.1080/14737175.2020.1796641
5. Multi-Society Task Force on PVS: Medical aspects of the persistent vegetative state. N. Engl. J. Med. **330**, 1572–1579 (1994). https://doi.org/10.1056/NEJM199406023302206
6. Laureys, S., Celesia, G.G., Cohadon, F., Lavrijsen, J., León-Carrión, J., Sannita, W.G., Sazbon, L., Schmutzhard, E., von Wild, K.R., Zeman, A., Dolce, G.: Unresponsive wakefulness syndrome: a new name for the vegetative state or apallic syndrome. BMC Med. **8**, 2–5 (2010). https://doi.org/10.1186/1741-7015-8-68
7. Bruno, M.A., Vanhaudenhuyse, A., Thibaut, A., Moonen, G., Laureys, S.: From unresponsive wakefulness to minimally conscious PLUS and functional locked-in syndromes: recent advances in our understanding of disorders of consciousness. J. Neurol. **258**, 1373–1384 (2011). https://doi.org/10.1007/s00415-011-6114-x
8. Giacino, J.T., Ashwal, S., Childs, N., Cranford, R., Jennett, B., Katz, D.I., Kelly, J.P., Rosenberg, J.H., Whyte, J., Zafonte, R.D., Zasler, N.D.: The minimally conscious state: definition and diagnostic criteria. Neurology **58**, 349–353 (2002). https://doi.org/10.1212/wnl.58.3.349
9. Hammond, F.M., Giacino, J.T., Nakase Richardson, R., Sherer, M., Zafonte, R.D., Whyte, J., Arciniegas, D.B., Tang, X.: Disorders of consciousness due to traumatic brain injury: functional status ten years post-injury. J. Neurotrauma. **36**, 1136–1146 (2019). https://doi.org/10.1089/neu.2018.5954
10. Wilkins, T.E., Beers, S.R., Borrasso, A.J., Brooks, J., Mesley, M., Puffer, R., Chang, Y.-F., Okonkwo, D.O., Puccio, A.M.: Favorable functional recovery in severe traumatic brain injury survivors beyond six months. J. Neurotrauma. **36**, 3158–3163 (2019). https://doi.org/10.1089/neu.2018.6153
11. Storm, J.F., Boly, M., Casali, A.G., Massimini, M., Olcese, U., Pennartz, C.M.A., Wilke, M.: Consciousness regained: disentangling mechanisms, brain systems, and behavioral responses. J. Neurosci. **37**, 10882–10893 (2017). https://doi.org/10.1523/JNEUROSCI.1838-17.2017
12. Koch, C., Massimini, M., Boly, M., Tononi, G.: Neural correlates of consciousness: progress and problems. Nat. Rev. Neurosci. **17**, 307–321 (2016). https://doi.org/10.1038/nrn.2016.22
13. Tononi, G., Boly, M., Massimini, M., Koch, C.: Integrated information theory: from consciousness to its physical substrate. Nat. Rev. Neurosci. **17**, 450–461 (2016). https://doi.org/10.1038/nrn.2016.44

14. Oizumi, M., Albantakis, L., Tononi, G.: From the phenomenology to the mechanisms of consciousness: integrated information theory 3.0. PLOS Comput. Biol. **10**, e1003588 (2014). https://doi.org/10.1371/journal.pcbi.1003588
15. Dehaene, S., Changeux, J.-P.: Experimental and theoretical approaches to conscious processing. Neuron **70**, 200–227 (2011). https://doi.org/10.1016/j.neuron.2011.03.018
16. Crick, F., Koch, C.: A framework for consciousness. Nat. Neurosci. **6**, 119–126 (2003). https://doi.org/10.1038/nn0203-119
17. Dougherty, J.H., Rawlinson, D.G., Levy, D.E., Plum, F.: Hypoxic-ischemic brain injury and the vegetative state: clinical and neuropathologic correlation. Neurology **31**, 991 (1981). https://doi.org/10.1212/WNL.31.8.991
18. Adams, J.H.: The neuropathology of the vegetative state after an acute brain insult. Brain **123**, 1327–1338 (2000). https://doi.org/10.1093/brain/123.7.1327
19. Giacino, J.T., Malone, R.: The vegetative and minimally conscious states. Handb. Clin. Neurol. **90**, 99–111 (2008). https://doi.org/10.1016/S0072-9752(07)01706-X
20. Kinney, H.C., Korein, J., Panigrahy, A., Dikkes, P., Goode, R.: Neuropathological findings in the brain of Karen Ann Quinlan – the role of the thalamus in the persistent vegetative state. N. Engl. J. Med. **330**, 1469–1475 (1994). https://doi.org/10.1056/NEJM199405263302101
21. Laureys, S.: The neural correlate of (un)awareness: lessons from the vegetative state. Trends Cogn. Sci. **9**, 556–559 (2005). https://doi.org/10.1016/j.tics.2005.10.010
22. Schnakers, C., Laureys, S.: Coma and Disorders of Consciousness, 2nd edn. Springer, Heidelberg (2017)
23. Jennett, B., Adams, J.H., Murray, L.S., Graham, D.I.: Neuropathology in vegetative and severely disabled patients after head injury. Neurology **56**, 486–490 (2001). https://doi.org/10.1212/WNL.56.4.486
24. Lutkenhoff, E.S., Chiang, J., Tshibanda, L., Kamau, E., Kirsch, M., Pickard, J.D., Laureys, S., Owen, A.M., Monti, M.M.: Thalamic and extrathalamic mechanisms of consciousness after severe brain injury. Ann. Neurol. **78**, 68–76 (2015). https://doi.org/10.1002/ana.24423
25. Morozova, S., Kremneva, E., Sergeev, D., Sinitsyn, D., Legostaeva, L., Iazeva, E., Krotenkova, M., Ryabinkina, Y., Suponeva, N., Piradov, M.: Conventional structural magnetic resonance imaging in differentiating chronic disorders of consciousness. Brain Sci. **8**, 144 (2018). https://doi.org/10.3390/brainsci8080144
26. Annen, J., Frasso, G., Crone, J.S., Heine, L., Di Perri, C., Martial, C., Cassol, H., Demertzi, A., Naccache, L., Laureys, S.: Regional brain volumetry and brain function in severely brain-injured patients. Ann. Neurol. **83**, 842–853 (2018). https://doi.org/10.1002/ana.25214
27. Zhang, J., Wei, R.-L., Peng, G.-P., Zhou, J.-J., Wu, M., He, F.-P., Pan, G., Gao, J., Luo, B.-Y.: Correlations between diffusion tensor imaging and levels of consciousness in patients with traumatic brain injury: a systematic review and meta-analysis. Sci. Rep. **7**, 2793 (2017). https://doi.org/10.1038/s41598-017-02950-3
28. van der Eerden, A.W., Khalilzadeh, O., Perlbarg, V., Dinkel, J., Sanchez, P., Vos, P.E., Luyt, C.-E., Stevens, R.D., Menjot de Champfleur, N., Delmaire, C., Tollard, E., Gupta, R., Dormont, D., Laureys, S., Benali, H., Vanhaudenhuyse, A., Galanaud, D., Puybasset, L., NICER (Neuro Imaging for Coma Emergence and Recovery) Consortium: White matter changes in comatose survivors of anoxic ischemic encephalopathy and traumatic brain injury: comparative diffusion-tensor imaging study. Radiology **270**, 506–16 (2014). https://doi.org/10.1148/radiol.13122720
29. Fernández-Espejo, D., Soddu, A., Cruse, D., Palacios, E.M., Junque, C., Vanhaudenhuyse, A., Rivas, E., Newcombe, V., Menon, D.K., Pickard, J.D., Laureys, S., Owen, A.M.: A role for the default mode network in the bases of disorders of consciousness. Ann. Neurol. **72**, 335–343 (2012). https://doi.org/10.1002/ana.23635

30. Fernández-Espejo, D., Bekinschtein, T., Monti, M.M., Pickard, J.D., Junque, C., Coleman, M.R., Owen, A.M.: Diffusion weighted imaging distinguishes the vegetative state from the minimally conscious state. Neuroimage **54**, 103–112 (2011). https://doi.org/10.1016/j.neuroimage.2010.08.035
31. Jensen, J.H., Helpern, J.A.: MRI quantification of non-Gaussian water diffusion by kurtosis analysis. NMR Biomed. **23**, 698–710 (2010). https://doi.org/10.1002/nbm.1518
32. Kremneva, E.I., Legostaeva, L.A., Morozova, S.N., Sergeev, D.V., Sinitsyn, D.O., Iazeva, E.G., Suslin, A.S., Suponeva, N.A., Krotenkova, M.V., Piradov, M.A., Maximov, I.I.: Feasibility of non-gaussian diffusion metrics in chronic disorders of consciousness. Brain Sci. **9**, 123 (2019). https://doi.org/10.3390/brainsci9050123
33. Zheng, Z.S., Reggente, N., Lutkenhoff, E., Owen, A.M., Monti, M.M.: Disentangling disorders of consciousness: insights from diffusion tensor imaging and machine learning. Hum. Brain Mapp. **38**, 431–443 (2017). https://doi.org/10.1002/hbm.23370
34. De Volder, A.G., Goffinet, A.M., Bol, A., Michel, C., Barsy, T., Laterre, C.: Brain glucose metabolism in postanoxic syndrome: positron emission tomographic study. Arch. Neurol. **47**, 197–204 (1990). https://doi.org/10.1001/archneur.1990.00530020103022
35. Rudolf, J., Ghaemi, M., Ghaemi, M., Haupt, W.F., Szelies, B., Heiss, W.D.: Cerebral glucose metabolism in acute and persistent vegetative state. J. Neurosurg. Anesthesiol. **11**, 17–24 (1999). https://doi.org/10.1097/00008506-199901000-00004
36. Stender, J., Kupers, R., Rodell, A., Thibaut, A., Chatelle, C., Bruno, M.A., Gejl, M., Bernard, C., Hustinx, R., Laureys, S., Gjedde, A.: Quantitative rates of brain glucose metabolism distinguish minimally conscious from vegetative state patients. J. Cereb. Blood Flow Metab. **35**, 58–65 (2015). https://doi.org/10.1038/jcbfm.2014.169
37. Laureys, S., Lemaire, C., Maquet, P., Phillips, C., Franck, G.: Cerebral metabolism during vegetative state and after recovery to consciousness. J. Neurol. Neurosurg. Psychiatry. **67**, 121 (1999). https://doi.org/10.1136/jnnp.67.1.121
38. Laureys, S., Goldman, S., Phillips, C., Van Bogaert, P., Aerts, J., Luxen, A., Franck, G., Maquet, P.: Impaired effective cortical connectivity in vegetative state: preliminary investigation using PET. Neuroimage **9**, 377–382 (1999). https://doi.org/10.1006/nimg.1998.0414
39. Laureys, S., Pellas, F., Van Eeckhout, P., Ghorbel, S., Schnakers, C., Perrin, F., Berré, J., Faymonville, M.E., Pantke, K.H., Damas, F., Lamy, M., Moonen, G., Goldman, S.: The locked-in syndrome: what is it like to be conscious but paralyzed and voiceless? Prog. Brain Res. **150**, 495–511 (2005). https://doi.org/10.1016/S0079-6123(05)50034-7
40. Lull, N., Noé, E., Lull, J.J., García-Panach, J., Chirivella, J., Ferri, J., López-Aznar, D., Sopena, P., Robles, M.: Voxel-based statistical analysis of thalamic glucose metabolism in traumatic brain injury: relationship with consciousness and cognition. Brain Inj. **24**, 1098–1107 (2010). https://doi.org/10.3109/02699052.2010.494592
41. Laureys, S., Faymonville, M.E., Luxen, A., Lamy, M., Franck, G., Maquet, P.: Restoration of thalamocortical connectivity after recovery from persistent vegetative state. Lancet **355**, 1790–1791 (2000). https://doi.org/10.1016/S0140-6736(00)02271-6
42. Lowe, M.J., Dzemidzic, M., Lurito, J.T., Mathews, V.P., Phillips, M.D.: Correlations in low-frequency BOLD fluctuations reflect cortico-cortical connections. Neuroimage **12**, 582–587 (2000). https://doi.org/10.1006/nimg.2000.0654
43. Demertzi, A., Antonopoulos, G., Heine, L., Voss, H.U., Crone, J.S., De Los Angeles, C., Bahri, M.A., Di Perri, C., Vanhaudenhuyse, A., Charland-Verville, V., Kronbichler, M., Trinka, E., Phillips, C., Gomez, F., Tshibanda, L., Soddu, A., Schiff, N.D., Whitfield-Gabrieli, S., Laureys, S.: Intrinsic functional connectivity differentiates minimally conscious from unresponsive patients. Brain **138**, 2619–2631 (2015). https://doi.org/10.1093/brain/awv169

44. Demertzi, A., Gómez, F., Crone, J.S., Vanhaudenhuyse, A., Tshibanda, L., Noirhomme, Q., Thonnard, M., Charland-Verville, V., Kirsch, M., Laureys, S., Soddu, A.: Multiple fMRI system-level baseline connectivity is disrupted in patients with consciousness alterations. Cortex **52**, 35–46 (2014). https://doi.org/10.1016/j.cortex.2013.11.005
45. Wu, X., Zou, Q., Hu, J., Tang, W., Mao, Y., Gao, L., Zhu, J., Jin, Y., Wu, X., Lu, L., Zhang, Y., Zhang, Y., Dai, Z., Gao, J.H., Weng, X., Zhou, L., Northoff, G., Giacino, J.T., He, Y., Yang, Y.: Intrinsic functional connectivity patterns predict consciousness level and recovery outcome in acquired brain injury. J. Neurosci. **35**, 12932–12946 (2015). https://doi.org/10.1523/JNEUROSCI.0415-15.2015
46. Bodien, Y.G., Chatelle, C., Edlow, B.L.: Functional networks in disorders of consciousness. Semin. Neurol. **37**, 485–502 (2017). https://doi.org/10.1055/s-0037-1607310
47. Vanhaudenhuyse, A., Noirhomme, Q., Tshibanda, L.J.-F., Bruno, M.-A., Boveroux, P., Schnakers, C., Soddu, A., Perlbarg, V., Ledoux, D., Brichant, J.-F., Moonen, G., Maquet, P., Greicius, M.D., Laureys, S., Boly, M.: Default network connectivity reflects the level of consciousness in non-communicative brain-damaged patients. Brain **133**, 161–171 (2010). https://doi.org/10.1093/brain/awp313
48. Silva, S., de Pasquale, F., Vuillaume, C., Riu, B., Loubinoux, I., Geeraerts, T., Seguin, T., Bounes, V., Fourcade, O., Demonet, J.-F., Péran, P.: Disruption of posteromedial large-scale neural communication predicts recovery from coma. Neurology **85**, 2036–2044 (2015). https://doi.org/10.1212/WNL.0000000000002196
49. Demertzi, A., Tagliazucchi, E., Dehaene, S., Deco, G., Barttfeld, P., Raimondo, F., Martial, C., Fernández-Espejo, D., Rohaut, B., Voss, H.U., Schiff, N.D., Owen, A.M., Laureys, S., Naccache, L., Sitt, J.D.: Human consciousness is supported by dynamic complex patterns of brain signal coordination. Sci. Adv. **5**, eaat7603 (2019). https://doi.org/10.1126/sciadv.aat7603
50. Sinitsyn, D.O., Legostaeva, L.A., Kremneva, E.I., Morozova, S.N., Poydasheva, A.G., Mochalova, E.G., Chervyakova, O.G., Ryabinkina, J.V., Suponeva, N.A., Piradov, M.A.: Degrees of functional connectome abnormality in disorders of consciousness. Hum. Brain Mapp. **39**, 2929–2940 (2018). https://doi.org/10.1002/hbm.24050
51. Bruno, M.A., Majerus, S., Boly, M., Vanhaudenhuyse, A., Schnakers, C., Gosseries, O., Boveroux, P., Kirsch, M., Demertzi, A., Bernard, C., Hustinx, R., Moonen, G., Laureys, S.: Functional neuroanatomy underlying the clinical subcategorization of minimally conscious state patients. J. Neurol. **259**, 1087–1098 (2012). https://doi.org/10.1007/s00415-011-6303-7
52. Laureys, S., Schiff, N.D.: Coma and consciousness: Paradigms (re)framed by neuroimaging. Neuroimage **61**, 478–491 (2012). https://doi.org/10.1016/j.neuroimage.2011.12.041
53. Di, H., Boly, M., Weng, X., Ledoux, D., Laureys, S.: Neuroimaging activation studies in the vegetative state: predictors of recovery? Clin. Med. Lond. **8**, 502–507 (2008). https://doi.org/10.7861/clinmedicine.8-5-502
54. Owen, A.M., Coleman, M.R., Boly, M., Davis, M.H., Laureys, S., Pickard, J.D.: Detecting awareness in the vegetative state. Science **313**, 1402 (2006). https://doi.org/10.1126/science.1130197
55. Boly, M., Coleman, M.R., Davis, M.H., Hampshire, A., Bor, D., Moonen, G., Maquet, P.A., Pickard, J.D., Laureys, S., Owen, A.M.: When thoughts become action: an fMRI paradigm to study volitional brain activity in non-communicative brain injured patients. Neuroimage **36**, 979–992 (2007). https://doi.org/10.1016/j.neuroimage.2007.02.047
56. Monti, M.M., Vanhaudenhuyse, A., Coleman, M.R., Boly, M., Pickard, J.D., Tshibanda, L., Owen, A.M., Laureys, S.: Willful modulation of brain activity in disorders of consciousness. N. Engl. J. Med. **362**, 579–589 (2010). https://doi.org/10.1056/NEJMoa0905370

57. Kondziella, D., Friberg, C.K., Frokjaer, V.G., Fabricius, M., Møller, K.: Preserved consciousness in vegetative and minimal conscious states: systematic review and meta-analysis. J. Neurol. Neurosurg. Psychiatry. **87**, 485–492 (2016). https://doi.org/10.1136/jnnp-2015-310958
58. Kondziella, D., Bender, A., Diserens, K., van Erp, W., Estraneo, A., Formisano, R., Laureys, S., Naccache, L., Ozturk, S., Rohaut, B., Sitt, J.D., Stender, J., Tiainen, M., Rossetti, A.O., Gosseries, O., Chatelle, C.: European Academy of Neurology guideline on the diagnosis of coma and other disorders of consciousness. Eur. J. Neurol. **27**, 741–756 (2020). https://doi.org/10.1111/ene.14151
59. Song, M., Zhang, Y., Cui, Y., Yang, Y., Jiang, T.: Brain network studies in chronic disorders of consciousness: advances and perspectives. Neurosci. Bull. **34**, 592–604 (2018). https://doi.org/10.1007/s12264-018-0243-5
60. Claassen, J., Doyle, K., Matory, A., Couch, C., Burger, K.M., Velazquez, A., Okonkwo, J.U., King, J.-R., Park, S., Agarwal, S., Roh, D., Megjhani, M., Eliseyev, A., Connolly, E.S., Rohaut, B.: Detection of brain activation in unresponsive patients with acute brain injury. N. Engl. J. Med. **380**, 2497–2505 (2019). https://doi.org/10.1056/NEJMoa1812757
61. King, J.-R., Sitt, J.D., Faugeras, F., Rohaut, B., El Karoui, I., Cohen, L., Naccache, L., Dehaene, S.: Information sharing in the brain indexes consciousness in noncommunicative patients. Curr. Biol. **23**, 1914–1919 (2013). https://doi.org/10.1016/j.cub.2013.07.075
62. Ragazzoni, A., Cincotta, M., Giovannelli, F., Cruse, D., Young, G.B., Miniussi, C., Rossi, S.: Clinical neurophysiology of prolonged disorders of consciousness: from diagnostic stimulation to therapeutic neuromodulation. Clin. Neurophysiol. **128**, 1629–1646 (2017). https://doi.org/10.1016/j.clinph.2017.06.037
63. Casali, A.G., Gosseries, O., Rosanova, M., Boly, M., Sarasso, S., Casali, K.R., Casarotto, S., Bruno, M.-A.M.A., Laureys, S., Tononi, G., Massimini, M.: A theoretically based index of consciousness independent of sensory processing and behavior. Sci. Transl. Med. **5**, 105–198 (2013). https://doi.org/10.1126/scitranslmed.3006294
64. Tononi, G., Edelman, G.M.: Consciousness and complexity. Science **282**, 1846–1851 (1998). https://doi.org/10.1126/science.282.5395.1846
65. Casarotto, S., Comanducci, A., Rosanova, M., Sarasso, S., Fecchio, M., Napolitani, M., Pigorini, A., Casali, A.G., Trimarchi, P.D., Boly, M., Gosseries, O., Bodart, O., Curto, F., Landi, C., Mariotti, M., Devalle, G., Laureys, S., Tononi, G., Massimini, M., Casali, A.G., Trimarchi, P.D., Boly, M., Gosseries, O., Bodart, O., Curto, F., Landi, C., Mariotti, M., Devalle, G., Laureys, S., Tononi, G., Massimini, M.: Stratification of unresponsive patients by an independently validated index of brain complexity. Ann. Neurol. **80**, 718–729 (2016). https://doi.org/10.1002/ana.24779
66. Bodart, O., Amico, E., Gómez, F., Casali, A.G., Wannez, S., Heine, L., Thibaut, A., Annen, J., Boly, M., Casarotto, S., Rosanova, M., Massimini, M., Laureys, S., Gosseries, O.: Global structural integrity and effective connectivity in patients with disorders of consciousness. Brain Stimul. **11**, 358–365 (2018). https://doi.org/10.1016/j.brs.2017.11.006
67. Lutkenhoff, E.S., Johnson, M.A., Casarotto, S., Massimini, M., Monti, M.M.: Subcortical atrophy correlates with the perturbational complexity index in patients with disorders of consciousness. Brain Stimul. **13**, 1426–1435 (2020). https://doi.org/10.1016/j.brs.2020.07.012
68. Bodart, O., Gosseries, O., Wannez, S., Thibaut, A., Annen, J., Boly, M., Rosanova, M., Casali, A.G., Casarotto, S., Tononi, G., Massimini, M., Laureys, S.: Measures of metabolism and complexity in the brain of patients with disorders of consciousness. NeuroImage Clin. **14**, 354–362 (2017). https://doi.org/10.1016/j.nicl.2017.02.002

Passive Intraoperative Language Mapping Using Electrocorticographic Signals

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Abstract. Intraoperative brain mapping is an important step in performing neurosurgery because it allows to spare the eloquent areas of the brain and increase the post-operative life quality for patients. However, the gold standard - electrical cortical stimulation - leads to seizures in up to 30% cases when language cortex is mapped intraoperatively in epilepsy patients. Modern neurosurgery is facing the need for a more innocuous method to intraoperatively map functionally critical cortical zones.

The goal of this study is to create a setup for passive intraoperative functional mapping, and to compare informativeness and safety of both mapping procedures.

We have created and tested a software and hardware setup for a high-resolution passive ECoG-based eloquent cortex mapping in a neurosurgical setting. Also, we have developed a mobile version of this platform that can be used in multiple hospitals and operating rooms across the country. We found precise localization of the Broca's area overlapping by more than 90% with the results of electrical cortical stimulation mapping in 3 out of 4 patients. In the fourth patient, the language cortex was not localized in the resection area, and the patient did not experience post-operative language deficiency.

Passive mapping of the Broca's area is a safe alternative to direct electrical stimulation. Further development of this approach includes mapping cortical activation in a patient in response to audited speech without the need to name the objects which may allow for mapping under anesthesia.

Keywords: Electrocorticography · Intraoperative brain mapping · Electrical cortical stimulation · Speech mapping · Broca's area · Functional brain areas · Cortical mapping · High-frequency gamma activity

1 Introduction

In order to prevent permanent neurological deficit after a neurosurgical intervention, it is necessary to gather highly precise information on the location of functionally significant areas of the cortex. Such information is invaluable in the process of resection of the

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supratentorial gliomas and surgical treatment of patients with extratemporal forms of pharmacoresistant epilepsy [1, 2].

In 1937, W. Penfield suggested measuring the location of the functional areas in the brain using direct electrical stimulation of the cortex and evaluating the clinical symptoms triggered by such stimulation [3]. Since then neurosurgery has acquired tremendous experience in applying electrical cortical stimulation (ECS), the parameters for stimuli have been determined, as well as the frequency and structure of possible complications of this investigative tool [4]. However, its usage remains limited due to the high risk of seizure occurrence, which in language mapping can be as high as 30% [5].

In 2005, A. Sinai et al. suggested to examine the dynamics of high-frequency gamma activity (HGA) oscillations using data received from electrocorticographic (ECOG) recordings during picture naming as a biomarker for the Broca's area in patients with drug-resistant epilepsy and chronically implanted subdural electrode grids [6], and H. Ogawa et al. [7] described the first attempt at applying passive language mapping in neurosurgical conditions.

Our research objective is to test the functional intraoperative mapping setup that is developed by us and compare accuracy and safety for passive versus active mapping of the language areas.

2 Materials and Methods

We have developed a software and hardware system for passive mapping of functional areas, which, combined with an innovative data processing algorithm, allows us to reliably map brain areas supporting speech function both in patients during neurosurgery and in patients with chronically implanted electrode grids. The hardware employed at the first stage consisted of a personal computer, a signal amplifier, the system for neurophysiologic experiments BE Plus, a microphone, and a tablet for picture presentation (see Fig. 1c).

Usually, a 64-microelectrode grid with interelectrode distance of 3–5 mm is used for mapping in our setup. Also, we record a signal from a microphone registering the patient's speech and a signal synchronizing presentation of pictures to the patient. Mathematical data processing algorithm ranks electrode signals in accordance with the likelihood of the hypothesis that the activity registered is indeed functionally connected to the performed naming task. The stimuli we present to patients include the battery of tests translated into Russian and adapted for it by O. Dragoy et al. [8].

We implemented the following experimental procedure. The anesthesia was performed in accordance with the protocol "asleep – awake – asleep": the patient was awakened only for the main operation stage. The opening of the dura mater and electrode grid placement took place after extracting the laryngeal mask airway and establishing contact with the patient. The microelectrode grid was placed onto the surface of the cortex where the language areas were supposedly located. The grid contained 64 electrodes with interelectrode space of 5 mm (AD-Tech Medical Instrument Corporation, USA) and was connected to the signal amplifier via a sterile cable connector L–DCL-64BDIN (AD-Tech Medical Instrument Corporation, USA).

In order to determine the basic cortical rhythm before presenting the stimuli, we recorded electrocorticography of rest for 300 s. The patient did not move, and absolute silence was maintained in the operating room. The next stage involved presenting pictures to the patient using the tablet. The patient was shown alternately pictures of actions and objects, with the interval of 400 ms between the pictures. In total, we utilized 30 pictures previously selected by good reproducibility of answers.

Right after the passive mapping was finished, the electrode grid was removed from the surface of the cortex, and the acquired results were analyzed by an algorithm of our own development. The following operations were performed with the recorded signals:

1. Bandpass signal filtration with a filter with finite pulse response (128 samples length) in the 60–80 Hz band [9];
2. Envelope calculation of the filtered process using Hilbert transform [9];
3. Identification of the regression model in order to predict the state code: 1 – action; 0 – rest. For this, the first half of the data envelope samples of rest and action states were used.
4. As the criterion, the coefficient of determination – R2 - was used. The R2 coefficient was calculated on the second half of the data. The coefficient values were then printed on a color-coded grid (see Fig. 1d).

Simultaneously with the mathematical analysis of the HGA desynchronization process, the ECS language mapping began in accordance with the classical W. Penfield procedure. The same pictures were presented for the active mapping, and at the moment of their presentation a bipolar probe was applied to the cortex surface near the supposed language areas. The cortical stimulator was set to produce electric impulses with the frequency of 50 Hz and duration of 4000 ms and the amperage of 10 mA. Any reproducible interruption of naming an action or an object was considered a positive result and the corresponding area was labeled, see the white frame in Fig. 1d.

Subsequently, we have improved the system by creating a partly wireless setup, which now consists of a tablet (Samsung Galaxy Tab A 8.0 SM-T290), a signal amplifier, a Wi-Fi modem (Asus WL-500W), and a laptop (Asus GL-502V). Thus, the laptop is connected to the tablet through Wi-Fi, and the tablet is used for picture presentation. The described setup demonstrates performance on the same level as the previous setup but allows for greeted flexibility in a cluttered operational room.

Additionally, the new setup has allowed us to synchronize the timing of picture presentation with the ECoG signal, recorded through the amplifier. This provided us with a possibility to focus our analysis on the specific stages of the picture comprehension and speech production process. The described framework in addition to providing vitally important mapping of the speech motor cortex facilitates collection of the unique datasets fostering fundamental research into uniquely human speech function.

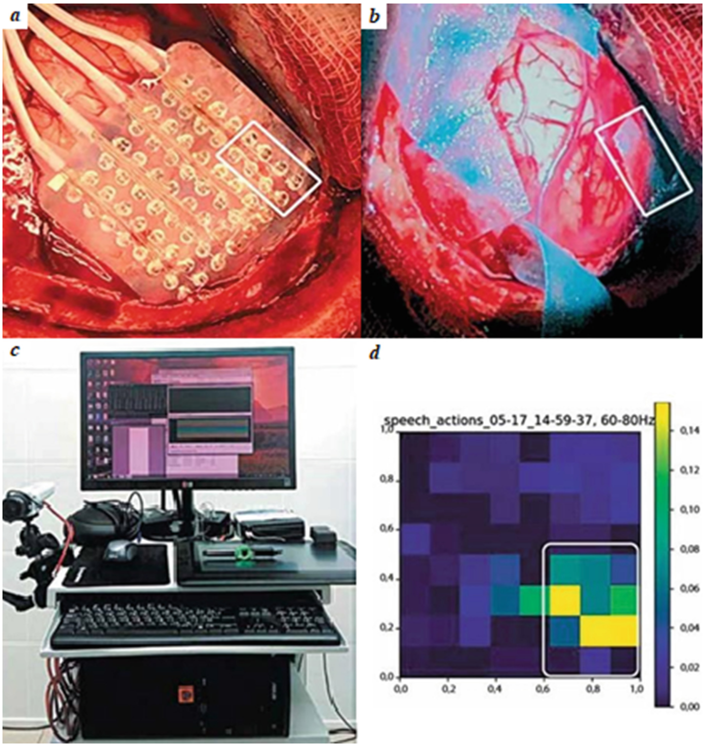

Fig. 1. **a** – The subdural electrode grid in the process of mapping. White rectangle encloses the electrodes where HGA desynchronization was the most observable (see also d); **b** – The cortex area where anomia occurred during ECS in accordance with the W. Penfield protocol. Both **a** and **b** are the intraoperative pictures which show correlation between the ECOG & ECS mapping results within a neurosurgical operation with awakening the patient. **c** – The setup for functional mapping in intraoperative environment. **d** – An example of a graphical representation of the bioelectrical HGA analysis. The white rectangle encloses the area determined by the Penfield's cortical stimulation procedure. The R^2 values of the regression model fit to gamma envelope profile are color-coded.

3 Results

In the course of the study, passive intraoperative speech mapping had been performed on four patients and compared to the results of the gold standard – electrical cortical stimulation mapping. All the attempts turned out to be successful: in three cases the observed functional areas overlapped by more than 90% (see Fig. 1a and 1b), in the fourth case, neither of the methods revealed a language area in the region of the electrode grid, and the subsequent resection did not lead to language function deficiency afterwards.

Thus, we acquired comparable results in both mapping techniques in all the cases. In the patients in whom the Broca's area was effectively localized, HGA desynchronization during naming was detected under the electrodes compactly located in the area of the size 1.5 × 2 cm in the lower segments of posterior frontal gyrus.

We observed precise overlap between the naming area determined by the ECS mapping and the localization established by the passive ECOG mapping in these patients. The points, stimulation of which caused anomia, were found in the area of the electrodes under which the most significant desynchronization of the bioelectrical activity was registered (see Fig. 1a and Fig. 1b).

4 Discussion

Identification of functional areas is an essential stage of any neurosurgical operation involving the cerebral cortex. The method of ECS, suggested by W. Penfield in 1937 [5], allowed to explore the location of the functional areas in detail and establish the functional map of the neocortex [11]. For a long time, ECS has remained the only way to perform intraoperative mapping of the areas associated with language and motor function. However, its major shortcoming is a high risk to induce an epileptic seizure [11]. Whereas locating primary motor cortex areas situated in the precentral gyrus is possible without awaking the patient [12], the same cannot be said about locating the language areas, when the patient has to be awake in order to perform the mapping procedure [10]. Nevertheless, a seizure attack can influence both mapping procedures. During motor mapping, a seizure attack in response to ECS can only slower down the process for the time necessary for the effect of the antiepileptic drugs to disappear, but even in this case the postictal decrease in neuronal excitability can lead to false negative results [12]. In case of language mapping, the patient's awakening is a crucial part of the procedure, therefore an occurrence of an epileptic seizure not relieved by spraying the surface of the cortex with cold saline solution allows neither to continue cortex mapping procedure nor to monitor the language function further in the process of the surgery [10].

In order to lower the frequency of ECS complications, M. Taniguchi et al. suggested a method of monopolar stimulation via sequences of short electric impulses [13]. In comparison to the method of W. Penfield, this method decreases the probability of a seizure attack by half, however, it does not fully prevent it. S.M. Verst et al. analyzed data from 41 patients and discovered similarity of the results between the ECS procedures of M. Taniguchi and W. Penfield, although the latter still remains the gold standard [14].

Among other options for intraoperative functional mapping are functional magnetic resonance imaging (fMRI) and navigated transcranial magnetic stimulation (nTMS) [15, 16]. However, the application of these methods is limited by the relatively low spatial resolution of fMRI and lack of a uniform protocol for mapping language areas through nTMS. Moreover, the most significant obstacle to wide implementation of the preoperative mapping methodology is the brain shift that occurs in response to craniotomy [4].

Multiple studies showed that during movement, speech or analysis of incoming information the most significant changes on electroencephalogram (EEG) appear in the gamma band, whose frequency is higher than 30 Hz [17–19]. But this biomarker cannot be properly put to use in clinical environment because of the low spatial resolution of scalp EEG (which does not exceed 6 cm^2) [20]. Implantation of subdural electrodes in patients with drug-resistant epilepsy for preoperative preparation for resection of the epileptogenic area allows to record ECOG, the spatial resolution of which is limited only by the interelectrode space, because the electrodes lie directly on the brain surface.

A. Sinai et al. demonstrated for the first time that it was technically possible to perform passive mapping of functional areas responsible for word production and articulation using the data on HGA desynchronization in patients with chronically implanted subdural electrodes. Nonetheless, the method has not been accepted for wide application due to lack of serially produced equipment and the fact that only patients with drug-resistant epilepsy actually needed it [6].

In clinical practice, intraoperative functional mapping is in the great demand, and at the moment it is commonly executed by means of ECS. If this procedure were replaced with safer passive HGA desynchronization analysis via ECOG, it would significantly alter the course of surgical intervention and increase the number of patients for whom functional mapping would be possible.

The first attempt at passive speech mapping during craniotomy in conscious patients, published by H. Ogawa et al. in 2014 [7] demonstrated the possibility to perform this directly in the operating room, where the electromagnetic noise intensity is extremely high due to all the surrounding equipment. In order to achieve this result, the authors used an amplifier of their own development and electrodes with standard interelectrode space, which limited the spatial resolution to 1 cm^2.

For our work, we utilized the amplifier BE Plus (EB Neuro, Italy) that is serially produced and accessible in Russian Federation. Signal processing was performed using an original decryption algorithm, at first installed on a computer with the operating system Windows. Later we installed it on a laptop with the screen diagonal of 17 in., which does not require any additional energy sources. This makes our setup mobile, reproducible and potentially accessible by other labs and clinics.

We have first used a subdural grid with platinum electrodes and interelectrode space of only 5 mm for passive intraoperative language mapping. This significantly exceeds the theoretical resolution of ECS, which is limited by the distance between the branches of the bipolar stimulator and the amount of electrical current accumulated on them, growing in proportion to the current intensity.

Functional mapping based on the analysis of changes in bioelectrical activity considerably simplifies the procedure and makes it absolutely innocuous even for patients with high risk of epileptic seizures. Utilization of grids with lesser interelectrode space increases the resolution for the acquired map of functional areas, which can potentially allow to widen the resection area to their actual boundaries.

The method of high density passive functional mapping implemented by us looks promising. It can be used for neurosurgical resections of the gliomas located near the language centers of the brain. However, before it can be applied routinely additional feasibility and congruence studies are needed.

5 Conclusion

We have implemented and tested a setup for passive intraoperative language mapping that demonstrated comparable informativeness and high precision in comparison to the classical ECS. Passive mapping of the functional area of the brain responsible for speech production – the Broca's area – is a safe alternative to direct electrical stimulation. It can be performed within the neurosurgical operation that includes awaking the patient.

However, further clarifying research of passive functional mapping of language and sensorimotor functions is required.

References

1. Krylov, V.V. (ed.): Нейрохирургия и нейрореаниматология (Neurosurgery and Neuroresuscitation). ABV-press, Moscow (2018)
2. Krylov, V.V., Gekht, A.B., Trifonov, I.S., Levedeva, A.V., Kaymovski, I.L., Sinkin, M.V., Grigoryeva, E.V., Grishkina, M.N., Shishkina, L.V., Kochetkova, O.O.: Хирургическое лечение больных с магнитно-резонансно-негативными фармакорезистентными формами эпилепсии (Surgical treatment of patients with magnetic resonance-negative drug-resistant forms of epilepsy). Неврологический журнал **21** (4), 213–218 (2016).
3. Penfield, W., Boldrey, E.: Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. Brain **60**(4), 389–443 (1937)
4. So, E.L., Alwaki, A.: A guide for cortical electrical stimulation mapping. J. Clin. Neurophysiol. **35**(2), 98–105 (2018)
5. Dineen, J., Maus, D.C., Muzyka, I., See, R.B., Cahill, D.P., Carter, B.S., Curry, W.T., Jones, P.S., Nahed, B.V., Peterfreund, R.A., Simon, M.V.: Factors that modify the risk of intraoperative seizures triggered by electrical stimulation during supratentorial functional mapping. Clin. Neurophysiol. **130**(6), 1058–1065 (2019).
6. Sinai, A., Bowers, C.W., Crainiceanu, C.M., Boatman, D., Gordon, B., Lesser, R.P., Lenz, F.A., Crone, N.E.: Electrocorticographic high gamma activity versus electrical cortical stimulation mapping of naming. Brain **128**(7), 1556–1570 (2005)
7. Ogawa, H., Kamada, K., Kapeller, C., Hiroshima, S., Prueckl, R., Guger, C.: Rapid and minimum invasive functional brain mapping by real-time visualization of high gamma activity during awake craniotomy. World Neurosurg. **82**(5), 912e1–912e10 (2014)
8. Dragoy, O.V., Chrabaszcz, A.V., Tolkacheva, V.A., Buklina, S.B.: Russian intraoperative naming test: a standardized tool to map noun and verb production during awake neurosurgeries. Russ. J. Cogn. Sci. **3**(4), 4–25 (2016)
9. Oppenheim, A.V., Schafer, R.W.: Digital Signal Processing. Prentice-Hall, Englewood Cliffs (1975)
10. Garrett, M.C., Pouratian, N., Liau, L.M.: Use of language mapping to aid in resection of gliomas in eloquent brain regions. Neurosurg. Clin. N. Am. **23**(3), 497–506 (2012)
11. Penfield, W., Jasper, H.: Epilepsy and the functional anatomy of the human brain. J. Am. Med. Assoc. **155**(1), 86 (1954)
12. Karakis, I., Leeman-Markowski, B.A., Leveroni, C.L., Kilbride, R.D., Cash, S.S., Eskandar, E.N., Simon, M.V.: Intra-stimulation discharges: an overlooked cortical electrographic entity triggered by direct electrical stimulation. Clin. Neurophysiol. **126**(5), 882–888 (2015)
13. Taniguchi, M., Cedzich, C., Schramm, J.: Modification of cortical stimulation for motor evoked potentials under general anesthesia: technical description. Neurosurgery **32**(2), 219–226 (1993)
14. Verst, S.M., de Aguiar, P.H.P., Joaquim, M.A.S., Vieira, M.G., Suscena, A.B.C., Maldaun, M.V.C.: Monopolar 250–500 Hz language mapping: results of 41 patients. Clin. Neurophysiol. Pract. **4**, 1–8 (2018)
15. Abdullah, A., El Shitany, H., Abbass, W., Safwat, A., Elsamman, A.K., Refaee, E.E.: Surgical resection of low-grade gliomas in eloquent areas with the guidance of the preoperative functional magnetic resonance imaging and craniometric points. J. Neurosci. Rural Pract. **7**(4), 571–576 (2016)

16. Poydasheva, A.G., Bakulin, I.S., Chernyavskiy, A., Suponeva, N.A., Piradov, M.A.: Motor cortex mapping with navigated transcranial magnetic stimulation and its clinical application. Med. Alphabet **2**(22), 21–25 (2017)
17. Pantev, C.: Evoked and induced gamma-band activity of the human cortex. Brain Topogr. **7**(4), 321–330 (1995)
18. Pfurtscheller, G., Neuper, C., Kalcher, J.: 40-Hz oscillations during motor behavior in man. Neurosci. Lett. **164**(1–2), 179–182 (1993)
19. Tallon-Baudry, C., Bertrand, O.: Oscillatory gamma activity in humans and its role in object representation. Trends Cogn. Sci. **3**(4), 151–162 (1999)
20. Ferree, T., Clay, M., Tucker, D.: The spatial resolution of scalp EEG. Neurocomputing **38–40**, 1209–1216 (2001)
21. Kapeller, C., Ogawa, H., Schalk, G., Kunii, N., Coon, W.G., Scharinger, J., Guger, C., Kamada, K.: Real-time detection and discrimination of visual perception using electrocorticographic signals. J. Neural Eng. **15**(3), 036001 (2018)

Functional Brain Connectivity in Speech Disfluency Perception

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Abstract. Speech disfluencies are a notable component of natural discourse production and comprehension that may play a role of signals that control the flow of communication. Using task-based functional MRI, we examined how brain functional connectivity changes when listeners encounter a disfluency. Participants listened to fragments of audio recordings of natural discourse from the RUPEX corpus while looking at the speaker's photograph and being engaged in a referential task locking their attention on the narration. Using the intrinsic connectivity contrast, as a measure for a data-driven approach, we found modified connectivity in different portions of the left parietal cortex in response to isolated phoneme lengthenings or clustered disfluencies including phoneme lengthenings. Given the important role of the parietal cortex in attention and sensory integration, our results indicate promising targets for further studies of functional connectivity and neural networks in speech disfluency perception. From a broader perspective our study demonstrates how corpus linguistics and neuroimaging may join their efforts for interdisciplinary research of the brain and language.

Keywords: Speech disfluency · Perception · fMRI · Functional connectivity

1 Introduction

Speech disfluencies are a notable component of natural discourse production and comprehension that may play a role of signals that control the flow of communication. For

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example, if a speaker hesitates while thinking about a better wording of their utterance, the listenter may interpret this as evidence of speech planning difficulty and as a signal of possible moment of turn-taking in the conversation. While brain mechanisms of fluent speech production and comprehension are the subject of intensive research in neuroimaging, the neural circuitry underlying speech disfluencies is almost an unknown territory with only a few attempts to chart it. From a speech production perspective, Kircher et al. [1] showed that within-clause speech pauses result in greater activation in the left tempoparietal junction compared to continuous speech. In speech perception, Eklund and Ingvar [2] found that both filled and silent hesitation pauses elicit greater activation in the primary auditory cortex and the motor components of the speech network in the listener's brain compared to fluent speech, with extra activation of the supplementary motor cortex (SMA) for filled vs. Silent pauses. In our recent pilot fMRI study [3], we explored the perception of four types of isolated speech disfluencies and their clusters annotated in the "Russian Pear Chats and Stories" corpus: silent pauses, filled pauses (like uh and um), lengthenings (phoneme prolongation as a hesitation marker), and self-repairs, or breaks (explicit corrections of an already started vocalization). We found neural correlates for the perception of silent pauses, self-repairs, and three types of disfluency clusters, mainly covering the extrastriate visual cortex, auditory and speech-related temporal cortices, as well as the insula. The present fMRI study continues the previous work with a larger sample and a different focus. For perception of the same types of disfluency, we were looking for neural correlates in the connectivity rather than the activation domain, that is, we tried to identify, using a data-driven approach, the brain regions that demonstrated changes in their functional connectivity when listeners encountered disfluencies compared to a fluent speech baseline.

2 Method

2.1 Participants

Thirty right-handed native speakers of Russian (mean age 25 ± 5 y.o.; 12 males and 18 females) recruited from the Moscow academic community took part in the study. Data from 14 participants were used for the brain activation analysis in [3]. No one reported any contra-indications for the MRI procedure, nor were there any hearing problems or any history of neurological or mental disease. All had either normal or corrected-to-normal visual acuity. The study was approved by the Interuniversity Ethics Committee of Moscow. Participants gave written consent to the experimental procedures and received financial compensation for their time and effort.

2.2 Equipment and Materials

As stimulus materials, we used fragments of the "Russian Pear Chats and Stories" corpus (RUPEX; [4]). This corpus includes video recordings of natural communication between four participants of an experiment who retell and discuss the so-called "Pear Film" which was created by a research group of Wallace Chafe in the 1970s [5]. In the corpus, the recordings are integrated with annotations of multiple communication channels such as intonation, manual gestures, eye movement, etc. Selection of the material for the present experiment was based on the speech disfluency and verbal channel annotations. Due to the slow dynamics of fMRI BOLD signal we selected discourse fragments that lasted no less than 10 s and contained annotated speech disfluencies separated by at least 2 s. The materials contained 154 disfluencies which were either isolated (7 silent pauses, 46 filled pauses, 17 lengthenings, 25 self-repairs, or breaks, and 4 miscellaneous disfluencies classified as ‘other’) or clustered (18 filled pause + lengthening, 9 filled pause + self-repair, 8 filled pause + lengthening + self-repair, 3 lengthening + self-repair, 17 ‘other’). Details of the speech disfluency classification and annotation as well as material selection procedures are provided in [3].

To restrict potentially confounding information available to participants from the other communication channels, the original video was removed and the audio recording of each discourse fragment was accompanied by a static screenshot introducing the speaker to the participants. Recordings of eight different speakers (male and female) were used. Discourse fragments were separated by a silent black screen presented for 2 s. Video and audio stimuli were delivered to the participants lying in the magnet bore with MRI-safe presentation equipment (InVivo display and custom headphones). The stimulus presentation was controlled by the VLC player for MacOS.

2.3 Procedure

Participants were instructed and given a practice trial of the task outside the scanner. During the structural and prior to the functional scanning, participants watched the “Pear Film” video discussed in the conversations from the corpus. Then the stimuli sound level was adjusted individually for each participant to make sure they felt comfortable but at the same time were able to distinctly hear the speech against the scanner noise. Fragments of the discussion material from the corpus were organized into two sessions of about 10 min each. Each session contained 4 trials of a referential task: instances of the pronoun ‘he’ in any form (*on* in Russian) accompanied by a red frame on the screen, to which the participant had to respond by a button press indicating which movie character the pronoun refers to. The task was introduced to guarantee participant attention to the material without informing them about the central role of disfluencies in the study.

2.4 Neuroimaging Data Collection and Analysis

Neuroimaging was performed with the Philips 3T Ingenia scanner at the Mental Health Research Center (Moscow, Russia). T2*-weighted functional images were collected using the FFE EPI pulse sequence with TR/TE = 2500 ms/35 ms, 34 slices oriented parallel to AC/PC plane and 3.2 mm isotropic voxels. Per participant, 267 and 271 volumes were acquired from the first and the second session respectively; 3 extra volumes from the beginning of each session were discarded. Additionally, the T1-weighted structural images were acquired (TFE sequence, TR/TE/FA = 8 ms/4 ms/8°, 170 near-transverse slices, 1-mm isotropic voxels) as well as two SE EPI sequences with opposite directions of the phase encoding (AP vs. PA) and with the same slice prescription and voxel resolution as the functional images; these volumes were further used for the calculation of a fieldmap.

The fMRI data were preprocessed with SPM12, FSL5.0.9 and Conn toolbox 17a; functional connectivity was analyzed using Conn. Preprocessing included slice timing correction, motion and inhomogeneity artifact correction, spatial coregistration of the functional and structural images, spatial normalization to the Montreal Neurological Institute (MNI) space, spatial smoothing of the functional images with FWHM $8 \times 8 \times 8$ mm, ART-based scrubbing, aCompCor and temporal high-pass filtering ([0.008 Inf]).

Each disfluency type was modelled as a separate condition. Lengthening + self-repair clusters were not included in the final analysis because they were represented by only 3 events. The fluent speech condition was modelled explicitly as 12 events per participant (elementary discourse units were selected in the middle of at least 10-s intervals between the two consecutive disfluency events). Normalized intrinsic connectivity contrast (ICC) was used as a data-driven measure of connectivity and was computed for each voxel. Each type of disfluency was compared to the fluent speech explicit baseline with a T-contrast for a GLM model (9 comparisons). The number of invalid scans per subject was included into each group model to control for possible residual effects of head motion. Clusters of voxels showing significant between-condition differences in ICC ($p < 0.005$ voxelwise, pFDR $< 0.006 = 0.05/9$ clusterwise) were included in the final results.

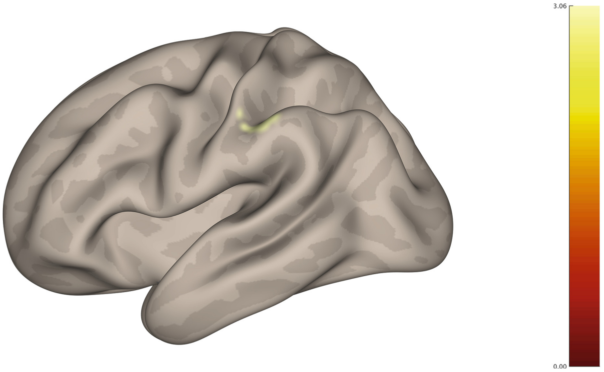

Fig. 1. Region in the left parietal cortex (anterior supramarginal gyrus) demonstrating greater ICC for isolated Lengthening > Fluent Speech. $N = 30$, $p < 0.005$ voxelwise, $pFDR < 0.006 = 0.05/9$ clusterwise.

3 Results

Functional connectivity changes in speech disfluency versus fluent speech perception were obtained for three out of nine conditions. A cluster in the left anterior supramarginal gyrus (1755 mm^3, center of mass at −60; −31; 47) demonstrated stronger functional connectivity with the rest of the brain during perception of lengthenings (Fig. 1). Clustered disfluency combining lengthening with filled pauses (Fig. 2) and lengthening, filled pauses, and self-repairs (Fig. 3) showed greater connectivity in the left superior parietal lobule and precuneus bilaterally (1890 mm^3, c.o.m. at 3; −43; 50) and weaker connectivity in the left superior parietal lobule and precentral gyrus (1701 mm^3, c.o.m. at −42; −43; 59), respectively.

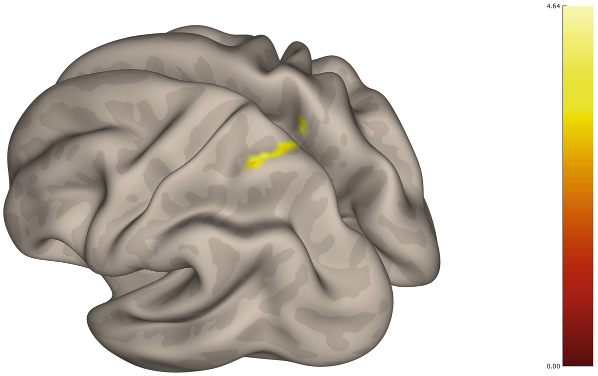

Fig. 2. Region in the left parietal cortex (superior parietal lobule) demonstrating greater ICC for disfluency clusters of Lengthening and Filled Pauses > Fluent Speech. $N = 30$, $p < 0.005$ voxelwise, $pFDR < 0.006 = 0.05/9$ clusterwise.

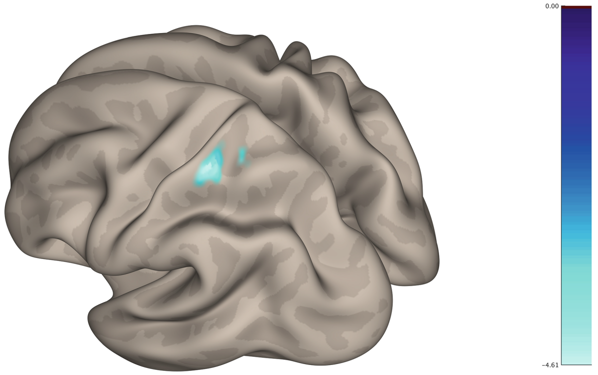

Fig. 3. Region in the left parietal cortex (left superior parietal lobule and precentral gyrus) demonstrating decreasing ICC for disfluency clusters of Lengthening, Filled Pauses and Self-Repairs vs. Fluent Speech. $N = 30$, $p < 0.005$ voxelwise, $pFDR < 0.006 = 0.05/9$ clusterwise.

4 Discussion

Notably, all of the functional connectivity changes revealed in the present study implicated lengthening (although in different combinations with other types of speech disfluency) and different portions of the left parietal cortex. Since the parietal cortex is included in networks underlying different aspects of information processing and cognitive control, speculative interpretation of the present findings seems to be premature since it may vary from relatively low-level (i.e., phoneme lengthenings result in increasing load of the phonological component of working memory which engages the parietal cortex) to relatively high-level (i.e., speech disfluencies may serve as attention-reorienting signals that are important for conversational turn-taking, and the attention-reorienting system also engages the parietal cortex). Given that the current analysis implemented a data-driven rather than hypothesis-driven approach, our results indicate some promising targets for further studies of the functional connectivity and neural networks in speech disfluency perception. From a broader perspective our study demonstrates how corpus linguistics and neuroimaging may join their efforts for interdisciplinary research of the brain and language.

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References

1. Kircher, T., Brammer, M., Levelt, W., Bartels, M., Mcguire, P.: Pausing for thought: engagement of left temporal cortex during pauses in speech. Neuroimage **21**, 84–90 (2004)
2. Eklund, R., Ingvar, M.: Supplementary motor area activation in disfluency perception. An fMRI Study of listener neural responses to spontaneously produced unfilled and filled pauses. In: Proceedings of Interspeech 2016, San Francisco, USA, pp. 1378–1381 (2016)
3. Smirnova, K.V., Korotaev, N.A., Panikratova, Y.R., Lebedeva, I.S., Pechenkova, E.V., Fedorova, O.V.: Using the RUPEX multichannel corpus in a pilot fMRI study on speech disfluencies. In: Proceedings of the 12th Language Resources and Evaluation Conference 2020, pp. 195–203 (2020)
4. Kibrik, A.A., Fedorova, O.V.: An empirical study of multichannel communication: Russian Pear Chats and Stories. Psixologija. Žurnal Vysšej Školy ėkonomiki **15**(2), 191–200 (2018)
5. Chafe, W. (ed.): The Pear Stories: Cognitive, Cultural, and Linguistic Aspects of Narrative Production. Ablex, Norwood (1980)

Interaction Between Oculomotor Impairments, Voluntary Attention and Working Memory Disorders in Children with Cerebellar Tumors

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Abstract. Visual cognition relies on a distinct type of eye movements called saccades. The cerebellum is important for all types of eye movements and gaze fixation stability and is involved in cognitive functions. In our previous research, we reported oculomotor deficits in cerebellar patients: unstable gaze fixation, incorrect hypermetric (‘overshooting’) saccades, increased trajectory of scanpath while examining the picture. The purpose of current research was to investigate the relations between eye movement parameters and visual attention and working memory in children who had undergone cerebellar tumor treatment. 55 children (age 9–17, mean = 12.0 ± 3.2) participated in the experiment. The subjects performed oculomotor (3 tasks, using Arrington eye tracker) and cognitive (4 tests, CANTAB) assessment. We found that gaze fixation stability correlated positively with the speed of RVP completion ($p < 0.001$) and negatively with the number of solved tasks in SOC ($p = 0.018$). Proportions of accurate visually guided saccades positively correlated with number of remembered elements in SWM ($p = 0.019$). Proportion of hypermetric saccades positively correlated with the number of errors in RVP ($p = 0.009$). In visual search task, trajectory length (scanpath) positively correlated with proportion of errors in SWM ($p = 0.003$), longer response times in RVP ($p < 0.001$) and smaller number of remembered elements in SSP ($p = 0.023$). Thus, oculomotor deficits resulting from cerebellar dysfunction are proved to be accompanied by cognitive deficits such as sustained attention disturbance and visuospatial working memory capacity decrease. These findings contribute to our understanding of visuomotor cognitive behavior mechanisms and may result in introduction of additional rehabilitation procedures for patients with cerebellar dysfunction.

Keywords: Cerebellum · Pediatric cancer · Executive functions · Eye tracking

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1 Introduction

Close interactions between eye movements and visual cognition have been shown in numerous reports originating from different fields of neuroscience [1, 2]. Visual cognition relies on a distinct type of eye movements called saccades to focus objects of interest on the fovea. Saccades, gaze fixations and their parameters are controlled by a complicated hierarchically organized saccadic system consisting of a complex of cortical areas and subcortical nuclei [3] as well as parts of the cerebellum [4].

The cerebellum is important for all types of eye movements and gaze fixation stability. The oculomotor cerebellum, consisting of the fastigial nuclei and dorsal vermis (lobules VI and VII), plays a major role in saccade processing, adaptation and controls their accuracy. In addition, cerebellum is involved in the smooth initiation of the eye chase, the horizontal eye alignment and the processing of vergence [5, 6]. Pathologies of different parts of cerebellum, particularly of cerebellar nuclei, disturb saccade execution, fixations and other types of eye movements [7].

For a long time, cerebellum was believed to be involved in body movements only [8]. Later multiple connections between cerebellum and different cortical structures such as premotor, prefrontal and posterior parietal areas were discovered, and cerebellum involvement in cognitive processes was shown both in animals and humans [9–11]. Therefore, cerebellum plays a central role in the functioning of not only motor, but also cognitive system [12]. However, how correct this theory is and exactly what contribution the cerebellum makes to cognitive processes remains unclear [13].

The contribution of the cerebellum to cognitive function was revealed by Schmahmann J. D. He examined patients with cerebellar lesions and described ‘cerebellar cognitive affective syndrome’, thus showing cerebellar involvement in cognitive processes [14]. This disorder affects cognitive control of executive functions, especially working memory, attention, planning, verbal fluency, spatial cognition, language, and causes overall cognitive decrease. It is frequent for common types of childhood cancer – medulloblastoma and astrocytoma. Medulloblastomas and astrocytomas account for more than 10% of all brain tumors in children. These tumors are located exclusively in the posterior fossa. Medulloblastomas and high-grade astrocytomas always require combined treatment consisting of surgery and radiation therapy [15]. Advances in medicine allow more children to get better, but the long-term effects of cancer treatment are poorly understood [16], and the number of children diagnosed with cancer is growing every year. Therefore, the study of the cerebellum on oncological models is of both theoretical and practical significance [17].

Cerebellar involvement in cognitive processes is currently being widely studied, and patients with cerebellar tumors are reported to have visuospatial perception and attention deficits [18], as well as impairments in working memory [19]. Moreover, in our previous research, we reported deficits in gaze fixation and execution of saccades, both visually guided and voluntary, in children with cerebellar tumors [20, 21]. Unstable gaze fixation, incorrect hypermetric (‘overshooting’) saccades were found in cerebellar patients, as well as increased trajectory of scanpath while examining the picture. We propose that visual attention and visual working memory are constantly interacting. As a result, the efficiency of their functioning depends on the integrity and coherence of the oculomotor system and adequate attention control [22]. Thereby, the purpose of our research was to investigate the relations between eye movement parameters and visual attention and working memory in children who had undergone cerebellar tumor treatment.

2 Materials and Methods

55 children patients (61% males; age 9–17, mean = 12.0 ± 3.2) earlier subjected to treatment of posterior fossa tumors participated in the experiment. 35 children (64%) were diagnosed with medulloblastoma, 20 (36%) children - with astrocytoma (mostly low-grade). They were staying at the Clinical Research Rehabilitation Center (Chechov, Russia) when the experiment was conducted. The time of remission was 48.1 ± 35.5 months. The experiment was approved by the Ethics Committee of Dmitry Rogachev National Medical Research Center of Pediatric Hematology, Oncology and Immunology (protocol number 8e/13-17 of 27.10.2017) and was run in accordance with the principles of Helsinki's declaration.

We analyzed oculomotor behavior and cognitive processes of the subjects. Oculomotor assessment consisted of three separate tasks: 1) gaze holding (to fix gaze at static stimulus), 2) visually guided saccades (VGS, to execute saccades to presented object), 3) visual search (to count objects). To determine gaze fixation stability, we computed ellipse approximations (in square degrees) of all gaze positions for every subject in gaze holding test using least squares method. In VGS test we determined the proportions (%) of accurate and hypermetric saccades (with the amplitude more than 10% larger than the required). In visual search test we computed the time of execution (s) and scanpath (degrees). Eye movements were recorded at 60 Hz using Arrington eye tracker (Arrington Research, Inc., USA).

Cognitive assessment consisted of four subtests assessing visual system performance quality from the CANTAB computerized neurocognitive tests system (Cambridge Cognition Ltd, UK). To assess sustained attention, the RVP (Rapid Visual Information Processing) test was performed (number of errors during test executing and response times (ms) were determined). To assess visual working memory, the SSP (Spatial Span) and SWM (Spatial Working Memory) tests were used. In SSP the number of elements retained in working memory was recorded, in SWM - number of errors during test executing. To evaluate spatial planning, the SOC (Stockings of Cambridge) test was performed (the number of solved task was determined). We used Spearman coefficient to evaluate correlation between oculomotor parameters and cognitive characteristics in subjects.

3 Results

We found that gaze fixation stability correlated positively with the speed of RVP test completion ($r = 0.458, p < 0.001$, Fig. 1) and negatively with the number of solved tasks in SOC ($r = -0.341$, $p = 0.018$). Bigger sizes of ellipse area reflected more unstable gaze fixation and were related to longer response times in sustained attention test and smaller number of solved tasks in spatial planning test.

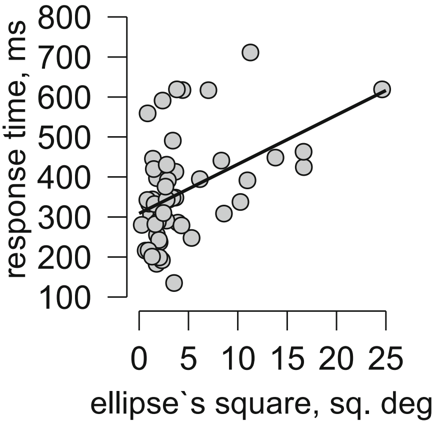

Fig. 1. Correlation between gaze fixation stability (size of ellipse's area, sq. degrees) and time of RVP test completion.

According to VGS test, the proportions of accurate visually guided saccades positively correlated with number of remembered elements in SSP ($r = 0.365$, $p = 0.019$). In contrast, proportion of hypermetric saccades positively correlated with the number of errors in RVP ($r = 0.416$, $p = 0.009$, Fig. 2). Thus, better visuospatial memory capacity and better performance in sustained attention test were related to higher accuracy of saccades.

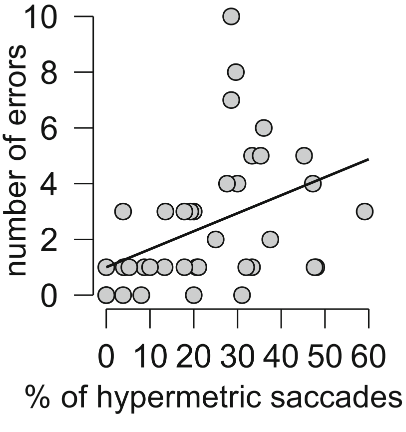

Fig. 2. Correlation between hypermetric saccade proportion and the numbers of errors in RVP test.

In visual search task, trajectory length (scanpath) positively correlated with errors in SWM test ($r = 0.414$, $p = 0.003$, Fig. 3), longer response times in RVP test ($r = 0.524$, $p < 0.001$) and smaller number of remembered elements in SSP ($r = -0.324$, $p = 0.023$). Moreover, visual search task execution time negatively correlated with the number of solved tasks in SOC ($r = -0.335$, $p = 0.028$). Hence, disturbances in visual search were reflected in greater execution time and longer scanpath due to difficulties in visual spatial working memory, sustained attention and planning.

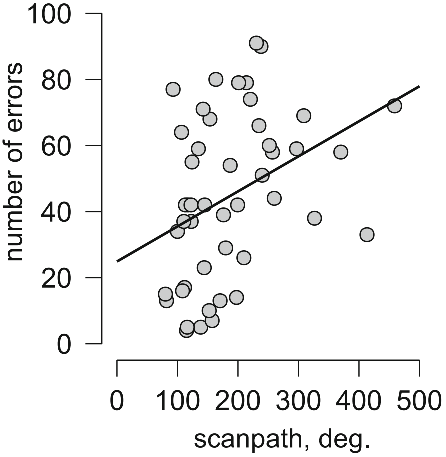

Fig. 3. Correlation between scanpath during visual search and the numbers of errors in SWM test.

4 Discussion

In this work we studied interactions between saccadic system functioning and visual cognition processes in children earlier subjected to cerebellar tumors treatment. Tumor process itself and subsequent treatment lead to injuries of oculomotor cerebellar regions and their interconnections to different cortical areas. Oculomotor deficits resulting from cerebellar dysfunction are proved to be accompanied by cognitive deficits such as sustained attention disturbance, visuospatial working memory capacity decrease and worse spatial planning. These results correspond to previous research revealed cognitive impairments in patients with cerebellar lesions [14, 16, 18]. The mechanism of cerebellar contributions to executive functions appears to be a part of interest [13]. In some studies, it was shown that one saccade is analogous to an element in working memory. An increase in the number of elements of working memory leads to a decrease in the accuracy of the answer [23]. Saccades, attention and working memory can be thought of as a single, interconnected system [24]. Saccades are very rapid eye movements that create a complete image of an object [25]. At the same time, the number of partial images of a visual stimulus generated during fixations after saccades is limited, and most of them are lost in preparation of a general image. Thus, saccadic impairments caused by lesions of oculomotor centers in cerebellar vermis and lobules, may result in errors in memorization, processing and visual cognition.

5 Conclusions

These findings contribute to our understanding of visuomotor cognitive behavior mechanisms and may lead to in introduction of additional rehabilitation procedures for patients with cerebellar dysfunction. In addition, the presented data contributes to the understanding of the relations between working memory attention and visuomotor systems. When planning rehabilitation programs, a comprehensive assessment of these functions is necessary, and rehabilitation process will benefit from such an integrated approach.

References

1. Grant, E.R., Spivey, M.J.: Eye movements and problem solving: guiding attention guides thought. Psychol. Sci. **14**(5), 462–466 (2003). https://doi.org/10.1111/1467-9280.0245
2. Poole, A., Ball, L.: Eye tracking in human-computer interaction and usability research: current status and future prospects, chap. 34. In: Encyclopedia of Human Computer Interaction, pp. 211–219. Idea Group Inc. (2005). https://doi.org/10.4018/978-1-59140-562-7.ch034
3. Coe, B.C., Munoz, D.P.: Mechanisms of saccade suppression revealed in the anti-saccade task. Philos. Trans. R. Soc. B Biol. Sci. **372**(1718), 20160192 (2017). https://doi.org/10.1098/rstb.2016.0192
4. Noda, H.: Cerebellar control of saccadic eye movements: its neural mechanisms and pathways. Jpn. J. Physiol. **41**(3), 351–368 (1991). https://doi.org/10.2170/jjphysiol.41.351
5. Kheradmand, A., Zee, D.S.: Cerebellum and ocular motor control. Front. Neurol. **2**, 53 (2011). https://doi.org/10.3389/fneur.2011.00053
6. Manto, M., Bower, J.M., Conforto, A.B., Delgado-García, J.M., Da Guarda, S.N.F., Gerwig, M., Habas, C., Hagura, N., Ivry, R.B., Mariën, P., Naito, E., Nowak, D.A., Ben Taib, N.O., Pelisson, D., Tesche, C.D., Tilikete, C., Timmann, D., Molinari, M.: Consensus paper: roles of the cerebellum in motor control—the diversity of ideas on cerebellar involvement in movement. Cerebellum **11**(2), 457–487 (2012). https://doi.org/10.1007/s12311-011-0331-9
7. Thurtell, M.J., Tomsak, R.L., Leigh, R.J.: Disorders of saccades. Curr. Neurol. Neurosci. Rep. **7**(5), 407–416 (2007). https://doi.org/10.1007/s11910-007-0063-x
8. Holmes, G.: Clinical symptoms of cerebellar disease and their interpretation. Lancet **1**(1117), 1231–1237 (1922). https://doi.org/10.1080/14734220701415208
9. Baillieux, H., De Smet, H.J., Paquier, P.F., De Deyn, P.P., Mariën, P.: Cerebellar neurocognition: insights into the bottom of the brain. Clin. Neurol. Neurosurg. **110**(8), 763–773 (2008). https://doi.org/10.1016/j.clineuro.2008.05.013
10. Schmahmann, J.D.: The Cerebellum and Cognition. Academic Press, San Diego (1999)
11. Heyder, K., Suchan, B., Daum, I.: Cortico-subcortical contributions to executive control. Acta Psychol. **2004**(115), 271–289 (1997). https://doi.org/10.1016/j.actpsy.2003.12.010
12. Peterburs, J., Desmond, J.E.: The role of the human cerebellum in performance monitoring. Curr. Opin. Neurobiol. **40**, 38–44 (2016). https://doi.org/10.1016/j.conb.2016.06.011
13. Pretegiani, E., Piu, P., Rosini, F., Federighi, P., Serchi, V., Tumminelli, G., Dotti, M.T., Federico, A., Rufa, A.: Anti-saccades in cerebellar ataxias reveal a contribution of the cerebellum in executive functions. Front. Neurol. **9**, 274 (2018). https://doi.org/10.3389/fneur.2018.00274
14. Schmahmann, J.D., Sherman, J.C.: The cerebellar cognitive affective syndrome. Brain J. Neurol. **121**(4), 561–579 (1998). https://doi.org/10.1093/brain/121.4.561
15. Millard, N.E., De Braganca, K.C.: Medulloblastoma. J. Child Neurol. **31**(12), 1341–1353 (2016). https://doi.org/10.1177/0883073815600866

16. Benzing, V. J., Spitzhüttl, J.S., Siegwart, V., Grotzer, M., Steinlin, M., Leibundgut, K., Everts, R., Schmidt, M.: Executive functions, motor abilities and quality of life in pediatric cancer survivors–the crucial role of motor coordination. In: 15th European Congress of Sport and Exercise Psychology, Münster (2019, unpublished). https://doi.org/10.7892/boris.140990
17. Hubbard, A.K., Spector, L.G., Fortuna, G., Marcotte, E.L., Poynter, J.N.: Trends in international incidence of pediatric cancers in children under 5 years of age: 1988–2012. JNCI Cancer Spectr. **3**(1), pkz007 (2019). https://doi.org/10.1093/jncics/pkz007
18. Starowicz-Filip, A., Chrobak, A.A., Milczarek, O., Kwiatkowski, S.: The visuospatial functions in children after cerebellar low-grade astrocytoma surgery: a contribution to the pediatric neuropsychology of the cerebellum. J. Neuropsychol. **11**(2), 201–221 (2017). https://doi.org/10.1111/jnp.12093
19. de Speville, E.D., Robert, C., Perez-Guevara, M., Grigis, A., Bolle, S., Pinaud, C., Dufour, C., Beaudré, A., Kieffer, V., Longaud, A., Grill, J., Valteau-Couanet, D., Deutsch, E., Lefkopoulos, D., Chiron, C., Hertz-Pannier, L., Noulhiane, M.: Relationships between regional radiation doses and cognitive decline in children treated with cranio-spinal irradiation for posterior fossa tumors. Front. Oncol. **7**, 166 (2017). https://doi.org/10.3389/fonc.2017.00166
20. Shurupova, M.A., Kasatkin, V.N., Anisimov, V.N., Ryabova, A.A., Latanov, A.V.: Dynamics of saccadic system functioning in patients with cerebellum tumors after rehabilitation. Theor. Exp. Psychol. **10**(3), 13–25 (2017). (in Russian)
21. Shurupova, M.A., Kasatkin, V.N., Anisimov, V.N., Latanov, A.V.: Influence of surgery-related cerebellar dysfunction on the saccadic system performance in children. Russ. J. Physiol. **106**(7), 866–879 (2020). https://doi.org/10.31857/S0869813920070079
22. Theeuwes, J., Belopolsky, A., Olivers, C.N.: Interactions between working memory, attention and eye movements. Acta Psychol. (Amst) **132**(2), 106–114 (2009). https://doi.org/10.1016/j.actpsy.2009.01.005
23. Schut, M.J., Van der Stoep, N., Postma, A., Van der Stigchel, S.: The cost of making an eye movement: a direct link between visual working memory and saccade execution. J. Vis. **17**(6), 15 (2017). https://doi.org/10.1167/17.6.15
24. Velichkovsky, B.B., Izmalkova, A.I.: Effect of verbal working memory load during the oculomotor activity in visual search. Exp. Psychol. (Russ.) **8**(2), 21–35 (2015). https://doi.org/10.17759/exppsy.2015080203
25. Niemeier, M., Crawford, J.D., Tweed, D.B.: Optimal inference explains dimension-specific contractions of spatial perception. Exp. Brain Res. **179**(2), 313–323 (2007). https://doi.org/10.1007/s00221-006-0788-9

Auditory Oddball P300 in Schizophrenia: An Update

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Abstract. P300 wave is associated with working memory update, allocation of attention resources, and decision making. Numerous studies have consistently revealed P300 abnormalities in schizophrenia making it a promising neurophysiological state and trait marker. The aim of the current paper was to revalidate P300 meaning in schizophrenia as well as to analyze its associations with brain structure and function as revealed by neuroimaging. The findings did not support the wave anomalies. The correlations of P300 with current psychopathology, neuroleptic medication as well as with prefrontal cortex thickness and subcortical structures morphometry and diffusion parameters were non-significant. The pilot study has revealed the relationships between P300 amplitude and functional connectivity between parietal and anterior cingulate subcomponents of fronto-parietal neuronal circuit, however, the inconsistent nature of correlations requires further research.

Keywords: Auditory P300 · Schizophrenia · MRI

1 Introduction

Among event-related potential (ERP) subcomponents, an auditory oddball P300 is one of the most extensively examined in studies of schizophrenia. The wave is associated with cognitive processes, which have been shown to be impaired in the disease, namely working memory update, allocation of attention resources, and decision making [1]. On the other hand, it is originated from multiple generators located in the superior temporal gyrus, temporal-parietal junction, prefrontal and cingulate cortex, thalamus, and hippocampus [2] – key brain elements affected by schizophrenia. Numerous studies have consistently revealed auditory P300 abnormalities in schizophrenia [3] making it a promising neurophysiological marker in biological psychiatry. Our previous studies also supported the findings on P300 reduction and/or prolongation in the disease indicative of deviations in corresponding brain structures and psychophysiological processes [4, 5]. Furthermore, the similarity of data to those in family high risk groups assumed endophenotype nature of these P300 anomalies [6].

Now, since more than ten years, P300 in schizophrenia merits attention again.

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A hypothesis arose that the contemporary psychiatry focus on cognitive abnormalities and appearance of antipsychotic medication more targeted to an improvement of cognition probably led to derangement of P300 role as a state and trait neurophysiological marker in schizophrenia.

In line to speculations above, the findings on the lack of P300 abnormalities have lately emerged in schizophrenia patients with very prolonged illness duration [7].

Another edge that must be considered is the hierarchy of associations between P300 and structural and other functional brain parameters as collected via neuroimaging modalities.

Hence, the aim of the current paper was to revalidate P300 meaning in schizophrenia in newly collected samples as well as to analyze its associations with brain structure and function as revealed by MRI.

2 Method

2.1 Participants

Out of the subjects pool collected for the decades (265 medicated patients with schizophrenia, schizoaffective disorder and non-psychotic patients at ultra-high risk of psychosis [UHR]), and 123 mentally healthy subjects without family loading by mental disorders) we have chosen the samples of those who underwent both ERP and high field (3T) MRI examination during the last years.

All subjects were right-handed males aged from 16 to 30 years. Except for a few subjects, all patients were on medication.

This study was approved by the Ethics Committee of the Mental health research center, and conformed to the Code of Ethics of the World Medical Association for experiments involving humans. All participants signed an informed consent form.

2.2 Auditory Oddball ERP Recording

The standard auditory oddball ERP was done on NeuroKM (Russia) system. The subjects were binaurally presented (via earphone) with pseudorandomized mixture of non-target (1000 Hz, $P = 80\%$) and target (2000 Hz, $P = 20\%$) stimuli. They were instructed to sit with eyes closed and push button by thumb of right hand in response to target stimuli and ignore the non-targets. EEG was recorded in 16 leads (10–20 system) with reference to linked ears leads, in 0.3–70 Hz range (with off-line filtration to 1.6–30 Hz band). Thirty artifact-free epochs containing correctly recognized targets were analyzed. P300 was determined as the largest positive wave in poststimulus interval of 280–450 ms (in F7, F3, F4, F8, T3, C3, CZ, C4, T4, P3, PZ, P4 leads).

The analyses comprised intergroup ANOVA comparison (with Bonferroni post-hoc correction; schizophrenia patients [$n = 41$] vs at ultra high risk patients [$n = 30$] vs mentally healthy subjects without family loading [$n = 41$]) as well as the analysis of correlations of P300 with psychopathology (PANSS scores), age of illness onset and illness duration in patients with schizophrenia ($n = 41$). Also the correlations were obtained between neurophysiological parameters and structural, diffusion, and resting-state functional MRI data.

2.3 MRI

MRI examination was done on 3T Phillips Achieva or Ingenia (the Netherlands) scanners. The modalities that will be discussed in the present paper comprised structural (cortical thickness), diffusion-weighted (probabilistic tractography), and resting-state fMRI.

Structural MRI. The T1-weighted images were analyzed using the FreeSurfer software [8] to provide detailed participant-specific anatomical information. In addition to the volume-based reconstructions, FreeSurfer produces vertex-based models of the cortical surface in the native anatomical space [9–12]. The vertex positions were adjusted such that the surface followed the T1 intensity gradient between the cortical WM and grey matter. Smoothness constraints allowed the surface to cut through a voxel to provide subvoxel (sub-millimeter) accuracy of the surface location [13]. As a result of structural image processing, the cortical thickness at each vertex along each subject's brain surface were quantified. The correlational analysis between P300 and cortical thickness and subcortical volumes was done in 41 first-episode patients with schizophrenia.

Diffusion-Weighted MRI. The DW-MRI data were analyzed using the TRACULA package [14], which uses global probabilistic tractography and incorporates anatomical priors derived from structural MR images. The overall workflow is comprised of two stages: 1) processing of T1-weighted images to obtain cortical parcellation and subcortical segmentation using the FreeSurfer software ; and 2) preprocessing of DW-MRI data, "ball-and-stick" diffusion modelling , and reconstruction of 18 pathways with computation of the fractional anisotropy (FA) and mean (MD), radial (RD) and axial diffusivities (AD) for each tract. The correlational analysis between P300 and white matter tracts diffusion characteristics was done in 23 first-episode patients with schizophrenia.

Resting-State fMRI. T2*-weighted images were obtained via EPI sequence. During the scanning (5 min), the participants were asked to lie motionless with open eyes, fix their gaze on a white cross in the center of grey field presented with special MR-safe monitor, and to avoid consistent thinking about one topic during the period of scanning. Pre-processing of the acquired images was conducted via SPM12 (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/). Further processing of resting-state fMRI data was carried out using CONN-fMRI toolbox 17.b (https://www.nitrc.org/projects/conn). Head-motion artifacts and physiological noise were corrected. Then we performed the analysis of functional connectivity between regions of interest (ROIs; ROI-to-ROI analysis). A set of ROIs comprised of frontoparietal network nodes was taken from the functional atlas [16]. Frontoparietal network was chosen as its within- and between-network dysconnectivity is a prominent neurophysiological marker of schizophrenia [17] and the circuit was found to be closely associated with P300 generation [18].

The pilot analysis was done in 13 first-episode patients with schizophrenia. By using general linear model with random effects, we looked for correlations between P300 parameters and the functional connectivity between components of the frontoparietal network separately in each hemisphere ($p < .05$, false discovery rate [FDR] corrected over the total number of connections included in the analysis).

3 Results and Discussion

Between-group analysis revealed significant ($p < 0.05$) increase in P300 latency prolongation in F8, C4 in UHR group compared to healthy controls, whereas patients with schizophrenia demonstrated intermediate values. The correlations between P300 and PANSS (positive, negative and summarized scores) as well as illness duration and age of onset did not reach the level of significance. Also, no significant correlations were found between P300 amplitudes and latencies and daily dose of neuroleptics (in chlorpromazine equivalent).

So, the absence of significant differences by P300 between schizophrenia patients and mentally healthy subjects challenges the usefulness of this ERP component as a marker of illness mechanisms.

Non-significant correlations with clinical parameters doubt that P300 parameters are state-dependent. Such negative results seem a robust finding and are due to a number of reasons [19]. In our study, an additional factor can be a clinically stable remitted state which contributed to normalization of psychophysiological processes.

There were no significant correlations between P300 and prefrontal cortex thickness, volumes of subcortical structures or white matter diffusion characteristics. These findings correspond to the results of some other multimodal studies that also find no such structural-functional associations [20]. One speculative interpretation is that such ERP measures may be associated with a complex system of structural and functional characteristics, rather than directly correlating with structural variability in separate cortical regions or white matter fascicles.

However, in the first-episode patients, P300 amplitudes in Pz negatively correlated with functional connectivity between parietal and anterior cingulate subcomponents of fronto-parietal neuronal circuit in the right hemisphere, while P300 amplitude in F8 positively correlated with connectivity between the same ROIs in the left hemisphere. Li et al. [21] applied event-related EEG-fMRI and found that healthy participants with higher P300 amplitude demonstrated decreasing connectivity when the brain switched from rest to oddball task, and vice versa. According to these results, our data might possibly mean that patients with more pronounced P300 amplitude in parietal areas need less additional brain resources for executive functions in mind-wandering. At the same time, inverse (i.e., positive) correlation between P300 amplitude in F8 and functional connectivity in frontoparietal network remains unclear. In any case, associations between P300 parameters and functional connectivity in resting-state fMRI in schizophrenia require further studies with larger samples.

So, our latest findings emphasize the fact on seemingly “normal” (or normalized) P300 parameters in quite significant percent of patients with schizophrenia. However, whether the core neurophysiological mechanisms remain abnormal should be a subject of further studies. Unexpectedly, the neurophysiological marker had few correlations with neuroimaging data (except for those with resting-state fMRI). This strongly adds to the functional-structural brain considerations in schizophrenia.

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References

1. Polich, J.: P300 in clinical application, 4th ed. In: Niedermeyer, E., Lopes da Silva, F. (eds.) Electroencephalography Basic Principles, Clinical Applications, and Related Fields, pp. 1073–1085. Williams & Wilkins, Baltimore (1999)
2. Kiehl, K.A., Liddle, P.F.: An event-related functional magnetic resonance imaging study of an auditory oddball task in schizophrenia. Schizophr. Res. **48**(2–3), 159–171 (2001). https://doi.org/10.1016/s0920-9964(00)00117-1
3. Onitsuka, T., Oribe, N., Nakamura, I., Kanba, S.: Review of neurophysiological findings in patients with schizophrenia. Psychiatry Clin. Neurosci. **67**(7), 461–470 (2013). https://doi.org/10.1111/pcn.12090
4. Lebedeva, I.S., Orlova, V.A., Kaleda, V.G., Tsutsulkovskaya, M.Y.: Auditory P300 ERP in schizophrenia. Korsakov's Zhneurolpsychiatry **1**, 47–49 (2000)
5. Lebedeva, I.S., Kaleda, V.G., Barkhatova, A.N.: Neurophysiological characteristics of cognitive functions in the first episode juvenile patients. Korsakov's Zhneurolpsychiatry **2**, 12–20 (2007)
6. Lebedeva, I.S., Kaleda, V.G., Abramova, A.N., Barkhatova, A.N., Omelchenko, M.A.: Neurophysiological anomalies in P300 paradigm as possible endophenotypes of schizophrenia. Korsakov's Zhneurolpsychiatry **1**, 61–70 (2008)
7. Lebedeva, I.S., Golubev, S.A., Klochkova, I.V., Kaleda, V.G.: Neurophysiological characteristics of patients with juvenile schizophrenia at the stage of remoted catamnesis. Korsakov's Zhneurolpsychiatry **3**, 26–32 (2020)
8. Fischl, B.: FreeSurfer. Neuroimage **62**(2), 774–781 (2012). https://doi.org/10.1016/j.neuroimage.2012.01.021
9. Dale, A.M., Fischl, B., Sereno, M.I.: Cortical surface-based analysis. I. Segmentation and surface reconstruction. Neuroimage **9**(2), 179–194 (1999). https://doi.org/10.1006/nimg.1998.0395
10. Fischl, B., Sereno, M.I., Dale, A.M.: Cortical surface-based analysis. II: inflation, flattening, and a surface-based coordinate system. NeuroImage **9**(2), 195–207 (1999). https://doi.org/10.1006/nimg.1998.0396
11. Fischl, B., van der Kouwe, A., Destrieux, C., Halgren, E., Segonne, F., Salat, D.H., et al.: Automatically parcellating the human cerebral cortex. Cereb. Cortex **14**(1), 11–22 (2004). https://doi.org/10.1093/cercor/bhg087
12. Dale, A.M., Sereno, M.I.: Improved localization of cortical activity by combining EEG and MEG with MRI cortical surface reconstruction: a linear approach. J. Cogn. Neurosci. **5**, 162–176 (1993)
13. Greve, D.N., Van der Haegen, L., Cai, Q., Stufflebeam, S., Sabuncu, M.R., Fischl, B., et al.: A surface-based analysis of language lateralization and cortical asymmetry. J Cogn Neurosci **25**(9), 1477–1492 (2013). https://doi.org/10.1162/jocn_a_00405
14. Yendiki, A., Panneck, P., Srinivasan, P., Stevens, A., Zollei, L., Augustinack, J., et al.: Automated probabilistic reconstruction of white-matter pathways in health and disease using an atlas of the underlying anatomy. Front. Neuroinf. **5**, 23 (2011). https://doi.org/10.3389/fninf.2011.00023
15. Behrens, T.E., Berg, H.J., Jbabdi, S., Rushworth, M.F., Woolrich, M.W.: Probabilistic diffusion tractography with multiple fibre orientations: what can we gain? Neuroimage **34**(1), 144–155 (2007). https://doi.org/10.1016/j.neuroimage.2006.09.018
16. Yeo, B.T., Krienen, F.M., Sepulcre, J., Sabuncu, M.R., Lashkari, D., Hollinshead, M., et al.: The organization of the human cerebral cortex estimated by intrinsic functional connectivity. J. Neurophysiol. **106**(3), 1125–1165 (2011). https://doi.org/10.1152/jn.00338.2011

17. Tu, P.C., Lee, Y.C., Chen, Y.S., Li, C.T., Su, T.P.: Schizophrenia and the brain's control network: Aberrant within- and between-network connectivity of the frontoparietal network in schizophrenia. Schizophr. Res. **147**(2–3), 339–347 (2013). https://doi.org/10.1016/j.schres.2013.04.011
18. Bocquillon, P., Bourriez, J.L., Palmero-Soler, E., Betrouni, N., Houdayer, E., Derambure, P., et al.: Use of swLORETA to localize the cortical sources of target- and distracter-elicited P300 components. Clin. Neurophysiol. Official J. Int. Fed. Clin. Neurophysiol. **122**(10), 1991–2002 (2011). https://doi.org/10.1016/j.clinph.2011.03.014
19. Ford, J.M.: The difficulty in finding relationships between ERPs and clinical symptoms of Schizophrenia. Clin. EEG Neurosci. **49**(1), 6–7 (2018). https://doi.org/10.1177/1550059417737416
20. Molina, V., Sanz, J., Munoz, F., Casado, P., Hinojosa, J.A., Sarramea, F., et al.: Dorsolateral prefrontal cortex contribution to abnormalities of the P300 component of the event-related potential in schizophrenia. Psychiatry Res. **140**(1), 17–26 (2005). https://doi.org/10.1016/j.pscychresns.2004.04.006
21. Li, F., Tao, Q., Peng, W., Zhang, T., Si, Y., Zhang, Y., et al.: Inter-subject P300 variability relates to the efficiency of brain networks reconfigured from resting- to task-state: evidence from a simultaneous event-related EEG-fMRI study. Neuroimage **205**, 116285 (2020). https://doi.org/10.1016/j.neuroimage.2019.116285

Alpha Oscillations in the Subthalamic Nucleus Interfere with Motor Functions in Patients with Parkinson's Disease

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Abstract. Basal ganglia electrophysiological oscillations are extensively studied. While beta oscillations are considered to contribute to motor dysfunction in Parkinson's Disease (PD), alpha oscillations have not been the focus of researchers. This study was inspired by observing stable oscillations in the alpha range during deep brain stimulation (DBS) surgeries in Parkinsonian patients. Hence, we aimed to investigate the role of alpha oscillations in motor performance of PD. We recorded local field potentials during DBS surgeries. We identified alpha and beta oscillation peaks and their localization, sensitivity to motor tests, and correlation between the oscillation power in both bands with symptoms severity on the contralateral side of the body. The alpha oscillation area was located ventrally to the beta oscillation area. Beta, but not alpha oscillations were sensitive to voluntary movements. Alpha oscillations were associated with a more severe bradykinesia score on the contralateral side of the body. We may conclude that alpha oscillations may interfere with motor performance in a different manner than beta. The high stability of alpha oscillations may contribute to both the insensitivity to motor tests and manifestation of bradykinesia.

Keywords: Basal ganglia · Parkinson's disease · Subthalamic nucleus · Microelectrode recordings · Alpha oscillations

1 Introduction

Parkinson's disease (PD) is a neurodegenerative movement disorder that is caused by basal ganglia dysfunction due to dopaminergic deficiency. Three decades ago, Albin and Delong proposed a model, stating that dopamine depletion causes insufficient activation of the prokinetic direct pathway from the striatum to the internal globus pallidus, along with insufficient inhibition of the indirect antikinetic pathway [1]. However, now it is widely assumed that basal ganglia dysfunction affects not only firing rate, but also firing pattern, in particular extensive neuronal synchronization and pathological oscillations in the basal ganglia structures [2].

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Commonly, rhythmic activity is split into several oscillation ranges, including theta, alpha, beta and gamma bands. Usually, the oscillation range limits are defined as 4–8 Hz for theta, 8–12 (or 13) Hz for alpha, 12 (or 14)-30 Hz for beta and 30–60 Hz for gamma bands. Oscillations in PD have been studied extensively, with special attention being paid to the theta range, which is correlated with tremor and the beta range, which is linked to other motor symptoms of PD. In several reports, the borders of the oscillation bands are shifted to widen the ranges in focus: some researchers view theta and alpha ranges together, expanding the border of the low frequency range in view to 10 Hz [3] or even 12 Hz [4]. In other cases, one may see an opposite approach, when the whole alpha range or some part of it is merged with the beta range [2, 5]. Although this shifting the borders of the range limits may be useful in some respects, it still needs careful investigation and justified scientific reasons to move the oscillation ranges to any level and in either direction. To date, these arbitrary shifts in the range limits may confuse and complicate the interpretation of the data from different reports, rather than improve our understanding of the pathophysiological changes in the basal ganglia network.

Currently, LFP oscillations in the basal ganglia network in the beta range are considered as being implicated in pathophysiological changes in the subthalamic nucleus (STN) in PD. Several studies have reported that oscillations in the beta range may contribute to clinical signs of PD [6–8] and are sensitive to voluntary movements [9, 10]. Oscillations in the theta range are commonly associated with tremor [11]. In basal ganglia studies, the alpha oscillation range is rarely examined as an isolated band. Commonly, the alpha range is not in the focus of studies of STN neurophysiological activity in PD patients, which search for a link between motor impairment in PD and oscillatory activity in the basal ganglia. We have not found reports concerning the features of alpha oscillations in STN motor regions and the possible implications of alpha band activity in motor processing in the STN.

This study was inspired by observing very stable rhythmic activity in the alpha range during deep brain stimulation (DBS) surgeries in PD patients. The aim of this study was to describe and explore the features of alpha and beta oscillations and localization of these two types of rhythmic activity.

2 Materials and Methods

2.1 Patients

Thirty-one Parkinsonian patients (18 females and 13 males, 36–66 years old) participated in this study. LFP recordings were collected in 2017–2018 in the Burdenko Centre for Neurosurgery during DBS surgeries. All the recordings were performed in the awake state under local anaesthesia. Preoperatively, patients were withdrawn from medications overnight. The details for all procedures were carefully explained to the participants before the operation. All participants gave their written informed consent. The study protocol was approved by the local Ethics Committee, in agreement with the Declaration of Helsinki.

All the patients underwent a neurological examination before the surgery to assess the severity of motor symptoms according to unified Parkinson's disease rating scale (UPDRS). Clinical data for the patients are provided in Table 1.

Table 1. Architecture and parameter details of the proposed network.

patient	gender	number of hemi-spheres	age of disease onset, y.o.	PD duration, yrs	age, y.o.	Hoehn-Yahr stage	LED, mg	UPDRS2 score, off-state	UPDRS3 score, off-state	UPDRS2 score, on-state	UPDRS3 score, on-state	off state hypokinesia, right side	off state hypokinesia, left side	off state rigidity, right side	off state rigidity, left side	off state tremor, right side	off state tremor, left side
1	f	2	40	11	51	3	1650	29	62	2	10	10	13	6	4	5	3
2	f	2	51	9	60	2,5	1200	12	28	1	3	4	7	1	2	0	2
3	f	2	56	10	66	3	1500	25	65	7	21	11	12	4	6	7	6
4	f	2	52	10	62	3	1050	24	46	12	17	11	9	4	3	0	2
5	f	1	31	5	36	2	300	8	37	7	24	12	4	6	2	7	0
6	f	2	56	8	64	3	2200	25	52	3	15	11	10	3	4	0	2
7	f	2	48	13	60	4	1995	27	41	7	14	6	6	3	3	2	3
8	f	2	39	12	51	4	2300	34	78	5	28	14	11	8	6	7	2
9	f	2	43	10	53	4	1766	31	76	10	31	14	16	8	8	2	2
10	f	2	56	10	66	4	2200	19	46	4	14	10	13	4	2	0	0
11	f	2	38	22	60	3	2150	24	54	1	8	12	8	6	4	2	1
12	f	1	29	19	48	4	300	37	76	8	22	15	13	6	4	7	6
13	f	2	45	17	62	3	2200	22	41	1	7	9	13	2	4	0	2
14	f	2	44	14	58	3	1600	19	69	2	16	9	12	6	4	10	7
15	f	2	55	11	66	3	1475	22	47	2	9	4	9	5	5	1	1
16	f	2	50	13	63	4	850	30	61	9	25	16	10	5	4	5	2
17	f	2	36	11	47	4	1887,5	30	56	3	8	9	11	7	7	2	2
18	f	2	39	8	47	2,5	950	15	24	0	2	3	7	2	4	0	2
19	m	2	34	20	54	3	2528	28	56	8	14	12	14	6	4	0	0
20	m	2	39	9	48	4	2500	16	51	1	12	9	8	6	6	5	2
21	m	1	51	12	63	3	1300	20	54	9	10	11	11	6	3	3	2
22	m	2	37	12	49	3	1600	19	57	1	12	12	10	6	4	5	5
23	m	2	52	8	60	3	2264	28	41	0	5	6	8	5	6	0	2
24	m	2	31	9	40	3	1500	20	37	2	13	4	3	3	2	7	6
25	m	2	37	8	45	3	1350	9	32	3	5	8	6	4	3	0	0
26	m	2	40	9	49	3	1950	18	39	4	14	8	4	6	5	1	0
27	m	2	38	12	50	3	2100	25	46	4	13	11	9	2	3	0	0
28	m	2	52	13	65	3	1450	11	18	3	6	6	1	4	0	0	0
29	m	2	37	7	44	4	4500	34	78	7	21	13	16	6	7	8	4
30	m	2	38	17	55	3	2100	28	34	6	8	4	8	2	4	0	0
31	m	2	37	14	51	3	1675	10	26	0	1	3	0	3	3	6	6

2.2 Procedure and Data Collection

Microelectrode recordings (MER) were performed during surgeries to localize the borders of the subthalamic nucleus for the proper implantation of the stimulating electrode. Before the operation, patients underwent Magnetic resonance imaging (MRI) with a fixed stereotactic frame using T1 and T2 weighted sequences on a Signa Horizon Speed 1.5T scanner (General Electric). The individual target coordinates were assessed based on MRI images using the stereotactic planning station Leksell G Surgiplan Software (Elekta, Sweden). The electrode was placed 10 mm above the target and immersed by increments of 0.1–0.3 mm along the trajectory, using the NeuroNav system (AlphaOmega, Israel). LFP recordings were performed with a sampling rate of 712 Hz.

In 11 cases, patients were asked to perform movements during the DBS surgeries. There were two types of tests: we asked patients to contract the fist and to move the foot contralaterally to the site of microelectrode recording. During the procedure, an electromyography (EMG) signal from the finger flexors and anterior tibialis muscle were recorded to control for the fist and foot movements.

2.3 Data Analysis

LFP Processing. We performed the analysis of LFP recordings using Neuroexplorer software. LFP recordings were pre-filtered using a 50 Hz notch filter. The segments of LFP recordings at rest and during hand or foot movements were analysed separately. In order to assess the level of rhythmic activity in different frequency ranges, we calculated the mean value of the power spectra density (PSD) in given frequencies (8–12, 12–20, 20–30, 30–60 Hz), and also the maximal values of the spectra (peak amplitudes) in the given frequencies.

We tested the amplitude of the alpha and beta peaks along with motor symptoms for the contralateral side of the body. Mixed effect models were applied to test the influence of bradykinesia, rigidity and tremor severity on oscillation levels in both bands.

The strength of oscillation was assessed based on maximal values and mean values of PSD spectra in given frequency ranges. We localized the position of the alpha and beta oscillations using maximal values of oscillations in 8–12 and 12–20 Hz across patients. To assess the influence of motor sign severity on the level of oscillations in the alpha and low and high beta bands, we measured the mean of power spectral values in given frequencies (8–12, 12–20 and 20–30 Hz, respectively).

Lead-DBS Analysis. To study whether alpha and beta oscillations have any differences in localization, we defined the coordinates of the peaks using Lead-DBS software (https://lead-DBS.org) within MATLAB 2016b (The MathWorks, USA). The sites with maximal values in alpha (8–12 Hz) and beta (12–30 Hz) frequencies extending to 90% quartiles of the whole data set values were localized along fitted electrode trajectories. For each site, x, y and z coordinates were assessed in dorso-ventral, latero-medial and anterio-posterior directions, respectively.

Statistical analysis of the data was performed using R (https://cran.r-project.org). The differences in the localization of alpha and beta peaks was measured using generalized linear model fitting. The sensitivity to voluntary movements was tested by applying a paired t-test. To measure the association of intensity of oscillations to the motor signs of Parkinsonism, we applied mixed effect models with the hemisphere of LFP recording acting as a random factor.

3 Results

We collected and analyzed 701 LFP recordings from 56 hemispheres with particular attention to oscillations in alpha and beta range. The specific activity in the alpha range had a peak frequency between 10 and 12 Hz, which differed from beta activity, which was not so stable and usually had a higher peak frequency, ranging from 15 to 25 Hz. We found 64 LFP recordings with an alpha maximal amplitude value above 2% of PSD (90% quantile for maximal alpha amplitude in our data set was 1.89) and 70 LFP recordings with a low beta maximal amplitude above 1.5% of PSD (90% quantile for maximal alpha amplitude in our data set was 1.49) on the PSD plots. Among them, 23 LFP recordings had simultaneous alpha and low beta peaks in the power spectrum.

Examples of LFP spectrograms with alpha, beta, and coexisting alpha and beta oscillations are shown at Fig. 1.

3.1 Localization of Alpha and Beta Peaks

First, we analyzed the localization of the most prominent oscillation peaks using Lead-DBS software. We assessed for statistical differences in coordinates for single alpha and beta peaks in different axes. We found differences in the dorso-ventral direction with alpha lying more ventrally and beta lying more dorsally (p-value = 0.015). Median values for x, y and z coordinates of alpha and beta peaks, and the interquartile range for peak positions in each direction may be seen along with spatial distribution of the peaks in Fig. 2.

3.2 Associations of the Oscillations with Voluntary Movements

For 11 patients, we obtained 47 LFP recordings at the same site at rest and during fist contraction and foot movements, contralateral to the side of electrode implantation.

We compared the recordings at rest and during voluntary movements in the same site in alpha, low and high beta, and gamma oscillation bands (Fig. 3). We found no significant changes in alpha between the states. There were significant increases in the low beta range during leg movements (p-value = 0.0022) and a significant increase in the high beta range during hand movements (p-value = 0.038). Additionally, we found a significant increase in the gamma range for both types of tests (p-values = 0.0098 and 0.0012 for foot and hand movements, respectively).

3.3 The Correlation Between Oscillations and Clinical Signs of PD

We tested the association between the intensity of oscillations in various ranges and bradykinesia, rigidity and tremor scores on the contralateral side of the body. As we

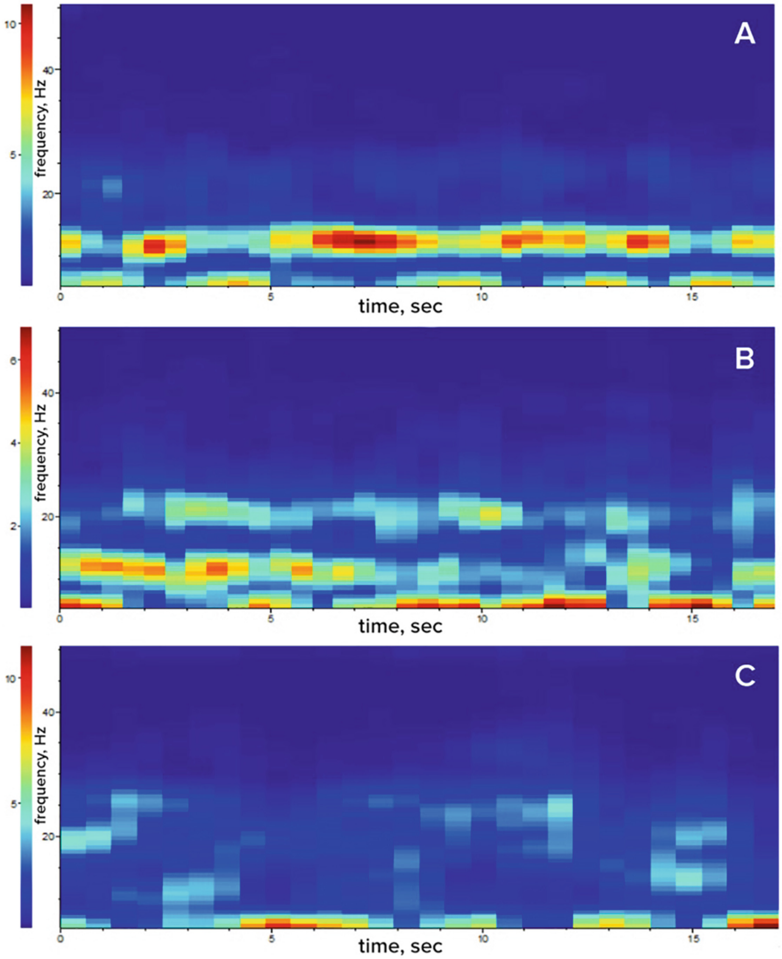
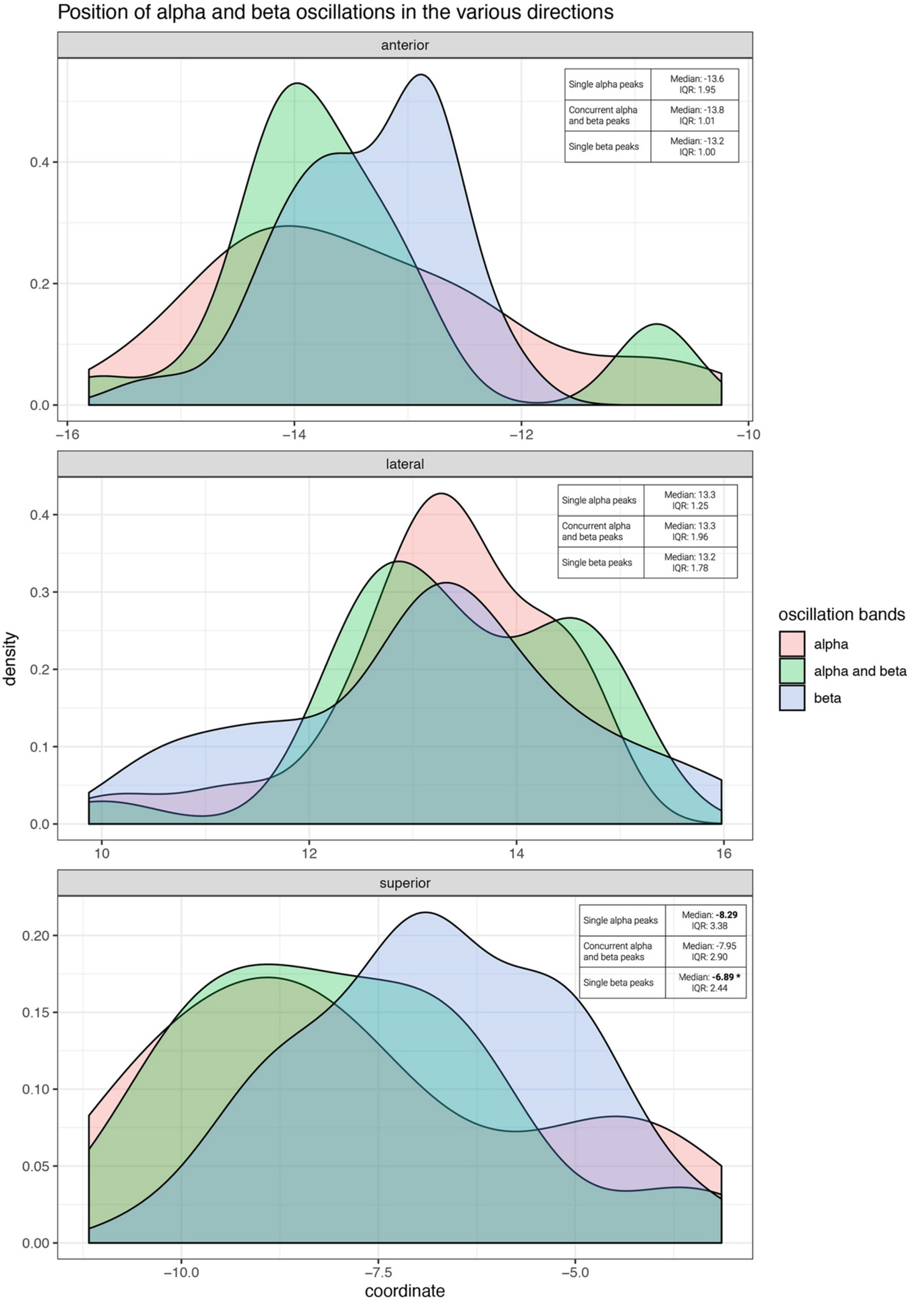


Fig. 1. Spectrograms for LFP recordings with alpha, beta and coexisting alpha and beta oscillations.

had multiple measures in each hemisphere, we applied mixed effects models with the hemisphere of LFP recording acting as a random factor.

The only significant correlation in this case was found between alpha oscillation severity as a dependent variable and the bradykinesia score as a predictor (p-value = 0.0081). The difference in the influence of alpha and beta oscillations on the bradykinesia may be visualized when comparing bradykinesia scores on the contralateral side of the body between the hemispheres with and without alpha and beta peaks in the STN (Fig. 4).

Additionally, we found significant correlations ($p < 0.05$) for UPDRS 2 and 3 scores in the off state with both alpha and beta oscillations. However, these scores do not account for the differences between the body sides for motor signs.



anterior

Single alpha peaks	Median: -13.6 IQR: 1.95
Concurrent alpha and beta peaks	Median: -13.8 IQR: 1.01
Single beta peaks	Median: -13.2 IQR: 1.00

lateral

Single alpha peaks	Median: 13.3 IQR: 1.25
Concurrent alpha and beta peaks	Median: 13.3 IQR: 1.96
Single beta peaks	Median: 13.2 IQR: 1.78

superior

Single alpha peaks	Median: **-8.29** IQR: 3.38
Concurrent alpha and beta peaks	Median: -7.95 IQR: 2.90
Single beta peaks	Median: **-6.89 *** IQR: 2.44

Fig. 2. Distribution of alpha and beta peaks across x,y,z coordinates according to LeadDBS imaging. Median values and interquartile ranges for each group are provided on the plots

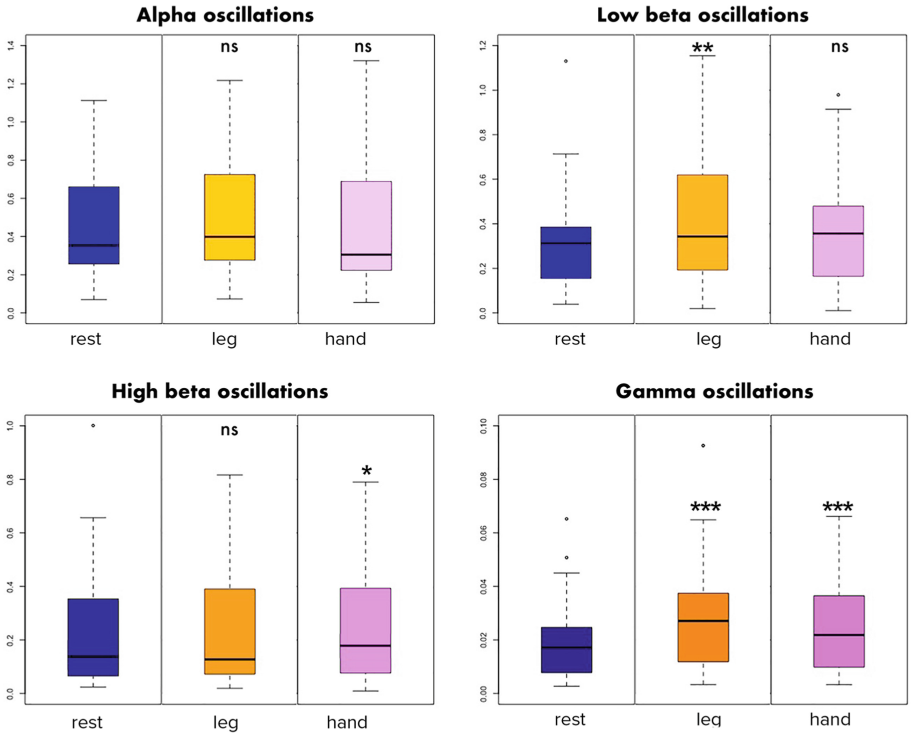


Fig. 3. Boxplots showing changes in ocillation scores at rest and during voluntary movements in the same site in alpha, low and high beta and gamma oscillations bands

4 Discussion

Levy and colleagues were the first to study pathological STN synchronization in the beta band in PD and its possible link to clinical symptoms in PD patients [12]. Since then, hundreds of reports on this topic have been published in the scientific literature. At some point, researchers studying oscillatory activity in the STN in PD expanded the focus to several oscillatory bands, including theta and gamma ranges. For many years, scientific reports have shown little or no interest in the alpha region, which was typically linked to cortical regions of the brain.

Recently, alpha oscillations in subcortical regions have attracted the attention of researchers. However, most of the reports imply that alpha contributes to the non-motor functions of the STN [13]. There is some evidence that alpha oscillations may be located in associative regions of the STN [14]. This notion is further supported by the data indicating that STN alpha oscillations are involved in non-motor tasks and processes, including emotional aspects of perception and risk of depression [13, 15–18].

As far as we know, to date there are no comparative studies of alpha and beta oscillations and their relation to motor signs in PD. This study was inspired by observations of stable LFP alpha oscillations in the range of 10–12 Hz intraoperatively in several cases

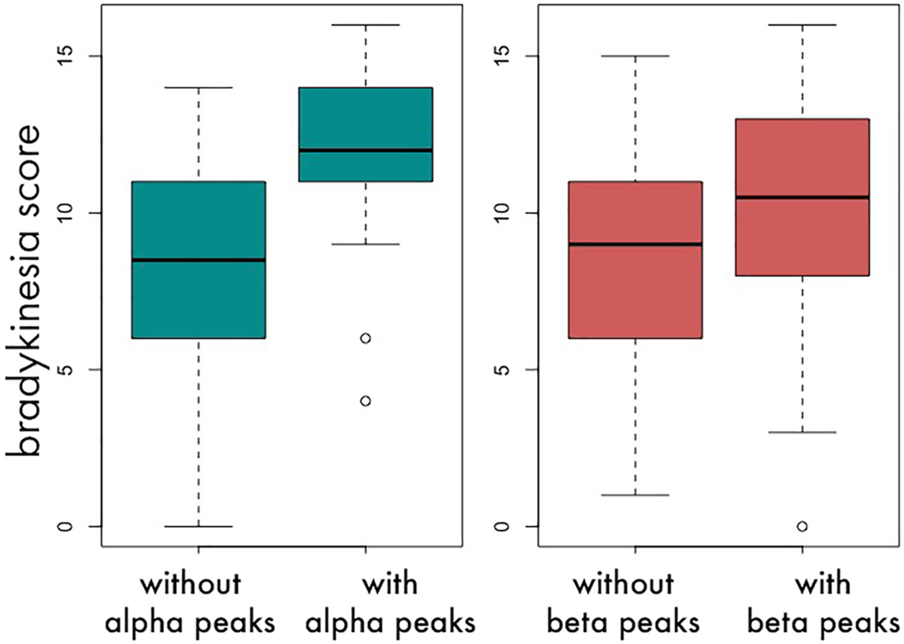


Fig. 4. Boxplots for bradykinesia scores in the hemispheres with and without alpha and beta peaks in the STN.

during DBS surgeries. During this study, we analyzed 701 LFP recordings in 56 hemispheres of 31 PD patients. The features of the observed 10–12 Hz alpha activity differed significantly from that of beta oscillations in the range of 13–30 Hz.

In several cases, alpha and beta oscillations were observed simultaneously in the same site of the STN, although alpha oscillations tended to occur more ventro-medially compared to beta oscillations. This coexistence of alpha and beta activity is the strongest evidence that indicates the independence of these two types of rhythmic activity, concerning the source and possible implications in the function of the basal ganglia network.

Using Lead-DBS tools, we confirmed that alpha and beta oscillations reside in separate, although overlapping, regions of the posterior STN. Beta oscillations are located in the dorsal region of the posterior STN, which coincides perfectly with the motor subdivision of this structure, while alpha oscillations are displaced toward the ventral associative STN subdivision. This fact indicates that alpha and beta activity may differ substantially in source and nature.

We have tested the sensitivity of oscillations in alpha, beta and gamma range to voluntary movements. As expected, we observed changes in oscillations during movements in gamma and beta, but not 10–12 Hz alpha band. Periods of motor activity were accompanied by an increase in beta oscillations, that may be viewed as contradiction to "antikinetic" properties of beta oscillations. Indeed, several groups have reported the decrease in beta band activity prior to and during the onset of the movement in Parkinsonian patients [19–21]. However, researchers that have studied continuous movements in

Parkinsonian state have observed statistically significant increase in beta oscillations [10, 22], which is in line with our data. Insensitivity of the alpha range to motor performance in contrast to beta and gamma oscillations also supports this assumption.

When we tested for a link of alpha and beta oscillations to the motor signs of PD on the contralateral side of the body, the only significant association was revealed between alpha oscillations and the bradykinesia score. According to our data, there was no significant association between beta oscillations and one-sided PD motor signs after multiple measures in the same hemisphere were taken into account. At the same time, we found significant associations between both alpha and beta oscillations and UPDRS 2 and UPDRS 3 off scores.

The high stability of alpha oscillations in the STN (as we can see on the spectrograms) may hamper information processing during voluntary movements more effectively than beta and this may imply both an insensitivity of alpha rhythm to movement and its apparent association with motor impairment on the contralateral side of the body.

In summary, we may state that alpha and beta oscillations should be viewed and studied separately, as they have different features (i.e. localization, stability, sensitivity to movement and clinical symptoms). We may hypothesize that stability of alpha oscillations in the STN may hamper information processing during voluntary movements and this may imply both a movement insensitivity and association with motor impairment, but further research is necessary to clarify that point.

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References

1. Albin, R.L., Young, A.B., Penney, J.B.: The functional anatomy of basal ganglia disorders. Trends Neurosci. **12**, 366–375 (1989). https://doi.org/10.1016/0166-2236(89)90074-x
2. Brown, P.: Oscillatory nature of human basal ganglia activity: relationship to the pathophysiology of Parkinson's disease. Mov. Disord. **18**, 357–363 (2003). https://doi.org/10.1002/mds.10358
3. Rodriguez-Oroz, M.C., López-Azcárate, J., Garcia-Garcia, D., et al.: Involvement of the subthalamic nucleus in impulse control disorders associated with Parkinson's disease. Brain **134**, 36–49 (2011). https://doi.org/10.1093/brain/awq301
4. Shimamoto, S.A., Ryapolova-Webb, E.S., Ostrem, J.L., et al.: Subthalamic nucleus neurons are synchronized to primary motor cortex local field potentials in Parkinson's disease. J. Neurosci. **33**, 7220–7233 (2013). https://doi.org/10.1523/JNEUROSCI.4676-12.2013
5. Hammond, C., Bergman, H., Brown, P.: Pathological synchronization in Parkinson's disease: networks, models and treatments. Trends Neurosci. **30**, 357–364 (2007). https://doi.org/10.1016/j.tins.2007.05.004
6. Sharott, A., Gulberti, A., Zittel, S., et al.: Activity parameters of subthalamic nucleus neurons selectively predict motor symptom severity in Parkinson's disease. J. Neurosci. **34**(18), 6273–6285 (2014). https://doi.org/10.1523/JNEUROSCI.1803-13.2014
7. Neumann, W.J., Degen, K., Schneider, G.H., et al.: Subthalamic synchronized oscillatory activity correlates with motor impairment in patients with Parkinson's disease. Mov. Disord. **31**(11), 1748–1751 (2016). https://doi.org/10.1002/mds.26759

8. Hirschmann, J., Abbasi, O., Storzer, L., et al.: Longitudinal recordings reveal transient increase of alpha/low-beta power in the subthalamic nucleus associated With the onset of Parkinsonian rest tremor. Front. Neurol. **10**, 145 (2019). https://doi.org/10.3389/fneur.2019.00145
9. Lofredi, R., Tan, H., Neumann, W.J.: Beta bursts during continuous movements accompany the velocity decrement in Parkinson's disease patients. Neurobiol. Dis. **127**, 462–471 (2019). https://doi.org/10.1016/j.nbd.2019.03.013
10. Florin, E., Erasmi, R., Reck, C., et al.: Does increased gamma activity in patients suffering from Parkinson's disease counteract the movement inhibiting beta activity? J. Neurosci. **237**, 42–50 (2013). https://doi.org/10.1016/j.neuroscience.2013.01.051
11. Contarino, M.F., Bour, L.J., Bot, M., et al.: Tremor-specific neuronal oscillation pattern in dorsal subthalamic nucleus of parkinsonian patients. Brain Stimul. **5**(3), 305–314 (2012). https://doi.org/10.1016/j.brs.2011.03.011
12. Levy, R., Ashby, P., Hutchison, W.D., et al.: Dependence of subthalamic nucleus oscillations on movement and dopamine in Parkinson's disease. Brain **125**(6), 1196–1209 (2002). https://doi.org/10.1093/brain/awf128
13. Eisinger, R.S., Urdaneta, M.E., Foote, K.D., et al.: Non-motor characterization of the basal ganglia: evidence from human and non-human primate electrophysiology. Front. Neurosci. **12**, 385 (2018). https://doi.org/10.3389/fnins.2018.00385
14. Horn, A., Neumann, W.J., Degen, K., et al.: Toward an electrophysiological "sweet spot" for deep brain stimulation in the subthalamic nucleus. Hum. Brain. Mapp. **38**(7), 3377–3390 (2017). https://doi.org/10.1002/hbm.23594
15. Brücke, C., Kupsch, A., Schneider, G.H., et al.: The subthalamic region is activated during valence-related emotional processing in patients with Parkinson's disease. Eur. J. Neurosci. **26**, 767–774 (2007). https://doi.org/10.1111/j.1460-9568.2007.05683.x
16. Eitan, R., Shamir, R.R., Linetsky, E., et al.: Asymmetric right/left encoding of emotions in the human subthalamic nucleus. Front. Syst. Neurosci. **7**, 69 (2013). https://doi.org/10.3389/fnsys.2013.00069
17. Huebl, J., Schoenecker, T., Siegert, S., et al.: Modulation of subthalamic alpha activity to emotional stimuli correlates with depressive symptoms in Parkinson's disease. Mov. Disord. **26**, 477–483 (2011)
18. Wojtecki, L., Elben, S., Vesper, J., Schnitzler, A.: The rhythm of the executive gate of speech: subthalamic low-frequency oscillations increase during verbal generation. Eur. J. Neurosci. **45**, 1200–1211 (2017). https://doi.org/10.1111/ejn.13429
19. Cassidy, M., Mazzony, P., Oliviero, A., et al.: Movement-related changes in synchronization in the human basal ganglia. Brain **125**(6), 1235–1246 (2002). https://doi.org/10.1093/brain/awf135
20. Alegre, M., Alonso-Frech, F., Rodriguez-Oroz, M.C., et al.: Movement-related changes in oscillatory activity in the human subthalamic nucleus: ipsilateral vs. contralateral movements. Eur. J. Neurosci. **22**(9), 2315–2324 (2005). https://doi.org/10.1111/j.1460-9568.2005.04409.x
21. Canessa, A., Pozzi, N.G., Arnulfo, G., et al.: Striatal dopaminergic innervation regulates subthalamic beta-oscillations and cortical-subcortical coupling during movements: preliminary evidence in subjects with Parkinson's disease. Front. Hum. Neurosci. **10**, 611 (2016). https://doi.org/10.3389/fnhum.2016.00611
22. Kochanski, R.B., Shils, J., Verhagen-Metman, L., et al.: Analysis of movement-related beta oscillations in the off-medication state during subthalamic nucleus deep brain stimulation surgery. J. Clin. Neurophysiol. **36**(1), 67–73 (2019). https://doi.org/10.1097/WNP.0000000000000521

Induced Delusional Disorder (Folie à Deux)

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Abstract. Induced delusions can act as a model of "learning error" when the recipient becomes convinced of delusional interpretations of events due to a distorted perception. The results of fMRI scanning of a pair of an inductor and a recipient with two stories of delusion - persecution and greatness are presented. Analysis of functional imaging shows different activities of the same areas of the cerebral cortex in the inducer and in the recipient. The volume and localization of activation of the cerebral cortex in the inducer is increased compared to the recipient. The data on the differences in the localization of the brain zones, which are activated in comparison with different plots of delirium, were obtained.

Keywords: Induced delusional disorder · Folie à deux · fMRI

1 Introduction

The term "induced delusional disorder" replaced the archaic "emotional contagion" [1] or "imposed psychosis" [2]," two-person obsession" [3], "induced insanity" [4], etc. The term is abolished in the updated versions of the international classifications of mental disorders due to its rarity and the diagnosis is recommended to be encoded as "chronic delusional disorder" without reference to etiopathogenetic mechanisms. The Genesis of induced delusional disorder remains unspecified due to the casuistic nature of observations. Thus, according to a systematic review [5], it is customary to give an indicator of 1.6–2.6% of the number of all hospitalizations in psychiatric hospitals [6] in the literature but the initial data for these figures is an article from 1942 [7], which makes it difficult to compare with modern index. In addition, there is a possibility that one of the pair of psychotic patients with folie à deux does not fall into the diagnostic field of psychiatrists for a long time due to the public acceptance of delusional ideas or tolerance to their ideas on the part of their close environment, primarily family members [8, 9]. Folie à deux assumes the presence of inductor (primary partner), who "shapes" recipient's (secondary partner) delusional ideas in close emotional contact [8, 10–12], the

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inductor (senior by age or status among the immediate environment) and recipient (who takes a subordinate position in a couple) often lead a secluded life with limited contacts, and the plot of delusional ideas along with psychosis concerns events or phenomena that are familiar to them [3].

Clinically speaking, there are several forms of folie à deux [3, 7, 9, 13] which depend on the chronology of delirium development, the degree of coverage, and the period of delirium reduction after the separation of a psychotic couple [7, 9].

- imposed (imposed, imposed - imposed psychosis), wherein he recipient is a mentally healthy person who is able to completely get rid of delusional beliefs after separation from the inductor [4, 7, 14];
- communicative psychosis [15], wherein he recipient takes a dim view of the inductor's delusional ideas for some time, but retains them in a reduced form even after separation from the inductor;
- induced psychosis in the classical description implies the transfer of delusional ideas from the inducer to the recipient with increased readiness for delusional formation [4].

In our opinion, the clinical case presented below is an example of the transformation of communicative psychosis into the classical form of Folie à deux on the example of a mother and daughter.

2 Anamnesis

It is known that relatives on both lines were closed, unsociable, reserved in the expression of emotions. The father did not participate in the upbringing of his daughter, and was not interested in her fate. Both patients are Caucasian and right-handed.

Mother: 61 years old, retired. She was anxious, responsible, executive and unsociable until the age of 30. Having mastered the specialty of an engineer, she's worked for ten years without career growth. She led a solitary life, was not interested in anything, and avoided the opposite sex. She gave birth to a daughter from a colleague without marriage. She changed her mind when she devoted her life to raising a child at the age of 30. She stopped communicating with the few people she knew and switched to a less skilled job with a flexible schedule. She considered herself to be the only one who knew what regime and loads were acceptable for a child. She was sure that the majority of teachers could not adequately assess all daughter's talents, that they envied, harmed her, built obstacles, etc. The mother considered her particularly gifted and talented, she talked to the daughter for several hours every day, settled to various extracurricular activities and dreamed of a brilliant career as a diplomat or as a specialist in international law. She filled her daughter's conscience with these ideas, regarded criticism or the slightest remarks about her daughter as an "insult", considered ratings below "excellent" as unjustified. However, such a mother avoided open conflicts due to being anxious and fearful. By the age of 55–60 years, she began to notice distraction, forgetfulness, which affected the quality of work - she did not understand the meaning of what she read, could hardly concentrate on things, forgot the instructions of her superiors and made mistakes in calculations. At the same time, the "head of the family" secretly appointed her daughter, shifting the responsibilities of earning money to her. At the same time, the responsibilities of earning money were shifted to the daughter who also became the "head of the family".

Daughter: 31 years old, a secretary. She was born after a normal pregnancy, emergency delivery, in early development without features. She was attached to her overprotective mother since childhood, convinced of her own exclusivity and believed that she was worthy of a brilliant career and high positions. She studied perfectly, tried to be the best in everything and to earn praise. She didn't seek to communicate with her peers and preferred to spend time alone with books. She felt no need for confidential communication with anyone else than her mother. As a teenager, she became more persistent in achieving career goals, focusing entirely on her studies. She graduated from the specialty and master's degree programs with honors and combined her final years of study with secretarial duties in the University administration. She enrolled in grad school with a plan to complete a dissertation research on international law, then she went to European countries to study archival documents in public libraries. She met a native of India during one of such trips and considered him her groom and planned to marry him. However, she did not receive a real offer and their communication was limited to several meetings and massaging.

She noted the special attitude of her colleagues since the age of 26. She complained to her mother that her colleagues ignored her achievements at work, downplayed her merits, and did not notice the amount of work done. She began to notice "signs of open hostility" from colleagues two years later. She became more tense, conflicted, rude and unrestrained communicating with others. During the same period, she began to notice unfamiliar lack of focus, difficulty concentrating and distraction. She fought for justice, wrote complaints to the supervisor with a request to resolve the situation in order to restore justice and prove her case. She hoped to be protected from undeserved attacks. She was sure that the supervisors were in a conspiracy with the colleagues to deprive her of her job because she didn't receive any support. She reproached her colleagues for allegedly reporting non-existent mistakes, accused them of deliberately damaging papers, breaking furniture and office equipment. When she came home, she discussed all the problems with her mother, condemned the behavior of colleagues, searched for the perpetrators of the conflict together, "calculated" the next steps of the enemies and came up with ways to "defeat everyone". A year later, she began to suspect colleagues of conspiring to cause physical damage, allegedly heard them discussing the attack plan. The daughter changed routes on the way home every day, recognized the faces of passers-by and noticed suspicious cars.

She began experiencing of severe anxiety, which made it difficult to fall asleep; she often woke up at night and did not feel rest in the morning, became absent-minded and could not cope with normal tasks a month before the first hospitalization (30 years old). Thinking about the situation at work, she realized in an instant that she had been in the center of the struggle for years because "she collected materials for her dissertation as a valuable employee and a qualified specialist that are of interest to the special services of different countries including India and Russia." She concluded that the groom "was sent by the CIA for recruiting and her colleagues at the Institute are on the opposite side, so they harassed her and put psychotropic drugs in food and drinks for poisoning." She found confirmation of her suspicions in random phrases, which were interpreted as threatening hints and she realized that an attack was being prepared for her. She barricaded the front door together with her mother at home, cut off all communications, considering them tracking devices, sealed the ventilation for fear of being poisoned. They lived for a week this way, recognized facts of their personal life on TV and saw coded threat massages from colleagues there. They ate almost nothing as they considered all the food poisoned. Eventually, they were hospitalized in a psychiatric clinic at the insistence of relatives. At first the patients remained confident in the prosecution even being divided into departments: the daughter searched for hidden cameras in the wards, accused the doctors of colluding with the special services and remained confident in her "great mission to save the world".

The treatment was carried out synchronously in the daughter and the mother: Sol. Haloperidoli 0,5% 2,0 ml + NaCl 0,9% 500,0 ml IV drip in the morning №3, Trihexyphenidili 2 mg –0–2 mg, Sol. Phenazepami 2,0 ml IM at night. After three days of intensive care, they were transferred to Risperidone 4 mg; after three weeks of the treatment, they were transferred to a prolonged injection of Risperidone 37.5 mg IM. At the same time, there was a rapid reduction of paraphrenic delusion in both patients, while maintaining the delusion of persecution in the daughter.

3 fMRI

3.1 Technical Specifications

The second week of the treatment during the period of hospitalization a single fMRI examination of both patients was performed for diagnostic purposes; by this time the patients' delusional symptoms were deactualized, but their conviction that the experience was not a manifestation of the disease continued. The fMRI-examination was conducted at the Kurchatov Institute Research Center using a Siemens Magnetom Verio 3T MR-tomograph. Three-dimensional T1-weighted sequence in the sagittal plane with high spatial resolution (176 sections, TR = 2530 MS, TE = 3.31 MS, section thickness = 1 mm, deflection angle = 7°, inversion time = 1200 MS, and FOV = 256×256 mm^2) was used to obtain anatomical MRI images. fMRI data were obtained using an ultra-fast sequence, which allows you to increase the frequency of fMRI data acquisition several times preserving all the spatial characteristics of the scan (51 sections, TR = 1100 MS, TE = 24 MS and an isotropic voxel $2 \times 2 \times 2$ mm^3). This study was approved by the ethics committee of the National Research Centre Kurchatov Institute, ref. no. 5 (from April 5, 2017). Additionally, the GFM (gre_field_map) MRI scan mode was used to take into account the inhomogeneity of the magnetic field of the tomograph and correct artifacts associated with this. Field map imaging was performed with a double-echo spoiled gradient echo sequence (gre_field_map; TR = 580.0 ms, TE = 4.92/7.38 ms, voxel size: $2 \times 2 \times 2$ (0.6-mm gaps), flip angle 90°) that generated a magnitude image and 2 phase images.

The fMRI and anatomical MRI data were pre-processed using Statistical Parametric Mapping (SPM12; Welcome Trust Centre for Neuroimaging, London, UK; available free at https://www.fil.ion.ucl.ac.uk/spm/software/spm12/) based on Matlab 2016a. After importing the Siemens DICOM files into the SPM NIFTI format, the center of anatomical and functional data was manually set to the anterior commissure for each subject. Broccoli's algorithm has been used to correct motor artifacts. The head movement parameter was less than 0.5 mm after the correction. Motion parameters were re-calculated in the realignment step and after were included as additional regressors in the general linear model (GLM) analysis. Spatial distortions of the EPIs resulting from motion-by-field inhomogeneity interactions were reduced using the FieldMap toolbox implemented in SPM12. Next, slice-timing correction for fMRI data was performed (the correction of the hemodynamic response in space and then in time to avoid pronounced motion artifacts. Anatomical MPRAGE images were segmented using the segmentation algorithm implemented in SPM, and both anatomical and functional images were normalized into the ICBM stereotactic reference frame (MNI (Montreal Neurological Institute) coordinates) using the warping parameters obtained from segmentation. Anatomical data were segmented into 3 possible tissues (grey matter, white matter, cerebrospinal fluid). The MELODIC ICA module of the FSL program was used for hand classification of fMRI ICA noise components and removal of physiological and motor artifacts. Functional data were smoothed using a Gauss function with an isotropic kernel of 6 mm FWHM.

3.2 The Method of Selection of the Stimulus Material

A set of inducements based on two delusional plots was formed as an auditory test material to identify the features of individual activity and brain abnormalities - paranoid delusions of persecution and paraphrenic syndrome, including 13 phrases for each in combination with 13 neutral phrases. In total, 52 inducements were used in the fMRI study of each patient (13 test inducements and 13 neutral inducements for paranoid and paraphrenic delusions). The subjective significance of phrases was assessed using the technology of control of the surveyed response to perceived audio inducements, based on synchronous registration of vegetative reactions using MRI-compatible polygraph [18, 19]. Such a technique made it possible to control the surveyed patients' response to stimulus phrases and discard those intervals when fMRI-data were exposed to various artifacts (failure in breathing, lack of skin-galvanic reaction with a subjectively significant stimulus, or the presence of skin-galvanic reaction in response to a neutral stimulus). It was performed the one-sample t-test and setting the height threshold at $p < 0.001$ and cluster size > 10 voxels.

3.3 The Results of fMRI

The results of statistical analysis of fMRI data are shown in Figs. 1–4. The indicated anatomical names of the selected areas are obtained by comparing their coordinates in the MNI system with the CONN Atlas implemented in the fMRI image analysis package of the same name [20].

Figure 1 and 2 show three (out of 91) selectively taken axial sections (along the vertical z axis) of structural images with statistical maps (Student's t-test, $p < 0.001$) that reflect the brain activity in response to phrases that are significant according to the plot of paranoid delusions of persecution.

Figure 3 shows three similar axial cross-sections that reflect the activity of brain areas in response to subjectively significant phrases according to the paraphrenic delusion plot

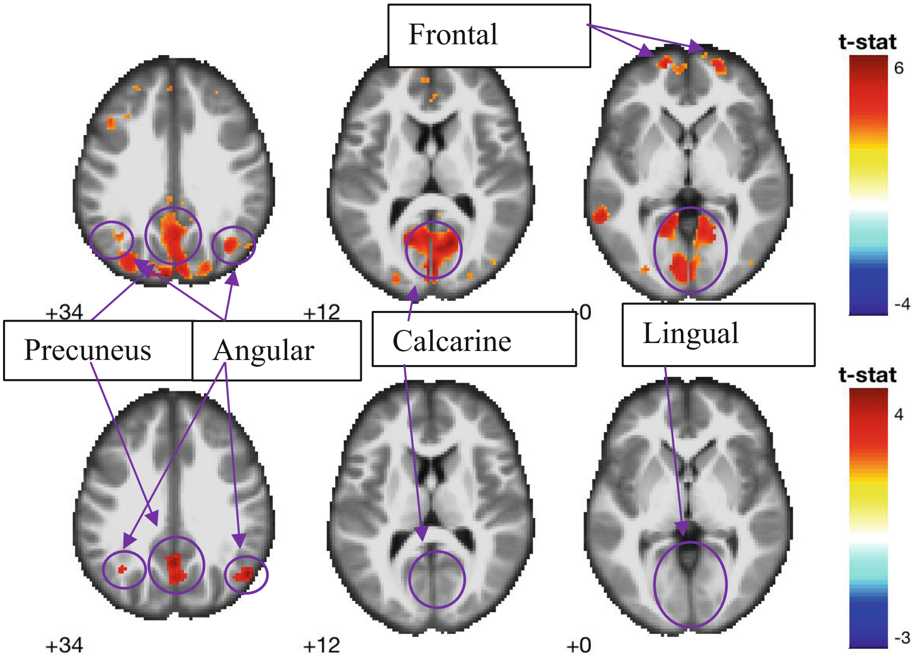

Fig. 1. Activation of the cerebral cortex in response to stimulus phrases that are significant and insignificant according to the plot of paranoid delusions of persecution in the daughter (above) and the mother (below)

in comparison with insignificant ones: the difference in the activity of brain areas in the mother is greater than in the daughter (if we compare with Fig. 1).

The use of culling in processing fMRI data obtained in response to phrases based on the paraphrenic delusion plot revealed significant changes in the activation pattern (Fig. 4).

4 Discussion

The delusional disorder in the presented clinical case meets the diagnostic criteria for both: induced delusional disorder (ICD-10) and general paranoid disorder (DSM-5). Analyzing clinical features, it is highly likely that the mother's mental disorder debuted in the postpartum period at 30 with a slow increase. A negative domain with restricted affect, diminished emotional range, poverty of speech, curbing of interests, reduction of sense of purpose and reduction of social drive is clearly identified [21–23]. There were also positive disorders in the form of paranoid ideas of pretension with the plot of the greatness of her daughter. However, the psychosis they experienced together is classified as delusions of persecution, including ideas of poisoning, damage, which turned into delusions of fantastic content.

As mild cognitive deficits increase, manifested by dysmnestic disorders in the form of impaired memorization of new information, incomplete reproduction of past events,

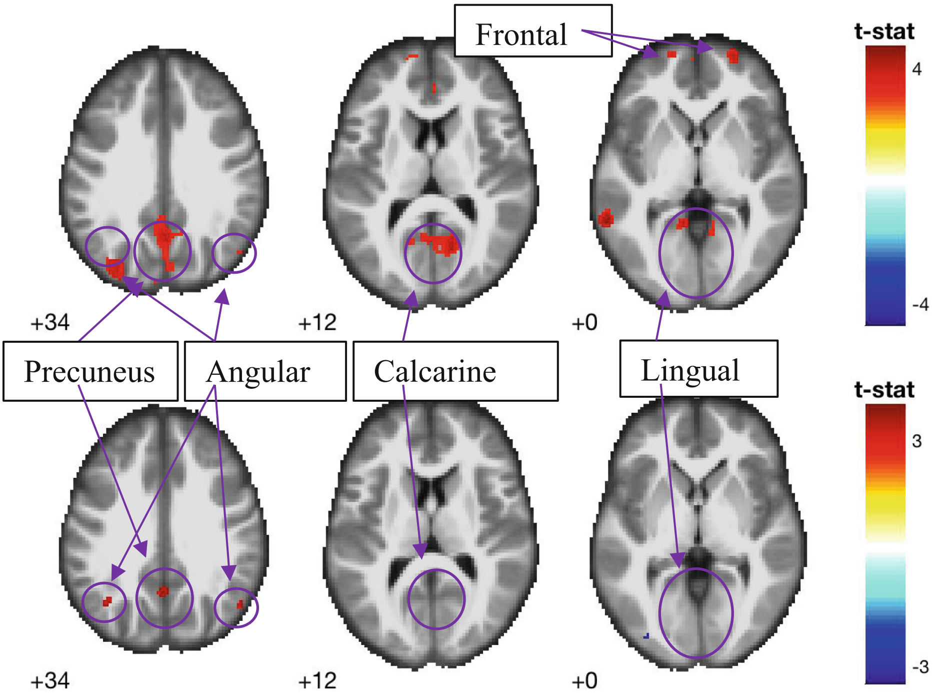

Fig. 2. Activation of the cerebral cortex in response to the stimulus phrases that are significant and insignificant according to the plot of paranoid delusions of persecution in the daughter (above) and the mother (below): fMRI data processing with culling in mind

and reduced attention function, the mother lost the dominant role in the symbiosis and, in fact, the daughter became the primary patient in the development of a psychotic disorder. Thus, the inducer (the primary patient of the plot of acute delirium folie à deux) is the daughter. It can be noted that the delusion of the relationship had been growing for two years against the background of a belief in their own significance and uniqueness. As a result, the ideas of the relationship were replaced by delusions, which in turned into paranoid delusions. Subsequently, there was a systematization of delirium by type of insight. Leading in the plot were the ideas of persecution, poisoning, which led to an increase in delusional activity, namely, "the persecuted persecutor" [9]. It should be noted that at this moment the psychotic experiences were synchronized, the plot of delusion became identical in the inducer and the recipient.

fMRI studies showed that both patients showed an increased hemodynamic signal in two zones – Precuneus and Angular, which are part of the Central-Executive Network and are responsible for consciousness, spatial thinking, attention and memory retrieval. Additionally, the inductor (the daughter) showed an increased hemodynamic signal in the Calcarine and Lingual zones, which are involved in the recognition of visual images and in the reproduction of visual memories. The results of fMRI data analysis showed a decrease in the difference of the Precuneus voxels activation, but voxel activations were obtained in the precentral gyrus of the motor cortex and temporal gyrus of the primary

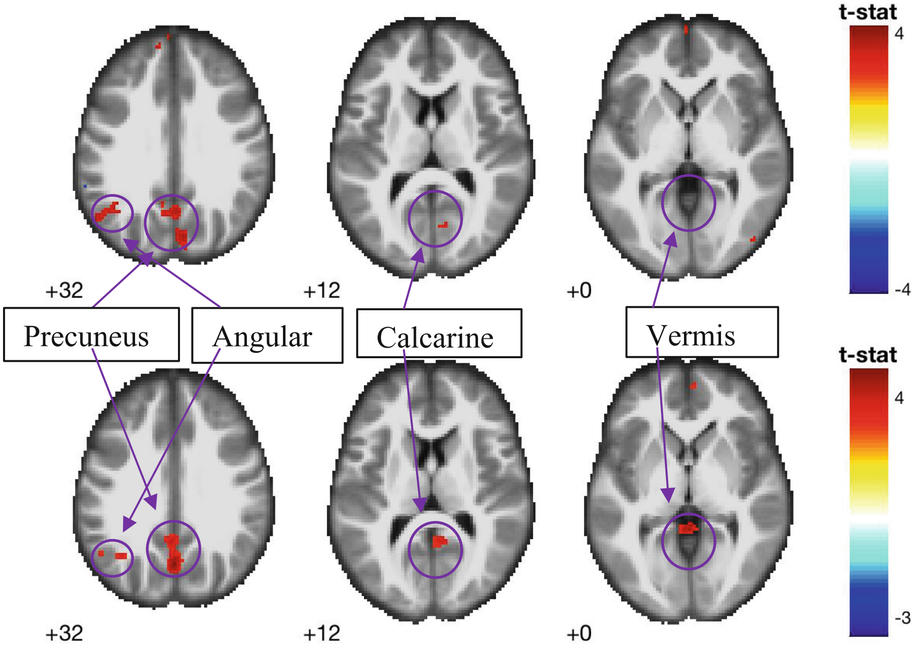

Fig. 3. Activation of the cerebral cortex in response to phrases based on the plot of paraphrenic delusion in the daughter (above) and the mother (below)

auditory cortex. The reaction of neural networks of the brain to the phrases of the plot of delusion is noticeably higher in the daughter than in the mother (either with fMRI data culling or without).

The recorded increase in activity in the precuneus area is a consequence of increased concentration of internalized attention on significant events. According to available data, a decrease in the volume of gray matter leads to a compensatory increase in functional activity [24]. The same authors found a correlation of reduced connectivity of this area with the postcentral gyrus in patients with schizophrenia, as an indicator of the growth of negative symptoms. Thus, a higher activity on fMRI for presenting inducements with the plot of delusions of persecution in the daughter may indicate a significantly greater prevalence of positive symptoms and more pronounced affective significance in comparison with the mother. This assumption is confirmed by data comparison of other areas [25, 26]. Thus, it was found that a compensatory increase in activity in the left hemisphere in patients with the first stage of schizophrenia is a consequence of a decrease in its volume. The asymmetry of activity and a decrease in the volume of angular gyrus is associated with a violation of the semantic-lexical network that ensures the assignment of meaning to sequences of sounds and the creation of associative connections in thinking processes [27]. In general, angular gyrus and precuneus are key areas that are parts of the frontoparietal network of cognitive control and are associated with conscious information processing and retrieval of important information from memory [28, 29].

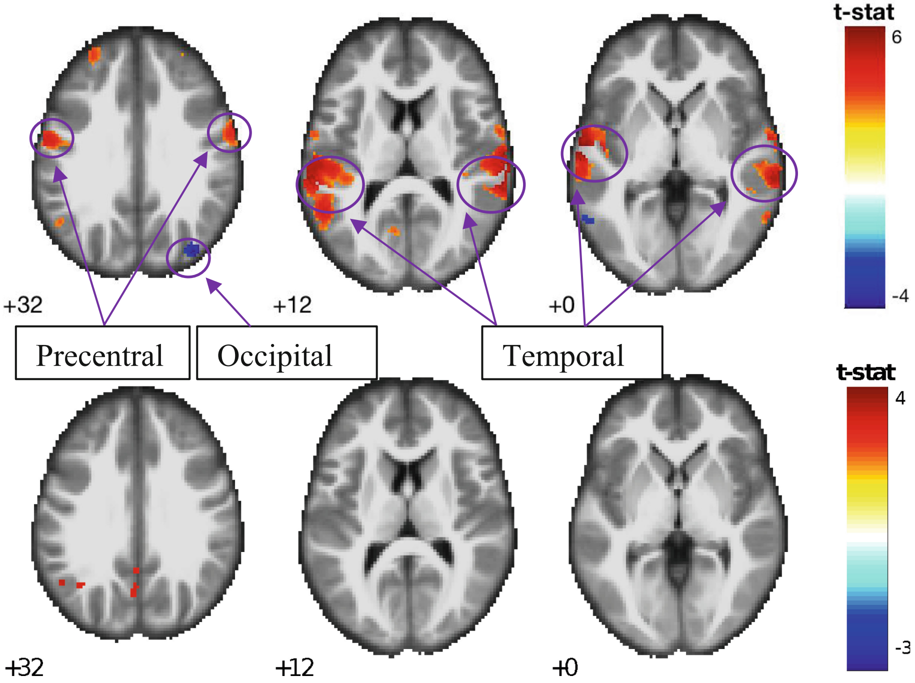

Fig. 4. Activation of the cerebral cortex in response to paraphrenic delusion phrases in the daughter (above) and the mother (below): fMRI data processing with culling in mind

Meta-analyses of experimental studies conducted in the Theory of Mind paradigm [30, 31] indicate a disorder of the emotional states, social relations and their assessment recognition network in patients with schizophrenia. It is assumed that the structures of the medial prefrontal regions (mPFC) and temporal areas of both hemispheres (temporal lobe) can play a key role in these disorders. Disorders of cognitive tasks are also related to dysfunction and impaired connectivity of the structures of the basal ganglia, thalamus, and cerebellum [32, 33]. In the study, we observed changes in the hemodynamic response in these structures with different comparison options, to a greater extent in the daughter.

5 Conclusion

As already mentioned, the above material should be considered with a proper measure of criticality – interesting facts were found when assessing the current state of only two patients. At the same time, the proposed approach to the cognition of neurocognitive mechanisms of mental pathology and the technology of a complex method – using fMRI and a compatible polygraph can be very useful in scientific and applied research on the nature of the origin and development of schizophrenia.

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References

1. Le Bon, G.: Psychologie des foules. FÉLIX ALCAN, ÉDITEUR, PARIS 108, BOULEVARD SAINT-GERMAIN, 108 (1895)
2. Grimm, F.: Politische Justiz: die Krankheit unserer Zeit. Verlag Bonner Universitäts-Buchdruckerei (1953)
3. Ch. Lasègue, J.F.: Pathologie. La folie à deux ou folie communiquée. Annales médico-psychologiques. **17**, 321–355 (1877)
4. Lehmann, G.: Zur Kasuistik des induzierten Irrsinns (Folie á deux). Archiv f. Psychiatrie **14**, 145–154 (1883)
5. Menculini, G., Balducci, P.M., Moretti, P., Tortorella, A.: "Come share my world" of "madness": a systematic review of clinical, diagnostic and therapeutic aspects of. Int. Rev. Psychiatry **32**, 412–423 (2020)
6. Wehmeier, P.M., Barth, N., Remschmidt, H.: Induced delusional disorder. a review of the concept and an unusual case of folie à famille. Psychopathology **36**, 37–45 (2003)
7. Gralnick, A.: Folie a deux-the psychosis of association: a review of 103 cases and the entire English literature: with case presentations. Psych Quar. **16**, 230–263 (1942)
8. Arnone, D., Patel, A., Tan, G.M.-Y.: The nosological significance of Folie à Deux: a review of the literature. Ann. Gen. Psychiatry. **5**, 11 (2006)
9. Mouchet-Mages, S., Gourevitch, R., Lôo, H.: Folie à deux: update of an old concept regarding two cases. Encephale. **34**, 31–37 (2008)
10. Gralnick, A.: Folie a deux-the psychosis of association (1942). https://doi.org/10.1007/bf01576134
11. Kashiwase, H., Kato, M.: Folie à deux in Japan – analysis of 97 cases in the Japanese literature. Acta Psychiatr. Scand. **96**, 231–234 (1997)
12. Catanesi, R., Punzi, G., Rodriguez, W.C., 3rd., Solarino, B., Di Vella, G.: Faith, folie à famille, and mummification: a brief review of the literature and a rare case report. J. Forensic Sci. **59**, 274–280 (2014)
13. Chenivesse, P., Marinescu, M., De Luca, M.: Folies de voisinage, folie à deux ? Étude de cas. L'Évolution Psychiatrique. **68**, 431–441 (2003)
14. Cawthra, R., O'Brien, G., Hassanyeh, F.: "Imposed psychosis". a case variant of the gaslight phenomenon. Br. J. Psychiatry. **150**, 553–556 (1987)
15. Baillarger, J.: Folie à double forme. Annales médico psychologiques. **6**, 369–438 (1854)
16. Régis, E. (1855–1918) A. du, T.: La folie à deux, ou Folie simultanée : avec observations recueillies à la clinique de pathologie mentale (asile Sainte-Anne)/par le Dr Emmanuel Régis (1880)
17. Jabs, B., Jabs, K., Reif, A., Pfuhlmann, B.: Die Folie à deux - Psychische Ansteckung oder eigenständige Psychoseerkrankungen? Fortschr. Neurol. Psychiatr. **76**, 149–154 (2008)
18. Zakharova, N.V., Kovalchuk, V.V., Kostyuk, G.P., Bravve, L.V., Kaydan, M.A., Kartashov, S.I., Malakhov, D.G., Kholodny, Y.: Possibilities of appliedusage of polygraph for investigation of negative symptomatics in patients with paranoidal schizophrenia. Psychic Health **12**, 50–60 (2019). (in Russian)
19. Ushakov, V.L., Malashenkova, I.K., Krynskiy, S.A., Kartashov, S.I., Orlov, V.A., Malakhov, D.G., Hailov, N.A., Ogurtsov, D.P., Zakharova, N.V., Didkovsky, N.A., Maslennikova, A.V., Arkhipov, A.Y., Strelets, V.B., Velichkovsky, B.M., Kholodny, Y.I., Kostyuk, G.P.: Basic Cognitive Architecture, Systemic Inflammation, and Immune Dysfunction in Schizophrenia. Sovrem Tehnol Med. **11**, 32 (2019)
20. Whitfield-Gabrieli, S., Nieto-Castanon, A.: Conn: A functional connectivity toolbox for correlated and anticorrelated brain networks. Brain Connect. **2**, 125–141 (2012)

21. Galderisi, S., Bucci, P., Mucci, A., Kirkpatrick, B., Pini, S., Rossi, A., Vita, A., Maj, M.: Categorical and dimensional approaches to negative symptoms of schizophrenia: Focus on long-term stability and functional outcome. Schizophr. Res. **147**, 157–162 (2013)
22. Galderisi, S., Mucci, A., Buchanan, R.W., Arango, C.: Negative symptoms of schizophrenia: New developments and unanswered research questions. The Lancet Psychiatry. **5**, 664–677 (2018)
23. Guessoum, S.B., Le Strat, Y., Dubertret, C., Mallet, J.: A transnosographic approach of negative symptoms pathophysiology in schizophrenia and depressive disorders. Prog. Neuropsychopharmacol. Biol. Psychiatry. **99**, 109862 (2020)
24. Gong, X., Lu, W., Kendrick, K.M., Pu, W., Wang, C., Jin, L., Lu, G., Liu, Z., Liu, H., Feng, J.: A brain-wide association study of DISC1 genetic variants reveals a relationship with the structure and functional connectivity of the precuneus in schizophrenia. Hum. Brain Mapp. **35**, 5414–5430 (2014)
25. Kim, D.I., Mathalon, D.H., Ford, J.M., Mannell, M., Turner, J.A., Brown, G.G., Belger, A., Gollub, R., Lauriello, J., Wible, C., O'Leary, D., Lim, K., Toga, A., Potkin, S.G., Birn, F., Calhoun, V.D.: Auditory oddball deficits in schizophrenia: an independent component analysis of the fMRI multisite function BIRN study. Schizophr. Bull. **35**, 67–81 (2009)
26. Ji, E., Guevara, P., Guevara, M., Grigis, A., Labra, N., Sarrazin, S., Hamdani, N., Bellivier, F., Delavest, M., Leboyer, M., Tamouza, R., Poupon, C., Mangin, J.-F., Houenou, J.: Increased and decreased superficial white matter structural connectivity in schizophrenia and bipolar disorder. Schizophr. Bull. **45**, 1367–1378 (2019)
27. Niznikiewicz, M., Donnino, R., McCarley, R.W., Nestor, P.G., Iosifescu, D.V., O'Donnell, B., Levitt, J., Shenton, M.E.: Abnormal angular gyrus asymmetry in schizophrenia. Am. J. Psychiatry. **157**, 428–437 (2000)
28. Guo, W., Liu, F., Chen, J., Wu, R., Li, L., Zhang, Z., Zhao, J.: Family-based case-control study of homotopic connectivity in first-episode, drug-naive schizophrenia at rest. Sci. Rep. **7**, 43312 (2017)
29. Fox, J.M., Abram, S.V., Reilly, J.L., Eack, S., Goldman, M.B., Csernansky, J.G., Wang, L., Smith, M.J.: Default mode functional connectivity is associated with social functioning in schizophrenia. J. Abnorm. Psychol. **126**, 392–405 (2017)
30. Jáni, M., Kašpárek, T.: Emotion recognition and theory of mind in schizophrenia: a meta-analysis of neuroimaging studies. World J. Biol. Psychiatry. **19**, S86–S96 (2018)
31. Li, S., Hu, N., Zhang, W., Tao, B., Dai, J., Gong, Y., Tan, Y., Cai, D., Lui, S.: Dysconnectivity of multiple brain networks in schizophrenia: a meta-analysis of resting-state functional connectivity. Front. Psychiatry. **10**, 482 (2019)
32. Wright, I.C., Rabe-Hesketh, S., Woodruff, P.W., David, A.S., Murray, R.M., Bullmore, E.T.: Meta-analysis of regional brain volumes in schizophrenia. Am. J. Psychiatry. **157**, 16–25 (2000)
33. Davis, K.L., Stewart, D.G., Friedman, J.I., Buchsbaum, M., Harvey, P.D., Hof, P.R., Buxbaum, J., Haroutunian, V.: White matter changes in schizophrenia: evidence for myelin-related dysfunction. Arch. Gen. Psychiatry. **60**, 443–456 (2003)

Convolutional Neural Networks for Automatic Detection of Focal Cortical Dysplasia

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Abstract. Focal cortical dysplasia (FCD) is one of the most common epileptogenic lesions associated with cortical development malformations. However, the accurate detection of the FCD relies on the radiologist professionalism, and in many cases, the lesion could be missed. In this work, we solve the problem of automatic identification of FCD on magnetic resonance images (MRI). For this task, we improve recent methods of Deep Learning-based FCD detection and apply it for a dataset of 15 labeled FCD patients. The model results in the successful detection of FCD on 11 out of 15 subjects.

Keywords: MRI · Deep learning · CNN · Computer vision · Medical detection · Epilepsy · FCD · Focal cortical dysplasia

1 Introduction

The imaging and computational technologies' latest achievements facilitated the rapid development of the decision support systems based on medical images [1]. Application of the machine learning and computer vision methods in medical imagery showed that the prediction and prognosis could be made automatically to identify pathological changes and make a medical prognosis [2]. At the same time, the high cost of the manual radiological examination determines the urge to develop such systems for the automated analysis in neuroimaging data as well as using machine learning methods to support the radiological process, increase the effectiveness and quality of the diagnostics.

Focal cortical dysplasia (FCD) is one of the most common epileptogenic lesions associated with malformations of cortical development [3]. The development of a decision support system for radiologists in FCD detection is important, and it urges large and rigorously annotated datasets. However, even on small number of samples, the FCD detection could be enhanced with the means of DL tricks, such as autoencoder pretraining on unannotated data.

We acknowledge our project medical partner science-practical center n.a.

Pirogov for annotated data. We acknowledge Zhores HPC cluster for the computation facilities. All code for experiments is publicly available[1].

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[1] https://github.com/alievrusik/cnn_fcd_detection.

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1.1 Related Works

Currently, there are plenty of methods for automatic FCD detections. Previous approaches rely on the brain's symmetric structure, template matching, anal feature estimations, using conventional machine learning techniques. Some statistics (e.g., cortical thickness, GM-WM blur, TI hyper-intensity) are estimated and fed into decision system (e.g. Support Vector Machine) [4, 5]. Such methods require severe feature engineering.

Recently, deep-learning-based methods were proposed for FCD detection. In [6, 7] authors use U-Net like architecture for building FCD segmentation model. They train the network using sagittal slices and get DICE score of 52.47, which is superior to non-neural-networks approaches. In [8], authors combine classical computer vision and deep learning techniques using special patch extraction techniques, CNN classification, and post-processing. It yields state-of-the-art results in terms of accuracy (classification) and Intersection over Union (detection).

In this paper, we reproduce the state-of-the-art method proposed in [8], and made several significant improvements to enhance its performance on the dataset provided by our medical partners.

2 Data and Methods

For training we used 15 labeled FCD subjects (from Pirogov center), 15 unlabeled FCD subjects (from Pirogov center) and 17 healthy control subjects from HCP [9] and LA5 [10] datasets. The subjects were scanned by the SIEMENS MAGNETRON Scyra 3T scanner with resolution $256 \times 256 \times 256$ voxels. In all experiments, we use leave-one-out (LOO) validation scheme.

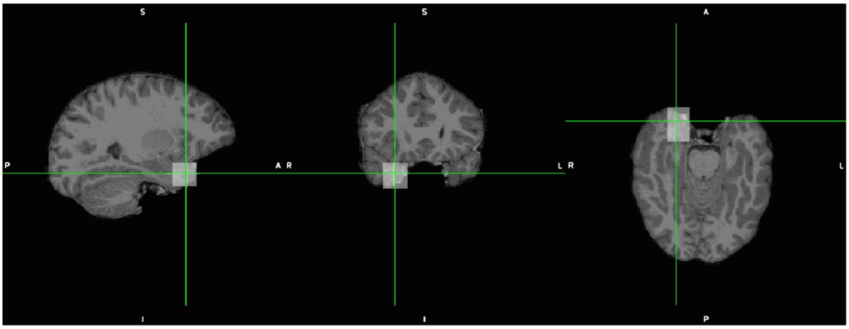
It worth to mention that unlikely to previous works we have weak annotation of FCD subjects [1I]. The labeled subjects are annotated with 2D bounding boxes per each view (sagittal, coronal, axial) by professional radiologist (see Fig. 1a). The input MR image is first preprocessed to correct the bias field, align with a standard atlas (MNI152 1 mm template [12]), and strip the non-brain tissues (FSL [13] and FreeSurfer [14] software). Also intensities were normalized with Histogram Standardization and Z-normalization using TorchIO library [15]. To obtain 3D FCD regions, for each subject we fitted parallelepiped into 2D boxes.

As a baseline model, we use the method proposed in [8]. It consists of 4 major steps: 1) preprocessing, 2) brain patch extraction, 3) deep learning classification, and 4) postprocessing. We suggest referring to the original article for details.

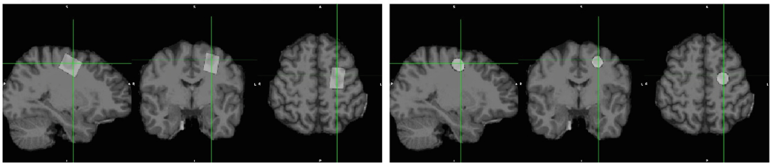
As a key part of the algorithm is patch extraction, it seems natural to assess models by evaluating probabilities assigned to patches. So we introduce *Top-k* score metric for model evaluation. At the inference stage, we take k top patches by probabilities and estimate whether at least one of them intersects with the ground-truth FCD region. In that case, we label it as successful detection. Then we average it across all validation subjects.

2.1 Improvements

The baseline model yielded a top-k score of 0.2. We made some iterative improvements to boost its performance. Careful ablation study is given in Table 1 (configurations a–g).



(a) 2D rectangular boxes provided by professional radiologist for each view.



(b) Rectangular mask (right). (c) Ellipse mask (right).

Fig. 1. FCD region annotations.

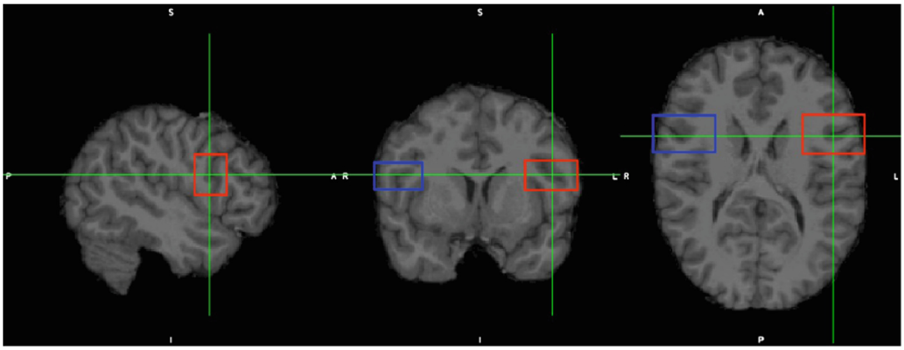
Data was labeled with 2D boxes on each of the axial, coronal, and sagittal slices. It is not correct to put a 3D rectangular box onto them, as, firstly, large non-FCD regions will be marked as FCD. Secondly. rectangularity is lost at the image alignment step. To overcome this issue, we inscribe a 3D ellipse to use it as a mask (see Fig. 1c).

Furthermore, we refused to use hard labeling (i.e., any non-zero intersection leads to ‘1’ labeling) for this task and, instead, use soft labeling. Ellipse mask still captures some non-FCD regions. Hence it is fair to give labels according to how big the overlap is. We calculated the number of overlapping voxels with an FCD mask for each patch, divided it by the maximum number for a given subject. We want labels for big-overlap patches to be close to 1, and labels for small-overlap patches to be around 0.5. This can be achieved by taking the root of the fifth degree of the acquired number.

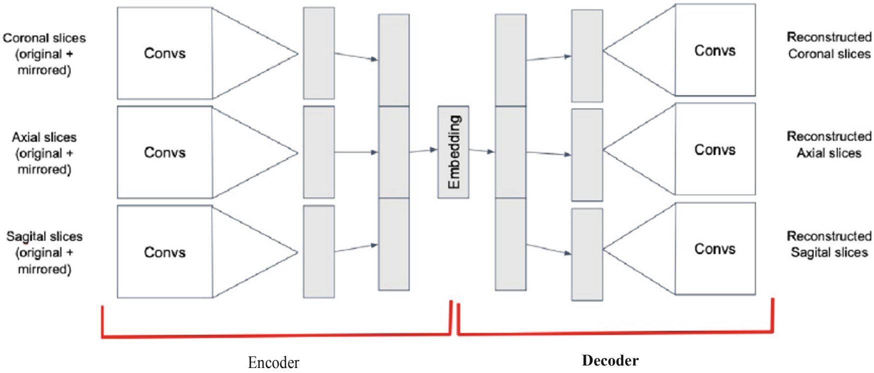
Analyzing the patch extraction procedure, we noticed that size 16×32 is actually too small to cover all brain regions. Some FCD areas were just missed. So we increased the patch size from 16×32 to 24×40.

As far as we had ground truth labels in three orthogonal planes, for each axial slice, we considered also the coronal slice crossing with the axial slice in its center; the sagittal slice again crossing with the axial slice in its center, as well as their ‘mirrored’ neighbors (see Fig. 2a). Therefore after these manipulations each input tensor is of shape $6 \times 24 \times 40$.

It worth to mention that 8 out of 15 subjects have FCD located in the temporal gyrus, while 7 out of 15 subjects have FCD located in the non-temporal region. Temporal and non-temporal FCD regions differ considerably from each other due to sharp differences in the brain anatomy of these regions. CNN model tends to overfit to temporal zone, which results in model yielding high probabilities for temporal patches of non-temporal



(a) Example stack of patches taken from multi dimensions. Red - original patches. Blue - their 'mirrored' versions.



(b) Autoencoder with '3 heads-3 tails' architecture

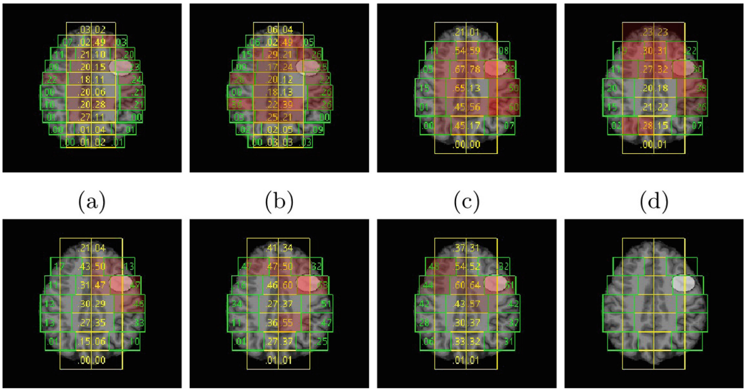
Fig. 2. Multi-dimension patches' processing scheme.

subjects. To overcome this issue, we separately train models for temporal and non-temporal FCD subjects. We will refer to it as *ensembling-specific-to-localization models.*

We also pretrain autoencoder to take advantage of 15 unlabeled FCD subjects of the same modality as the 15 labeled ones. It is incorrect to concatenate all slices into multi-channel image, so we use autoencoder with '3 heads - 3 tails' architecture (see 2b). Each slice pair is processed by its own convolution, concatenating results and applying one more linear operation afterwards. The decoder is a mirrored version of the encoder.

3 Results

In Table 1, it is shown that the largest boost in model performance was given by ensembling specific-to-localization models. Using coronal or sagittal slices did not lead to better results, though without ensembling specific-to-localization models, it did.



(a) (b) (c) (d)

(e) (f) (g) (h) Original slice

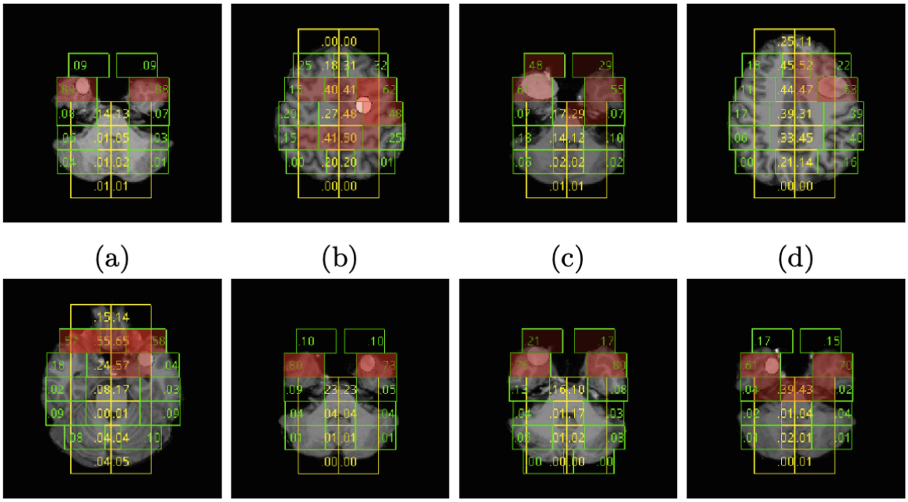
Fig. 3. Example of model performance on the same slice for different configura- tions (a)−(g). (h) - original slice without models' predictions. Green - side patches, yellow - middle patches, light ellipse - FCD region. For each patch probability yielded by model is shown.

Table 1. Top-20 score ablation study

Model	Top-20 score
(a) baseline model	0.200
(b) + soft patch labeling	0.266
(c) + increased patch size	0.400
(d) + autoencoder pretraining	0.533
(e) + specific-to-localization models	**0.733**
(f) + coronal slices	0.667
(g) + sagittal slices	**0.733**

For each configuration visualization is provided on Fig. 3. For configuration (a), one can notice that model tends to give higher probabilities for middle patches. Configurations (a)−(d) provides relatively high probabilities for non-FCD patches (False Positives), but captures desired ones. Configuration (f) tends to give lower probabilities in general. However, it does give the highest probabilities to FCD patches (see 3f). We did not notice an improvement in visualization for configurations (f) and (g) compared to (e).

We provide several examples of configuration (e) model's performance (see Fig. 4). Generally, model tends to capture all FCD-located patches. However, model has problem with distinguishing FCD patches and their mirrored versions, especially for ones located in temporal gyrus. Some FCD regions are predicted with relatively small probability. It is caused either by small size of FCD regions (4b) or by lack of characteristic features of FCD, e.g. increased thickness or assymetry (4 g).



(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 4. Example of performance of model with configuration (e) on FCD subjects.

The best top-20 score is 0.733, so FCD regions were successfully detected for 11 out of 15 subjects. We recommend using configuration (e), as it is harder to interpret results by models using slices from extra dimensions (f, g).

4 Conclusions

In the current work we reproduced a state-of-the-art DL-based method for FCD detection and proposed new metric for FCD detection algorithm's assessment. We investigated several ways to improve current approach specifically to deal with weakly annotated FCD data. We significantly boosted the FCD-detection CNN models performance with the use of soft labeling, autoencoder pretraining and ensembling specific-to-localization models.

References

1. Shin, H.C., Roth, H.R., Gao, M., Lu, L., Xu, Z., Nogues, I., Yao, J., Mollura, D., Summers, R.M.: Deep convolutional neural networks for computer-aided detection: Cnn architectures, dataset characteristics and transfer learning. IEEE Trans. Med. Imaging **35**(5), 1285–1298 (2016)
2. Sharaev, M., et al.: Mri-based diagnostics of depression con-comitant with epilepsy: in search of the potential biomarkers. In: 201D IEEE 5th International Conference on Data Science and Advanced Analytics (DSAA), pp. 555–564 (2018)
3. Tassi, L., Colombo, N., Garbelli, R., Francione, S., Lo Russo, G., Mai, R., Cardinale, F., et al.: Focal cortical dysplasia: neuropathological subtypes. EEG, neuroimaging and surgical outcome. Brain **125**(8), 1719–1732 (2002)

4. Besson, P., Bernasconi, N., Colliot, O., Evans, A., Bernasconi, A.: Surface-based texture and morphological analysis detects subtle cortical dysplasia. In: MICCAI, pp. 645–652 (2008)
5. Colliot, O., Mansi, T., Bernasconi, N., Naessens, V., Klironomos, D., Bernasconi, A.: Segmentation of focal cortical dysplasia lesions on mri using level set evolution. Neuroimage **32**(4), 1621–1630 (2006)
6. Pominova, M., Artemov, A., Sharaev, M., Kondrateva, E., Burnaev, A., Bern-stein, E.: Voxelwise 3d convolutional and recurrent neural networks for epilepsy and depression diagnostics from structural and functional mri data. In: Proceedings of IEEE International Conference on Data Mining Workshops (ICDMW), pp. 299–307 (2018)
7. Dev, K.B., Jogi, P.S., Niyas, S., Vinayagamani, S., Kesavadas, C., Rajan, J.: Automatic detection and localization of focal cortical dysplasia lesions in MRI using fully convolutional neural network. Biomed. Signal Process. Control **52**, 218–225 (2019)
8. Wang, H., Ahmed, S.N., Mandal, M.: Automated detection of focal cortical dys- plasia using a deep convolutional neural network. Comput. Med. Imaging Graph. **79**, 101662 (2020)
9. Van Essen, D.C., et al.: The WU-Minn human connectome project: an overview. Neuroimage **80**, 62–79 (2013)
10. Poldrack, R.A., Barch, D.M., Mitchell, J., Wager, T., Wagner, A.D., Devlin, J.T., Cumba, C., Koyejo, O., Milham, M.: Toward open sharing of task-based fmri data: the openfMRI project. Frontiers neuroinformatics **7**, 12 (2013)
11. Pavlov, S., Artemov, A., Sharaev, M., Bernstein, A.E.: Weakly supervised fine tuning approach for brain tumor segmentation problem. In: Proceedings of ICMLA, pp. 1600–1605 (2019)
12. Mazziotta, J., Toga, A., Evans, A., Fox, P., Lancaster, J., Zilles, K., Woods, R., Paus, T., Simpson, G., Pike, B., et al.: A probabilistic atlas and reference system for the human brain: Inter national consortium for brain mapping (icbm). Philosophical Trans. of the Royal Society of London. Ser. B: Biol. Sci. **356**(1412), 1293–1322 (2001)
13. Jenkinson, M., Beckmann, C.F., Behrens, T.E., Woolrich, M.W., Smith, S.M.: Fsl. Neuroimage **60**(2), 782–790 (2012)
14. Reuter, M., Schmansky, N.J., et al.: Within-subject template estimation for unbi-ased longitudinal image analysis. Neuroimage **61**(4), 1402–1418 (2012)
15. Pérez-Garcia, F., Sparks, R., Ourselin, S.: TorchIO: a python library for efficient loading, preprocessing, augmentation and patch-based sampling of medical images in deep learning. arXiv: 2003.04696 [cs, cess, stat] (2020)

Influence of Dominance on Human Brain Activity During Voluntary Movement in Parkinson's Disease

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Abstract. Hand dominance is known to make a robust bias on human brain activity in a normal state. Recent studies showed that simple motor tasks performed by a non-dominant hand caused increased activation, similar to that which occurs when more complex tests are performed with a dominant hand. The influence of dominance on brain activity in Parkinon's disease (PD) remains unclear. In the present study we made an attempt to analyse the differences between brain activity during dominant and non-dominant hand movements in PD and compare it with the control group. We used functional MRI and an event-related paradigm to study the brain activity of 16 subjects in control group and 16 patients with PD during left and right hand movements. Data analysis showed few clearly lateralized clusters of activity in major motor areas in the control group and two hemispheric activation in motor and non-motor areas in PD group during both hand movements. We also found a deficit in the activation of the primary somatosensory cortex, primary motor cortex, basal ganglia, and insula during both movements in the PD group compared to controls. At the same time we found brain activity asymmetry caused by the dominance influence in the PD group. Thus, we have shown that although motor deficit in Parkinson's disease has a greater effect on habitual movement, the influence of dominance still persists and should be taken into account in PD studies.

Keywords: Voluntary movement · Basal ganglia · Parkinson's disease · Functional MRI · Handedness

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1 Introduction

Hand dominance is usually considered as a cortical phenomenon resulting from lateralization of the hemisphere [1]. The influence of handedness on human brain activity remains unclear and important to study pathophysiological mechanisms and clinical asymmetry in Parkinson's disease. Mattay and colleagues showed that simple motor tasks performed by a non-dominant hand caused increased activation of the ipsilateral cortex in the primary sensorimotor and lateral premotor areas, similar to that which occurs when more complex tests are performed with the dominant hand [2]. Increased activation of the ipsilateral cortex may be due to the lack of automation of these movements for the non-dominant hand. Moreover, studies of the non-dominant hand movements showed that the intracerebral loop basal ganglia-thalamus motor cortex plays an important role in controlling the speed of self-initiated, but not externally evoked movements [3].

It was shown that handedness does not predict the side of onset of motor symptoms in Parkinson's disease [4]. On the other hand, a meta-analysis of previously provided evidence showed the association between the predominant side of PD symptoms and hand dominance [5]. It has been suggested that the side of onset of initial motor symptoms of PD and the dominant hand are independently related [6–8]. Previous study has shown that movements by a non-dominant hand are more complex and unhabitual than for a dominant hand, therefore, they require the activation of additional brain structures [9]. According to the recent PD model simple automated movements are controlled by a motor loop, including the sensorimotor parts of the striatum and cortex [10–12]. More complex, unhabitual movements are carried out with the involvement of the associative sections of the striatum and cortex. They suggest that in patients with PD the sensorimotor loop is disturbed, therefore, motor control is performed through a more complex associative loop.

The literature contains many studies devoted to the study of differences in brain function during left and right hand movements in normal state and the Parkinson's disease, but researchers have rarely considered results in terms of dominance [9, 13–15]. These studies have provided important knowledge on our understanding of several aspects of motor control in PD, from simple motor execution to more complex behaviors, like motor coordination or automation. In our study we made an attempt to estimate the influence of dominance to brain activity in Parkinson's patients and compare it with control group. We suppose that despite the fact that dominant hand movements are more habitual and thus should be more affected in PD the influence of handedness to brain activity remains significant and should be considered during PD study.

2 Materials and Methods

The study was performed using the functional MRI method, in which 20 volunteers and 25 patients with Parkinson's disease took part. All participants were right-handed, and lateralization was estimated by the Edinburgh Handedness Inventory [16]. Before performing the scan, the subjects were given instructions on how to perform motor tests. Written consent was obtained from each participant. The study was approved by the Ethics Committee of the Burdenko National Medical Research Center of Neurosurgery

(01/2018). Head movements were determined by General Electric (GE) software. Video was recorded during each study, to estimate the errors in motor test performance. Patients with severe motor fluctuations and more than 10% of errors were excluded. The final group included 16 patients with PD and 16 age- and gender-matched control group. The severity of the disease, according to a unified Parkinson's disease rating scale (UPDRS - III, OFF-State), ranged from 21 to 71 points, with an average disease duration of 13 ± 5 years. Averaged hypokinesia score was 9 ± 3 and rigidity score 4 ± 2 (Table 1). The differences between both scores for right and left hands were insignificant ($p > 0.1$). Patients did not take their medicine for more than 12 h before the start of the study (OFF state).

Table 1. Patients data

Patient	Gender	Y.O.	Duration of illness	Hoehn-Yahr off	UPDRS III off	Debutside	R hipokinesia	L hipokinesia	R rigidity	L rigidity
1	f	62	21	2,5–3	34	Left	4	8	2	4
2	f	52	11	3	71	Left	10	13	6	4
3	f	70	21	4	54	Left	9	11	7	8
4	f	61	11	3	65	Left	12	14	5	6
5	f	63	8	3	48	Left	11	10	3	4
6	f	51	12	4	78	Right	14	11	8	6
7	f	55	9	3	44	Left	9	10	7	6
8	f	59	22	3	45	Right	12	8	6	4
9	f	63	13	3	47	Right	10	5	5	5
10	f	62	17	3	41	Left	9	13	2	4
11	m	43	6	2,5	21	Right	11	5	2	0
12	f	57	11	3	37	Right	14	6	5	2
13	m	45	8	2,5	32	Right	8	6	4	3
14	m	65	13	3	23	Right	6	1	4	0
15	f	56	10	3	42	Left	11	12	4	6
16	f	67	7	4	49	Left	9	12	3	4

Image collection was carried out on a 3 T MRI scanner GE Signa HD GE Healthcare with an eight-channel head coil. The protocol included: (1) T1-weighted sagittal 3D fast gradient echo sequence for anatomical data (TR = 8.8 ms, TE = 3.5 ms, voxel size 1 × 1 × 1 mm) and (2) T2 echo-planar sequence for functional images (TR = 2000 ms, TE = 3.5 ms, voxel size 1.8 × 1.8 × 4 mm). ROI included the whole brain without the brainstem.To fix the head, we used positioning wedges-inserts.

The study used an event-related experimental paradigm, which was a sequence of verbal commands provided with headphones. One series consisted of the commands: "Get Ready!", "Left/Right Hand in a Fist…" (LH/RH), "Clench!", "Unclench!" (Appendix Fig. 5). The total duration of one episode was 18 s, the total number of episodes was 20. For each hand tests were carried out 10 times in a certain sequence.

Analysis of MRI and anatomical data were performed using SPM12 software (https://www.fil.ion.ucl.ac.uk/spm/software/spm12/). Pre-processing included the following steps: reduction the center of the anatomical and functional images to the anterior commissure (CA); realignment to exclude artifacts associated with head movement; co-registration of functional images with anatomical ones; correction of differences in image acquisition time between slices; segmentation of anatomical data; spatial normalization of data to the Montreal Neurological Institute (MNI) standard using ICBM space template; smoothing functional slices using a Gaussian function (Gaussian kernel = 6). Next, the first-level analysis was performed using a general linear model (GLM) with contrasts: LH > Rest and RH > Rest. For GLM we used the moment of clenching the hand into a fist as onsets and 2 s duration. The second-level analysis was performed by a two-sample t-test ($p < 0.05$), corrected with FWE. Contrasts between groups were performed by a two-sample t-test ($p < 0.001$), uncorrected. To localize the activity areas of the brain and create an ROI mask, the WFU PickAtlas software package was used (https://www.nitrc.org/projects/wfu_pickatlas/).

3 Results

The brain activity of 16 volunteers and 16 patients with PD during the movements of the right (dominant) and left (non-dominant) hands was analyzed.

3.1 Control Group

The control group showed activation of 7 clusters (Fig. 1, Appendix Table 2) during the movement of the dominant hands. Activation was localized in the motor areas of the brain: in the contralateral primary motor cortex (M1), the primary somatosensory cortex (PSC), and supplementary motor area (SMA). Also, movements caused activation of the contralateral insula/operculum and supramarginal gyrus (parietal cortex). Subcortical structures were represented by the thalamus and posterior putamen. We also observed activation in the ipsilateral cerebellum. Motor tests performed by the non-dominant hand caused activation in the cortical structures of the contralateral hemisphere: M1, PSC, SMA, as well as the ipsilateral cerebellum. In the subcortical structures, activation was observed in the middle part of the contralateral striatum.

The dominant hand movement caused a greater volume of activation cluster size in all structures, except M1 where the activation for both hand movements was similar. PSC activation volume was twice when moving a dominant hand. Activation clusters in the SMA differed by more than 6 times between left and right hand movements. Cerebellar activity increased more than 4 times during dominant movement. Moreover, we did not find activation in the thalamus, parietal cortex, insula, and operculum during non-dominant hand movement. Meanwhile, we observed anterior displacement of the activation in the putamen.

3.2 Parkinsonian Patients

Patients with Parkinson's disease showed activation of 17 clusters during the dominant hand movements (Fig. 2, Appendix Table 2), localized in both motor and non-motor

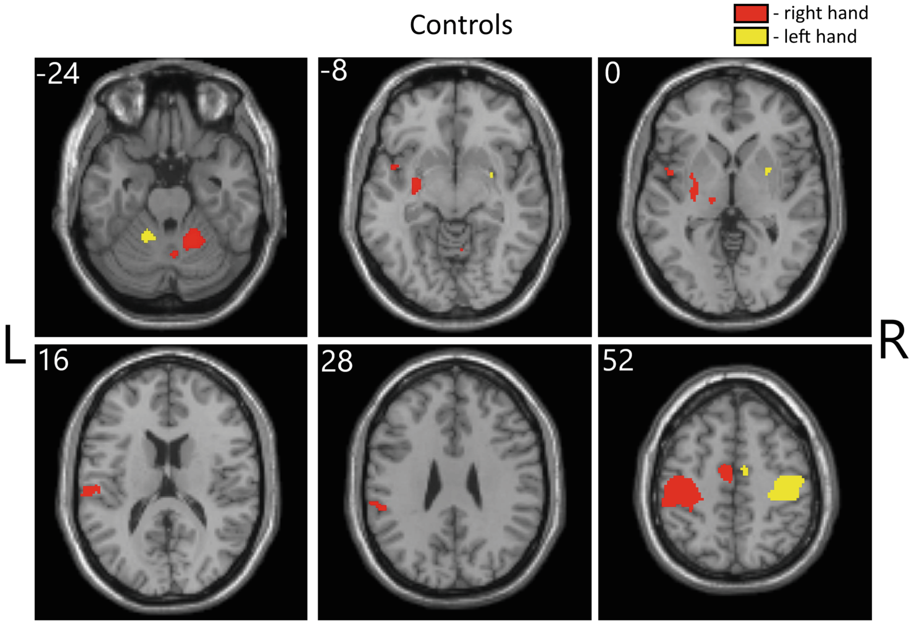

Fig. 1. Activated areas during left and right hand movements superimposed on anatomic slice of averaged brain in control group. Numbers on the images indicate the slice coordinates the z-axis as determined by the MNI.

brain structures. We observed the largest clusters in the bilateral M1, PSC, and SMA. In addition, we found activation in the contralateral insula/operculum and bilateral supramarginal gyrus (parietal cortex). The activity of subcortical structures was localized in the thalamus and rostral ipsilateral putamen. We also observed activation in the ipsilateral cerebellum and in several small clusters located in different parts of the brain. Motor tests performed by the non-dominant hand caused activation of the same structures but excluded the putamen. There were also a few small clusters in other parts of the brain.

We observed a greater volume of activation in the PSC, SMA, and thalamus during dominant movement. Activation was less in the M1, parietal lobe and cerebellum compared with movements by the non-dominant hand. In the PSC, we observed a 5-fold reduction in activation volume when moving the left hand. It is curious that there was 2-fold less activation volume in the M1, and at the same time there was a 3-fold increase in activation volume in the SMA during dominant hand movement. In the parietal lobe, we observed a 3-fold significant increase in activation volume during non-dominant motion. Movement by the dominant hand caused a 2-fold greater volume of activation in the thalamus. We found activation in the left insula/operculum, independently of the clenched hand, but when moving the left hand, this was 2-fold lower. Rostral putamen activation was observed only when moving a dominant hand. The volume of activation in the cerebellum was similar for both hands.

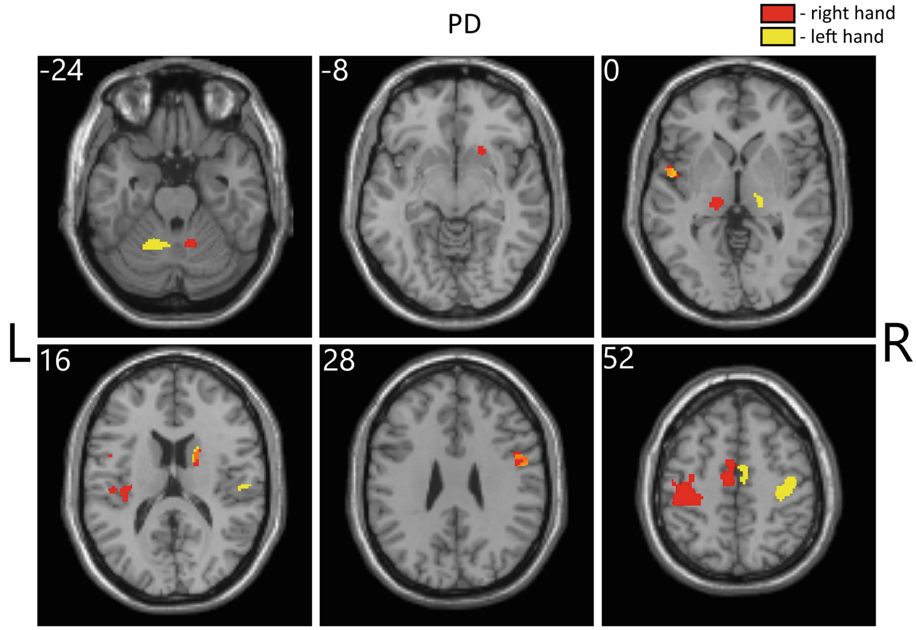

Fig. 2. Activated areas during left and right hand movements superimposed on anatomic slice of averaged brain in PD patients. Numbers on the images indicate the slice coordinates the z-axis as determined by the MNI.

3.3 Parkinsonian and Control Groups Contrast

We found that, in contrast to volunteers, in which the brain activity was concentrated in several (mainly motor) areas, patients with PD had many small clusters dispersed in the different brain structures, including non-motor areas (Fig. 3, Fig. 4, Appendix Table 2). Volunteer vs PD contrast showed a similar decrease in activity for both dominant and non-dominant hands. The patients had decreased activity in the contralateral motor cortex, in the contralateral basal ganglia, and also in both insula. Basal ganglia activity included mostly posterior putamen and pallidum. Also we observed a decrease in activity in the ipsilateral cerebellum. Non-dominant hand movement caused additional activation in more anterior part of putamen and lateral part of insula (Fig. 3). The opposite contrast showed few clusters localized in the ipsilateral motor cortex, SMA, thalamus and contralateral auditory cortex, insula and cerebellum during dominant hand movement. Non-dominant hand movement also caused additional activation in bilateral precentral and postcentral gyri, SMA, parietal lobe and somatosensory areas. We also found activity in the contralateral cerebellum (Fig. 4).

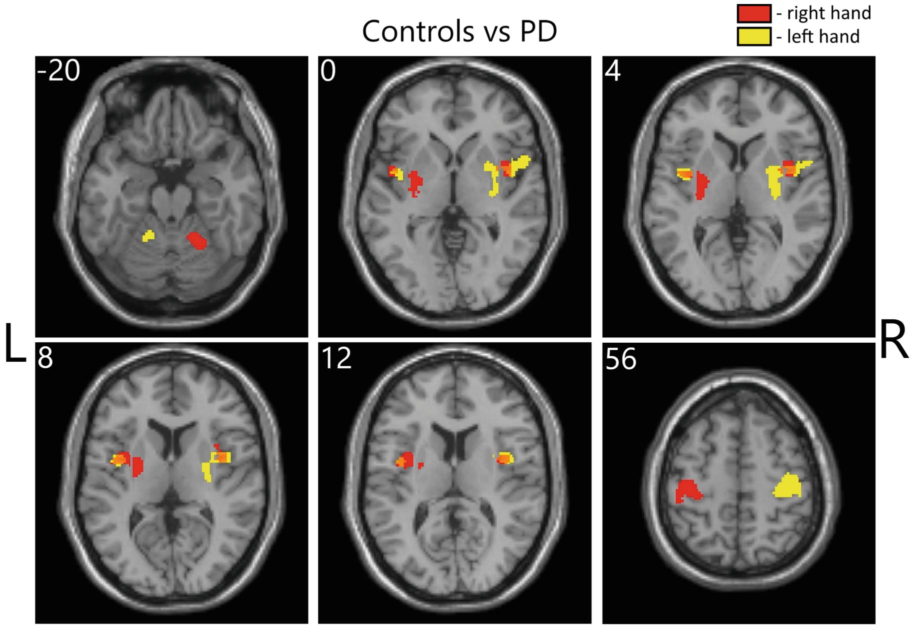

Fig. 3. Activated areas for Control > PD contrast during left and right hand movements superimposed on anatomic slice of averaged brain. Numbers on the images indicate the slice coordinates the z-axis as determined by the MNI.

4 Discussion

Neuroimaging studies have investigated different aspects of motor control in PD related to movement automaticity, execution of self initiated and externally triggered movements [11, 12, 14, 17, 18]. These reports revealed some typical motor-related neural responses in PD, like hypoactivation in the striatum and SMA, with hyperactivation in the premotor cortex, parietal cortex, and cerebellum compared with control group [11, 12]. Hyperactivity in the putamen during internally but not externally generated movements has also been observed in PD [17]. Many studies reported the influence of the affected side and side of onset of motor symptoms to brain activity in Parkinson's disease [9, 13–15]. A recent study reported that the dominant side of PD symptoms is usually in accordance with handedness [19]. However, the influence of handedness on brain activity during voluntary movement in PD remains unclear. In the present study, we characterized the patterns of brain activity evoked by dominant and non-dominant hand movements in PD subjects and compared it with a control group.

Our data showed that in the control group there are robust differences in brain activity between dominant and non-dominant sides. The major difference in localization was observed in the basal ganglia and thalamus. We propose that activation of the posterior putamen and thalamus during dominant hand movement could result from it's high automaticity. The activation of the more anterior parts of the putamen during non-dominant left hand movement suggests that these movements are less habitual, since the anterior

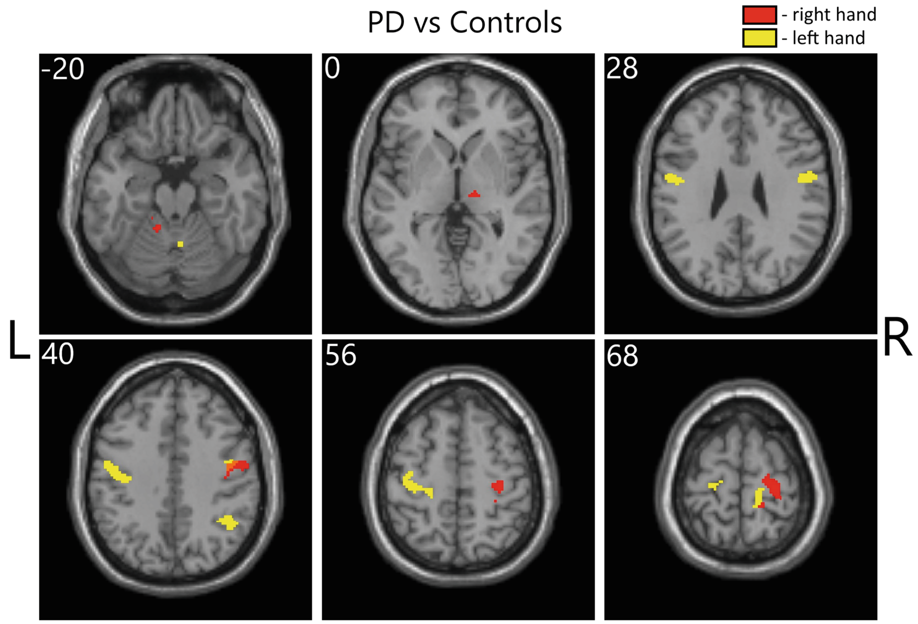

Fig. 4. Activated areas for PD > Control contrast during left and right hand movements superimposed on anatomic slice of averaged brain. Numbers on the images indicate the slice coordinates the z-axis as determined by the MNI.

putamen performs several functions related to controlling movement and learning [20]. Left hand requires more cognitive effort in order to plan, select, and execute movements [9, 20]. Moreover, previous studies showed that movements of the non-dominant hand resulted in a more balanced pattern of activation in the two hemispheres, due to relatively greater ipsilateral activation [2, 9]. We did not find any additional activity of nonmotor cortical areas in the contralateral and ipsilateral hemisphere during both movements. However, our data are consistent with the fact that movements of the dominant hand elicited large contralateral activation which may provide a neural substrate for higher efficiency and a greater motor skill repertoire of the preferred hand [21].

We showed that brain activity in patients with PD was less lateralized. In contrast to volunteers, where the activity of the brain was concentrated in the contralateral hemisphere (except the cerebellum), in patients we observed the activity in both hemispheres, especially when moving with a non-dominant hand. It is believed that the involvement of the ipsilateral hemisphere in motor behavior may be due to the fact that this simple movement is a complex motor task for patients and requires extra brain resources [9, 22].

The specificity of these differences during dominant and non-dominant hand movement should also be separately noted. Dominant hand movement was characterized by significantly lower activation area in M1 in the PD group, while in the control group it was similar. We propose that these differences in M1 could result from the lack of motor information through the basal ganglia associated with the disturbance of habitual motor control in PD [10]. At the same time, we observed the opposite activation pattern in the PSC and SMA, which could be considered as a compensatory mechanism. We also found bilateral activation of the parietal cortex during dominant hand movement and contralateral activation during non-dominant hand movement. In contrast, in control group, bilateral activation of the parietal cortex was observed when moving the left (non-dominant) hand and contralateral activation when moving the right (dominant) hand [13].

The intergroup comparison showed a decrease in brain activity in the primary somatosensory cortex, primary motor cortex, basal ganglia, and insula during both movements in the PD group compared with the control. These data are in accordance with the pathophysiological model of Parkinson's disease resulting from dopaminergic deficit in substantia nigra, which leads to basal ganglia dysfunction [14]. Wherein it should be noted that during dominant hand movement, the decrease in the posterior motor areas of the putamen and pallidum was stronger than during movement with the non-dominant hand. The opposite contrast showed that non-dominant hand movement in PD was accompanied by an activation of many non-motor cortical areas, which probably compensated the lack of activation in the main motor structures.

Generally, our study showed that dominance strongly affects brain activation both in control group and Parkinson's disease. There are few study limitations which should be noted. First of all it's a rather small sample of participants and the lack of a group with a left dominant hand, as well as group heterogeneity in the affected side and gender. We suppose that further investigation is needed to study the influence of the affective side and dominant side on motor control in Parkinson's disease.

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Contributors. All authors have made substantial contributions to the study, as follows: Alexey Sedov, Alexey Tomskiy, Igor Pronin, the conception and design of the study; Veronika Filyushkina, Valentin Popov, Vadim Ushakov, Artem Batalov, acquisition of data; Alexey Sedov, Veronika Filyushkina, Valentin Popov, analysis and interpretation of data; Alexey Sedov, Veronika Filyushkina, drafting the article or revising it critically for important intellectual content. All authors gave final approval of the version to be submitted.

Declarations of Interest. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix

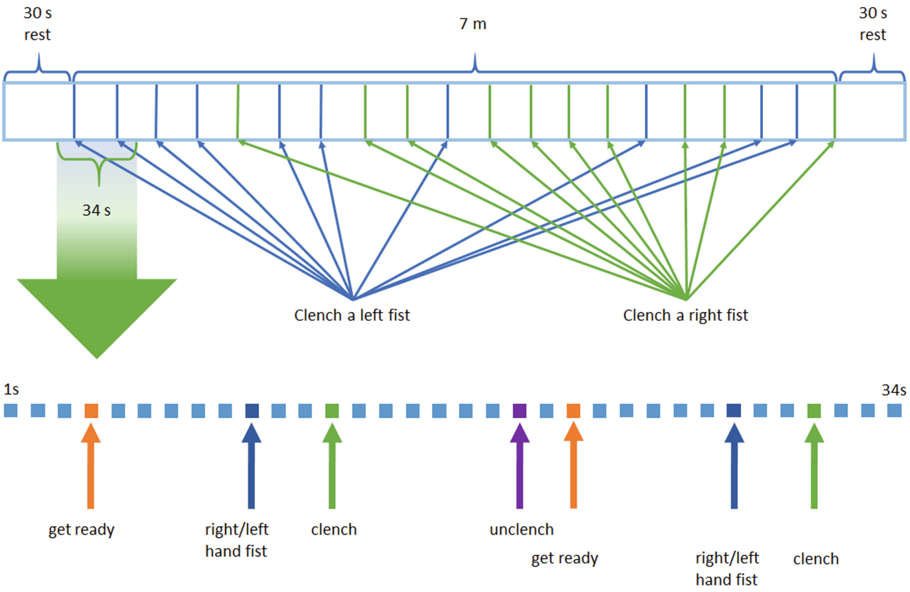


Fig. 5. Research design.

Table 2. Localization of activated areas during left and right hands movements in control group and PD patients

Control													
Left hand							Right hand						
Cluster	N voxels	Peak MNI coordinate			Lable (aal)	Mean T	Cluster	N voxels	Peak MNI coordinate			Lable (aal)	Mean T
		x	y	z					x	y	z		
1	718	35	-18	50	Precentral R	8,1	1	1024	-41	-20	54	Postcentral L	8,0
					Postcentral R	6,7						Precentral L	8,4
					Frontal Sup R	6,4						Parietal Inf L	6,4
2	63	-12	-48	-18	Cerebelum 4 5 L	6,9						Frontal Sup L	6,0
					Cerebelum 6 L	6,1						Parietal Sup L	6,4
3	14	29	3	-2	Putamen R	6,4	2	279	14	-56	-18	Cerebelum 4 5 R	8,1
4	13	9	-9	54	Supp Motor Area R	6,1						Cerebelum 6 R	7,3
												Vermis 4 5	6,7
												Vermis 6	6,2
												Fusiform R	6,2
							3	119	-5	-7	54	Supp Motor Area L	6,9
												Cingulum Mid L	6,9
							4	256	-27	-18	6	Putamen L	6,7
												Insula L	6,6
												Rolandic Oper L	6,2
												Pallidum L	6,4
												Temporal Sup L	6,1
												Temporal Pole Sup L	6,0
							5	43	-61	-22	18	SupraMarginal L	6,6
												Postcentral L	6,3
												Temporal Sup L	6,0
							6	12	-14	-20	2	Thalamus L	6,3
							7	20	-59	-33	30	SupraMarginal L	6,1
PD													
Left hand							Right hand						
Cluster	N voxels	Peak MNI coordinate			Lable (aal)	Mean T	Cluster	N voxels	Peak MNI coordinate			Lable (aal)	Mean T
		x	y	z					x	y	z		
1	310	37	-22	62	Precentral R	7,2	1	513	-40	-26	54	Postcentral L	7,7
					Postcentral R	6,9						Precentral L	6,9
2	232	59	-33	26	SupraMarginal R	6,9						Parietal Inf L	6,8
					Rolandic Oper R	6,5	2	174	-5	-12	50	Supp Motor Area L	6,7
					Temporal Sup R	6,4						Cingulum Mid L	6,5
					Postcentral R	6,4						Paracentral_Lobule_L	6,0
					Angular R	6,3						Supp Motor Area R	6,0
3	50	-20	-52	-26	Cerebelum_4_5_L	6,3	3	111	50	3	30	Putamen	6,5
					Cerebelum_6_L	6,1						Precentral_R	6,6
					Vermis_4_5	6,2						Caudate_R	6,6
4	45	-3	-16	30	Corpus Callosum	6,2						Frontal_Inf_Oper_R	6,1
					Cingulum Mid R	6,5						Postcentral_R	6,2
5	42	7	-7	58	Supp Motor Area R	6,7	4	77	-48	1	2	Rolandic_Oper_L	6,6
					Cingulum Mid R	6,5						Frontal_Inf_Oper_L	6,3
6	40	-48	1	2	Temporal Sup L	6,5						Precentral_L	6,5
					Rolandic Oper L	6,7						Insula_L	6,1
					Insula L	6,0						Temporal_Sup_L	6,0
7	39	31	8	22	Frontal_Inf_Tri_R	6,0	5	63	-35	-22	22	Rolandic_Oper_L	6,1
					Frontal_Inf_Oper_R	5,8						Insula_L	6,1
8	21	52	3	30	Precentral R	6,4						SupraMarginal_L	6,2
					Postcentral R	6,3						Postcentral_L	5,9
9	20	18	-22	2	Thalamus_R	6,4	6	52	59	-26	26	SupraMarginal_R	6,4
10	20	8	18	30	Cingulum_Mid_R	6,2						Postcentral_R	6,3
11	19	-1	29	30	Cingulum_Mid_L	6,0	7	37	-12	-22	-2	Thalamus_L	6,9
					Cingulum_Ant_L	6,1	8	24	-46	-27	6	Temporal_Sup_L	6,2
12	18	18	5	18	Caudate_R	6,3						Temporal_Mid_L	6,1
13	16	-1	5	62	Supp_Motor_Area_L	6.1	9	20	22	16	-2	Putamen_R	6,5
14	15	-48	-26	2	Temporal_Sup_L	6,5	10	17	31	44	14	Frontal_Mid_R	6,3

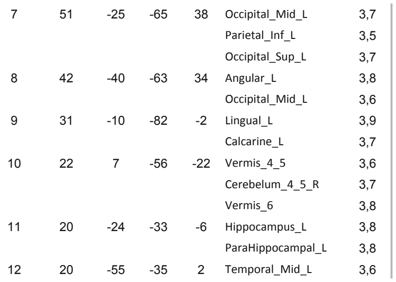
(*continued*)

Table 2. (*continued*)

					Temporal_Mid_L	6,1						Frontal_Sup_R	6,4
							11	15	46	14	26	Frontal_Inf_Oper_R	6,5
							12	13	12	-56	-22	Cerebelum_4_5_R	6,7
												Cerebelum_6_R	6,5
Control>PD													
Left hand							**Right hand**						
Cluster	**N voxels**	**Peak MNI coordinate**			**Lable (aal)**	**Mean T**	**Cluster**	**N voxels**	**Peak MNI coordinate**			**Lable (aal)**	**Mean T**
		x	y	z					x	x	x		
1	455	29	3	2	Putamen_R	4,7	1	318	-37	-3	14	Putamen_L	4,3
					Insula_R	4,1						Insula_L	4,9
					Rolandic_Oper_R	4,0						Rolandic_Oper_L	4,1
					Frontal_Inf_Oper_R	3,7						Temporal_Sup_L	3,8
					Amygdala_R	4,0						Pallidum_L	4,0
					Temporal_Pole_Sup_R	3,7						Temporal_Pole_Sup_L	3,5
2	335	35	-18	50	Precentral_R	5,0	2	219	-42	-24	58	Precentral_L	4,5
					Postcentral_R	3,8						Postcentral_L	4,4
					Frontal_Sup_R	3,8	3	148	40	3	2	Insula_R	4,1
3	74	-39	-1	6	Insula_L	4,4						Rolandic_Oper_R	3,9
					Rolandic_Oper_L	3,7						Putamen_R	3,8
4	39	-59	-33	30	SupraMarginal_L	3,7	4	53	18	-48	-22	Cerebelum_4_5_R	4,1
					Parietal_Inf_L	3,6						Cerebelum_6_R	3,9
					Postcentral_L	3,4						Fusiform_R	3,7
5	32	-14	-48	-18	Cerebelum_4_5_L	4,0							
PD>Control													
Left hand							**Right hand**						
Cluster	**N voxels**	**Peak MNI coordinate**			**Lable (aal)**	**Mean T**	**Cluster**	**N voxels**	**Peak MNI coordinate**			**Lable (aal)**	**Mean T**
		x	y	z					x	y	z		
1	876	-5	-26	58	Paracentral_Lobule_L	4,2	1	222	23	-20	66	Precentral_R	4,5
					Precentral_L	4,0						Postcentral_R	3,7
					Postcentral_L	4,2						Frontal_Sup_R	4,0
					Precuneus_L	3,9	2	122	-52	-27	2	Temporal_Mid_L	3,8
					Paracentral_Lobule_R	4,0						Temporal_Sup_L	3,8
					Cingulum_Mid_L	3,6						Heschl_L	3,8
					Postcentral_R	4,1	3	87	48	-9	38	Precentral_R	4,1
					Precentral_R	4,1						Postcentral_R	3,8
					Supp_Motor_Area_L	4,2	4	54	-37	25	-10	Frontal_Inf_Orb_L	3,9
					Supp_Motor_Area_R	3,7						Insula_L	3,6
2	605	14	-44	34	Precuneus_R	3,9	5	29	8	-42	62	Postcentral_R	3,6
					Cingulum_Mid_R	4,2						Postcentral_R	3,7
					Precuneus_L	3,7						Precuneus_R	3,7
					Cingulum_Mid_L	3,8						Parietal_Sup_R	3,6
					Cingulum_Post_L	3,8	6	26	8	-16	50	Cingulum_Mid_R	4,3
					Cingulum_Post_R	4,0						Supp_Motor_Area_R	3,9
					Cuneus_R	3,5	7	17	-14	-39	-14	Cerebelum_4_5_L	3,6
3	328	42	-48	42	Angular_R	3,7						Fusiform_L	3,9
					Parietal_Inf_R	3,9						ParaHippocampal_L	4,0
					SupraMarginal_R	3,7	8	11	14	-18	2	Thalamus_R	3,7
4	225	42	-7	42	Postcentral_R	4,3							
					Precentral_R	4,5							
5	190	-31	-27	14	Temporal_Sup_L	4,1							
					Heschl_L	4,2							
					Rolandic_Oper_L	4,3							
					Insula_L	4,1							
					Temporal_Mid_L	3,5							
6	74	-5	40	22	Frontal_Sup_Medial_L	3,6							
					Cingulum_Ant_L	3,6							
					Cingulum_Ant_R	3,6							
					Frontal_Sup_Medial_R	3,5							
					Cingulum_Mid_R	3,6							

(*continued*)

Table 2. (*continued*)



7	51	-25	-65	38	Occipital_Mid_L	3,7
					Parietal_Inf_L	3,5
					Occipital_Sup_L	3,7
8	42	-40	-63	34	Angular_L	3,8
					Occipital_Mid_L	3,6
9	31	-10	-82	-2	Lingual_L	3,9
					Calcarine_L	3,7
10	22	7	-56	-22	Vermis_4_5	3,6
					Cerebelum_4_5_R	3,7
					Vermis_6	3,8
11	20	-24	-33	-6	Hippocampus_L	3,8
					ParaHippocampal_L	3,8
12	20	-55	-35	2	Temporal_Mid_L	3,6

References

1. de Poel, H.J., Peper, C.L.E., Beek, P.J.: Handedness-related asymmetry in coupling strength in bimanual coordination: furthering theory and evidence. Acta Psychol. **124**, 209–237 (2007). https://doi.org/10.1016/j.actpsy.2006.03.003
2. Mattay, V.S., Callicott, J.H., Bertolino, A., Santha, A.K.S., Van Horn, J.D., Tallent, K.A., Frank, J.A., Weinberger, D.R.: Hemispheric control of motor function: a whole brain echo planar fMRI study. Psychiatry Res. Neuroimag. **83**, 7–22 (1998). https://doi.org/10.1016/S0925-4927(98)00023-7
3. Taniwaki, T., Okayama, A., Yoshiura, T., Nakamura, Y., Goto, Y., Kira, J., Tobimatsu, S.: Reappraisal of the motor role of basal ganglia: a functional magnetic resonance image study. J. Neurosci. **23**, 3432–3438 (2003). https://doi.org/10.1523/JNEUROSCI.23-08-03432.2003
4. Štochl, J., Hagtvet, K.A., Brožová, H., Klempíř, J., Roth, J., Růžička, E.: Handedness does not predict side of onset of motor symptoms in Parkinson's disease. Mov. Disord. **24**, 1836–1839 (2009). https://doi.org/10.1002/mds.22653
5. van der Hoorn, A., Burger, H., Leenders, K.L., de Jong, B.M.: Handedness correlates with the dominant Parkinson side: a systematic review and meta-analysis. Mov. Disord. **27**, 206–210 (2012). https://doi.org/10.1002/mds.24007
6. Amick, M.M., Schendan, H.E., Ganis, G., Cronin-Golomb, A.: Frontostriatal circuits are necessary for visuomotor transformation: mental rotation in Parkinson's disease. Neuropsychologia **44**, 339–349 (2006). https://doi.org/10.1016/j.neuropsychologia.2005.06.002
7. Jellinger, K.A.: The pathomechanisms underlying Parkinson's disease. Expert Rev. Neurother. **14**, 199–215 (2014). https://doi.org/10.1586/14737175.2014.877842
8. Yust-Katz, S., Tesler, D., Treves, T.A., Melamed, E., Djaldetti, R.: Handedness as a predictor of side of onset of Parkinson's disease. Parkinsonism Relat. Disord. **14**, 633–635 (2008). https://doi.org/10.1016/j.parkreldis.2008.01.017
9. François-Brosseau, F.-E., Martinu, K., Strafella, A.P., Petrides, M., Simard, F., Monchi, O.: Basal ganglia and frontal involvement in self-generated and externally-triggered finger movements in the dominant and non-dominant hand. Eur. J. Neurosci. **29**, 1277–1286 (2009). https://doi.org/10.1111/j.1460-9568.2009.06671.x
10. Redgrave, P., Rodriguez, M., Smith, Y., Rodriguez-Oroz, M.C., Lehericy, S., Bergman, H., Agid, Y., DeLong, M.R., Obeso, J.A.: Goal-directed and habitual control in the basal ganglia: implications for Parkinson's disease. Nat. Rev. Neurosci. **11**, 760–772 (2010). https://doi.org/10.1038/nrn2915
11. Wu, T., Chan, P., Hallett, M.: Effective connectivity of neural networks in automatic movements in Parkinson's disease. Neuroimage **49**, 2581–2587 (2010). https://doi.org/10.1016/j.neuroimage.2009.10.051

12. Wu, T., Hallett, M., Chan, P.: Motor automaticity in Parkinson's disease. Neurobiol. Dis. **82**, 226–234 (2015). https://doi.org/10.1016/j.nbd.2015.06.014
13. Aznárez-Sanado, M., Fernández-Seara, M.A., Loayza, F.R., Pastor, M.A.: Functional asymmetries in early learning during right, left, and bimanual performance in right-handed subjects. J. Magn. Reson. Imaging **37**, 619–631 (2013). https://doi.org/10.1002/jmri.23841
14. Herz, D.M., Eickhoff, S.B., Løkkegaard, A., Siebner, H.R.: Functional neuroimaging of motor control in parkinson's disease: a meta-analysis. Hum. Brain Mapp. **35**, 3227–3237 (2014). https://doi.org/10.1002/hbm.22397
15. Martin, J.A., Zimmermann, N., Scheef, L., Jankowski, J., Paus, S., Schild, H.H., Klockgether, T., Boecker, H.: Disentangling motor planning and motor execution in unmedicated de novo Parkinson's disease patients: An fMRI study. NeuroImage Clin. **22**, 101784 (2019). https://doi.org/10.1016/j.nicl.2019.101784
16. Oldfield, R.C.: The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia **9**, 97–113 (1971). https://doi.org/10.1016/0028-3932(71)90067-4
17. Filyushkina, V., Popov, V., Medvednik, R., Ushakov, V., Batalov, A., Tomskiy, A., Pronin, I., Sedov, A.: Hyperactivity of basal ganglia in patients with parkinson's disease during internally guided voluntary movements. Front. Neurol. **10**, 847 (2019). https://doi.org/10.3389/fneur.2019.00847
18. Wu, T., Hallett, M.: A functional MRI study of automatic movements in patients with Parkinson's disease. Brain **128**, 2250–2259 (2005). https://doi.org/10.1093/brain/awh569
19. Riederer, P., Jellinger, K.A., Kolber, P., Hipp, G., Sian-Hülsmann, J., Krüger, R.: Lateralisation in Parkinson disease. Cell Tissue Res. **373**, 297–312 (2018). https://doi.org/10.1007/s00441-018-2832-z
20. Jueptner, M., Weiller, C.: A review of differences between basal ganglia and cerebellar control of movements as revealed by functional imaging studies. Brain **121**, 1437–1449 (1998)
21. Gut, M., Urbanik, A., Forsberg, L., Binder, M., Rymarczyk, K., Sobiecka, B., Kozub, J., Grabowska, A.: Brain correlates of right-handedness. Acta Neurobiol. Exp. **67**, 43–51 (2007)
22. Jenkins, I.H., Jahanshahi, M., Jueptner, M., Passingham, R.E., Brooks, D.J.: Self-initiated versus externally triggered movements. Brain **123**, 1216–1228 (2000). https://doi.org/10.1093/brain/123.6.1216

Gamma Activity During Observation, Imagination, and Execution of Movements in Patients with Epilepsy: Invasive Study

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Abstract. The mirror neuron system (MNS) is a key component in the neurophysiological mechanisms of social behavior. At the same time, the properties of the mirror neurons are very difficult to study using indirect methods such as fMRI and EEG. Also, invasive registration of neural activity in people is possible only in the case of serious medical interventions. This MNS study was conducted in patients with pharmacoresistant epilepsy, and the gamma activity of local potentials in the frontal and temporal lobes was studied using depth invasive electrodes. The MNS activation was accompanied by increased gamma activity in the left inferior frontal gyrus, anterior insula, caudate nucleus, and in the right hippocampus. The degree of activity was related to the complexity of the hands movement.

Keywords: Mirror neuron system · Gamma activity · Epilepsy

1 Introduction

Mirror neurons have been studied since 1996 when Rizzolatti with his colleagues discovered neurons with mirror properties that increase their activity during observation and execution of the same action [1]. There were a lot of attempts to investigate mirror neurons in humans and a lot of disputes about whether the mirror neurons exist in humans or not. The point is that there were only indirect methods of mirror neurons studying in humans like fMRI, EEG, or PET. Such methods couldn't reveal that activation during observation and execution of social movements occurs in the same neurons. Despite this fact, a lot of new interesting properties of the mirror neurons system (MNS) were uncovered. First of all, Rizzolatti reported that mirror neurons were activated during action observation when the subject understood the purpose of the action and was able to repeat that action [2]. The mirror neuron system has been found to play an important role in empathy, learning, understanding other people's intentions, and social

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interaction in general [3–7]. Finally, in 2010 Mukamel published joint work with neurosurgeons where they recorded single neuron activity in patients with pharmacoresistant epilepsy [8].

This work put an end to the debate about the existence of mirror neurons in humans: there were very accurately measured the activity of more than 1,000 neurons in different regions of the brain, and there were found neurons that respond when viewing and performing the same action by a person. Of course, this work was unique in its complexity and accuracy. Furthermore, the invasive implantation of recording electrodes into the patients' brains required compliance with all ethical standards. This is why the invasive recording was only possible for patients with epilepsy who were preparing for surgical removal of the focus of epileptic activity. As a result, Mukamel found mirror neurons in the motor and premotor cortex, as well as the hippocampus and amygdala [8].

So far, there are not many papers that cover the MNS work using invasive registration of extracellular neurons activity. One of the works was done on patients with Parkinson's disease, a bilateral desynchronization of beta activity during action observation and execution was found [9]. In 2014, when investigating the capabilities of the invasive brain-computer interface, it was shown that subdural electrodes registered similar patterns of alpha-beta and gamma activity when observing and capturing objects [10]. Waldert with his team registered local field potentials (LFP) in the premotor and primary motor cortex of two monkeys [11]. The authors showed that the low-frequency LFP signal can be modulated while observing the action in both considered areas of the cerebral cortex. A comparative study of the sensorimotor and speech functions of the MNS using ECOG recording was provided in 2015 [12] and obtained desynchronization of alpha, and beta rhythms in the frontal, parietal, temporal regions, and lower frontal gyrus when observing and performing both visual-motor and speech tasks. Several papers have reported changes in invasive gamma activity in their MNS studies, which we will consider in more detail during the discussion [13–16].

Thus, invasive studies of the MNS are unique and extremely necessary works for understanding the mirror properties of neurons. This work aimed to identify changes in LFP gamma activity in the lower frontal gyrus and temporal regions, including the hippocampus, in tasks that activate the MNS.

2 Methods

2.1 Ethics Statement

The research methods were approved by the local ethical committees of the Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences (Moscow, Russia) and were performed under the ethical standards laid down in the Declaration of Helsinki of 1964.

2.2 Subjects

The study involved 11 patients (10 men, 1 woman, right-handed, aged 21 to 39 years, average 29 years) with a diagnosis of focal intractable epilepsy, preparing for surgical removal of the epileptic focus. All patients were admitted to the neurosurgical department of Clinical Medical Center of Moscow State Medical and Dental University. All subjects gave their informed consent and were free to withdraw from the study at any time. Before the operation, this group of patients was equipped with depth electrodes for invasive video EEG monitoring to determine the “attack onset area” and “irritative area”. All subjects fully understood the experimenters’ instructions and easily performed the experimental task. The study of the MNS activity was conducted at least 5 h after the operation to insert the electrodes when the patient was already fully conscious and showed adequate activity.

2.3 Experimental Design

The method of conducting the MNS study should include the tasks of observing and performing (also often used imagination) biological gestures, for which a video clip was mounted. This video clip included fragments with various hand movements, as well as a fragment with a non-biological moving object (a ball that rolls on a table). In the video, all the movements were performed by an actor in neutral clothing, and only the hands, forearms, and part of the table were visible (the face was not visible). Three different movements were selected – a simple motor act (clenching the right hand), an emotional movement involving both hands (clapping), and a purposeful movement (grasping and moving the cup). The patient was instructed to observe the demonstration of movement (“observation” task), then imagine this movement (“imagination” task), then repeat it (“execution“ task). The duration of each task was 10 s, and there were pauses between tasks, during which the researcher reminded what the next task would be. As a baseline, the neural activity was recorded in a resting state with open eyes in the same body position. The video also included a 10-s fragment with a static image, where the same actor didn’t show any movements (the task of observing a “static image”). The demonstration of a static image was carried out in order to differentiate the reaction to the “picture” and to the social movement.

The video clip was demonstrated from a 17-inch laptop monitor, which was placed on a stand in front of the patient. The distance from the monitor screen to the patient’s face was 40–50 cm. Patients were placed on their hospital bed, the back of the bed was brought to a semi-vertical position. Before the experiment began, patients were brought to the most convenient position for video viewing and performing movements with their right hand. Before starting the experiment, patients were explained the essence of the study and given the necessary instructions.

2.4 Electrodes and Signal Acquisition

The electrodes were implanted in the hippocampus of the right and left temples and in the frontal lobes. Sterile disposable AD-TECH® electrodes with platinum contacts (1.12 mm diameter) were used to monitor epileptic activity. Each depth electrode had 4 or 6 contacts located at a distance of 10 mm from each other, the distance between the first and last contact of the electrode was 32 mm for 4-contact and 52 mm for 6-contact electrodes. The deepest contact was located at a depth of about 60 mm. In the frontal lobes, the electrodes were passed through the lower frontal gyrus with the tip in the projection of the caudate nucleus in the left and right hemispheres. Temporal electrodes were inserted through the middle or upper temporal gyrus with the tip located in the projection of the right hippocampus also in the left and right hemispheres. Electrodes screwed into the scalp were used as reference and grounding electrodes. The localization of invasive electrodes was monitored using computed tomography.

2.5 Data Processing and Analysis

The signal from the depth electrodes was recorded at a sampling rate of 2 kHz (in 3 patients), 8 kHz (in 1 patient), and 4 kHz (in 7 patients), then a bandpass filter of 1–300 Hz and a 50 Hz rejection filter with harmonics were performed using the free EDF browser program. For each patient in each task, spectral power values of gamma (35–300 Hz) rhythm were identified with a standard fast Fourier transform (FFT). The absolute power values of each sample were also recalculated relative to the baseline and normalized by natural logarithm. Relative values of gamma power were analyzed using Analysis of Variance (ANOVA, Statistica V.7.0 by StatSoft © Inc., USA) with factors such as "hemisphere" and "lobe" depending on whether the recording electrodes were located. Also for the tasks of observation, imagination, and execution, ANOVA was performed taking into account the "motor movement" factor, depending on the type of hand movement observed and performed.

When the location of the epileptic focus was determined, the signals of the same hemisphere were excluded from the patient's data pool.

3 Results

3.1 Gamma Activity in Various Tasks

Normalized relative values of the gamma rhythm power were used to analyze its changes when performing tasks in comparison with the baseline (see Fig. 1). The repeated measures ANOVA taking into account the "hemisphere" and "lobe" factors revealed a significant influence of factors combination R1 * "hemisphere"* "lobe", current effect $F(4, 1400) = 30.43$, $p = 0.000$. Changes in the gamma rhythm in each of the tasks are shown in Fig. 2 for the frontal and temporal electrodes in the left and right hemispheres (the value in the baseline corresponds to zero on the y-axis).

One can see a significant increase in gamma activity during the imagination and execution task in the left frontal lobe and right temporal lobe. At the same time, there was a significant decrease in gamma activity in the left temporal lobe during the execution task. Gamma activity was lower baseline during observation of the static image and non-biological motion of a ball.

3.2 Gamma Activity and Different hand's Movements

The next step in our analysis was to determine whether gamma activity depends on the type of hand's movement. repeated measures ANOVA was carried out taking into account the following factors: hemisphere (1), lobe (2), type of movement (3), and repeated task (R1 – observation, imagination, execution). The following Table 1 gives the indicators of the ANOVA and p-values for significant effects.

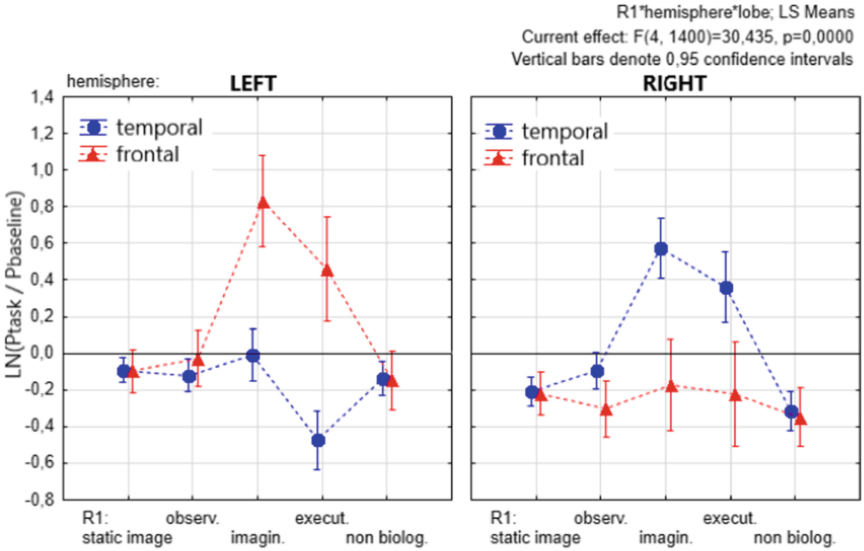

Fig. 1. Relative changes in gamma activity when performing various tasks (static image observation, observation, imagination, and execution of the biological movements, and non-biological motion observation) in the left and right hemispheres in the temporal (blue circles) and frontal (red triangles) lobes. The baseline values are zero.

Table 1. Repeated measures analysis of variance.

Effect	SS	Degree of Freedom	MS	F	p
Intercept	17,30	1	17,30	19,02	0,00
{1} hemisphere	5,40	1	5,41	5,95	0,02
{2} lobe	12,02	1	12,02	13,22	0,0003
{3} movement	9,16	2	4,58	5,04	0,006
hemisphere * lobe	56,38	1	56,38	61,98	0,00
1 * 2 * 3	7,85	2	3,93	4,32	0,01
Error	512,98	564	0,90		
{4} R1	22,54	2	11,27	41,04	0,00
R1 * hemisphere	2,13	2	1,07	3,88	0,02
R1 * lobe	3,35	2	1,68	6,12	0,002
R1 * movement	3,12	4	0,78	2,85	0,02
R1 * 1 * 2	14,54	2	7,27	26,47	0,00
R1 * 1 * 3	5,97	4	1,49	5,44	0,00
R1 * 2 * 3	2,88	4	0,72	2,62	0,03
Error	309,83	1128	0,27		

One can also see differences in gamma changes during observation, imagination, and execution of three types of hand movement: hand clenching, clapping, and cup grasping (see Fig. 2). There were significant increases in gamma activity in left frontal electrodes during imagination and execution for all movements and during observation of the clapping and cup grasping only. In the right temporal lobe there were significant gamma increases during imagination and execution of the same movements (clapping and cup grasping only). There was a significant decrease in gamma activity in the left temporal lobe during execution of the hand clenching and clapping.

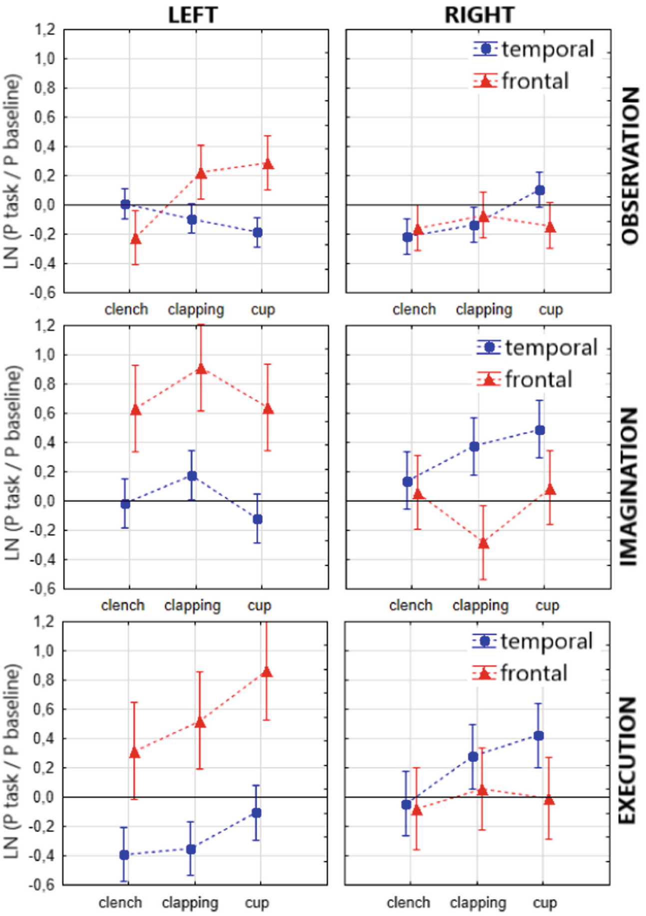

Fig. 2. Relative changes in gamma activity when performing various tasks (static image observation, observation, imagination, and execution of the biological movements, and non-biological motion observation) in the left and right hemispheres in the temporal (blue circles) and frontal (red triangles) lobes. The baseline values are zero.

4 Discussion and Conclusions

The main idea of this work was to use more objective indicators of neural network activity in the study of the MNS. It is a gamma signal that is associated with the neurons' activity, therefore in this paper, we are talking about the gamma activity of the LFP signal, which reflects the electric potential changes of nearby neural circuits. At the moment, there are many fMRI and EEG studies that investigate the properties of the MNS. But such methods always cause a lot of doubts, since the BOLD signal and mu-rhythm suppression are indirect indicators of network activity. Gamma changes in the LFP signal is a more direct activation indicator of surrounding neural networks.

The strongest increase in gamma activity in our work was obtained when performing all "mirror" tasks in the left frontal electrodes, namely in the lower frontal gyrus, anterior insula, and head of the caudate nucleus. Also, a significant, but not so strong increase in gamma activity was in the right temporal lobe, namely in the hippocampus. Analysis of the literature gave the following.

Caruna used the ECOG method, when analyzed the gamma range in the premotor cortex only during observation, without using execution and imagination tasks [13]. Babiloni in 2016 showed that in patients with epilepsy in the sensorimotor, premotor, and prefrontal cortex regions, both when observing and performing hand movement, alpha and beta suppression and gamma increasing of ECOG were occurred [14]. In a recent study, Perry and colleagues [15] examined the MNS activity using ECOG in prefrontal, motor, temporal, or parietal regions of the right or left hemisphere. The results showed an increase in the gamma power when observing and performing tasks. Simultaneous recording of multi unit activity, LFP, and EEG from the ventral premotor cortex in monkeys were provided in a recent study [16]. There were revealed that the activity of the premotor cortex significantly correlates with an increase in the LFP gamma range, as well as with a decrease of the sensorimotor EEG rhythms.

Thus, our results of measuring gamma activity are in good agreement with the literature data. As for the activation regions, the premotor cortex and lower frontal gyrus have long been mentioned in works on the mirror system of the brain [3, 5, 6]. The insula through which the frontal electrodes passed has extensive connections with both the limbic system and the motor cortex, so it can be an intermediary in the mirror system between motor functions and feelings of empathy [7]. Activation of the right hippocampus was not as strong and was not shown in all tasks, but only in more complex ones. This effect may be associated with memory retrieval processes when trying to imagine and repeat the hand movement seen. At the same time, Mukamel in their work found in the hippocampus neurons with mirror properties [8].

The greatest increases in gamma rhythm were in the presentation and execution tasks. When considering different motor acts, it became clear that when observed, gamma increased only in two more complex tasks - clapping hands and moving the cup. The first movement of clenching the hand, probably, was the easiest to perceive. The increase in activity exactly in the left frontal lobe is probably because all the subjects were right-handed and the left hemisphere dominates in planning actions. Thus, all the necessary elements of mirroring have worked. Interestingly, when observing a non-biological object (the movement of the ball) there was even a decrease in gamma power, which may be associated with a decrease in the MNS activity.

In conclusion, we can state that this study revealed the mirror neurons activity in the left lower frontal gyrus, anterior insula, and caudate nucleus head in all "mirror" tasks, as well as in the right hippocampus when performing the most complex tasks of imagination and repetition. The degree of activity was related to the complexity of the hands movement, and the activation side was related to the dominant hemisphere of the participants.

The authors declare that the research was conducted in the absence of any commercial relationships that could be construed as a potential conflict of interest.

References

1. Gallese, V., Fadiga, L., Fogassi, L., Rizzolatti, G.: Action recognition in the premotor cortex. Brain **119**, 593–609 (1996). https://doi.org/10.1093/brain/119.2.593
2. Grafton, S., Arbib, M., Fadiga, L., Rizzolatti, G.: Localization of grasp representations in humans by positron emission tomography. Exp. Brain Res. **112**, 103–111 (1996). https://doi.org/10.1007/BF00227183
3. Grèzes, J.: Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. Hum. Brain Mapp. **12**, 1–9 (2001). https://doi.org/10.1002/1097-0193(200101)12:1
4. Lebedeva, N.N., Karimova, E.D., Karpichev, V.V., Maltsev, V.: The human brain mirror system in the observation, implementation and representation motor tasks – neurophysiological reflection of another conscious perception. Zhurnal Vysshei Nervnoi Deyatelnosti Imeni I.P. Pavlova **68**, 204–215 (2018). https://doi.org/10.7868/S0044467718020065
5. Ensenberg, N.S., Perry, A., Aviezer, H.: Are you looking at me? mu suppression modulation by facial expression direction. Cogn. Affect. Behav. Neurosci. **17**, 174–184 (2017). https://doi.org/10.3758/s13415-016-0470-z
6. Buccino, G., Binkofski, F., Riggio, L.: The mirror neuron system and action recognition. Brain Lang. **89**, 370–376 (2004). https://doi.org/10.1016/S0093-934X(03)00356-0
7. Iacoboni, M.: Understanding others: imitation, language, empathy. Perspect. Imitation Cogn. Neurosci. Soc. Sci. **1**, 77–99 (2005)
8. Mukamel, R., Ekstrom, A.D., Kaplan, J., Iacoboni, M., Fried, I.: Single-neuron responses in humans during execution and observation of actions. Curr. Biol. **20**, 750–756 (2010). https://doi.org/10.1016/j.cub.2010.02.045
9. Alegre, M., Rodríguez-Oroz, M.C., Valencia, M., Pérez-Alcázar, M., Guridi, J., Iriarte, J., Obeso, J.A., Artieda, J.: Changes in subthalamic activity during movement observation in Parkinson's disease: is the mirror system mirrored in the basal ganglia? Clin. Neurophysiol. **121**, 414–425 (2010). https://doi.org/10.1016/j.clinph.2009.11.013
10. Collinger, J.L., Vinjamuri, R., Degenhart, A.D., Weber, D.J., Sudre, G.P., Boninger, M.L., Tyler-Kabara, E.C., Wang, W.: Motor-related brain activity during action observation: a neural substrate for electrocorticographic brain-computer interfaces after spinal cord injury. Front. Integr. Neurosci. (2014). https://doi.org/10.3389/fnint.2014.00017
11. Waldert, S., Vigneswaran, G., Philipp, R., Lemon, R.N., Kraskov, A.: Modulation of the intracortical LFP during action execution and observation. J. Neurosci. **35**, 8451–8461 (2015). https://doi.org/10.1523/JNEUROSCI.5137-14.2015
12. Halje, P., Seeck, M., Blanke, O., Ionta, S.: Inferior frontal oscillations reveal visuo-motor matching for actions and speech: evidence from human intracranial recordings. Neuropsychologia **79**, 206–214 (2015). https://doi.org/10.1016/j.neuropsychologia.2015.08.015

13. Caruana, F., Sartori, I., Lo Russo, G., Avanzini, P.: Sequencing biological and physical events affects specific frequency bands within the human premotor cortex: an intracerebral EEG study. PLoS ONE **9**, e86384 (2014). https://doi.org/10.1371/journal.pone.0086384
14. Babiloni, C., Del Percio, C., Vecchio, F., Sebastiano, F., Di Gennaro, G., Quarato, P.P., Morace, R., Pavone, L., Soricelli, A., Noce, G., Esposito, V., Rossini, P.M., Gallese, V., Mirabella, G.: Alpha, beta and gamma electrocorticographic rhythms in somatosensory, motor, premotor and prefrontal cortical areas differ in movement execution and observation in humans. Clin. Neurophysiol. **127**, 641–654 (2016). https://doi.org/10.1016/j.clinph.2015.04.068
15. Perry, A., Stiso, J., Chang, E.F., Lin, J.J., Parvizi, J., Knight, R.T.: Mirroring in the human brain: deciphering the spatial-temporal patterns of the human mirror neuron system. Cereb. Cortex. **28**, 1039–1048 (2018). https://doi.org/10.1093/cercor/bhx013
16. Bimbi, M., Festante, F., Coudé, G., Vanderwert, R.E., Fox, N.A., Ferrari, P.F.: Simultaneous scalp recorded EEG and local field potentials from monkey ventral premotor cortex during action observation and execution reveals the contribution of mirror and motor neurons to the mu-rhythm. Neuroimage **175**, 22–31 (2018). https://doi.org/10.1016/j.neuroimage.2018.03.037

Diagnostics of Ataxia in Children Who Survived Cerebellar Tumor: The Relationship Between Parameters of Tandem Gait, Saccadic System and Postural Stability

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Abstract. Children who survived cerebellar tumor occur with atactic motor disorders. These disorders could be represented in postural, locomotor and oculomotor domains. The gait efficiency depends on visual information acquired from saccadic eye movements. The aim of the study was to establish the relationships between measures of tandem gait and saccades and to verify them by stabilometry and general motor score using Bruininks-Oseretsky Test. We used motion capture system (Optitrack) for gait registration and Arrington eye tracker for saccade detection. 15 patients (9–17 years old) survived cerebellar tumors and stayed in rehabilitation center, participated in the study. We found significant relationships between the parameters of tandem gait and saccades: high percent of hypermetric saccades (saccades which overshoot the target) was strongly associated with high tandem gait variability ($r = 0.552$). Moreover, the degree of impairment of gait and saccadic parameters significantly related to worse postural disturbances ($r = 0.752$; $r = 0.541$) and motor skills ($r = -0.673$; $r = -0.612$). Observed findings comprehensively characterize the severity of ataxia and could provide new approach for the diagnosis of CNS lesions.

Keywords: Cerebellum · Pediatric cancer · Tandem gait · Motion capture · Eye tracking

1 Introduction

An integral part of the functioning of the locomotor system is the complex interaction of different areas of the brain, providing reliable feedback from the visual system [1]. Effective locomotion relies on visual input received via saccadic eye movements (rapid oculomotor movements) [2]. Understanding the relationship between saccades, fixations

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and locomotor acts (such as gait) can provide insight into the parallel and collaborative work of these two systems [3].

Neural networks subserving the integration work of saccadic system and locomotion coincide in regions of brainstem and the cerebellum [3]. The cerebellum is crucial for gross and fine motor skills, balance and gait. According to gait generation, cerebellar cortex and deep cerebellar nuclei (dentate and fastigal, where representations of single muscles are located) form complex circuit with inferior olivary nuclei, providing combination of motor acts [4, 5]. Fastigal nucleus has projections to the brainstem reticular formation and is thought to be an important locomotor region controlling proximal limb movements [6]. Saccade regulation involves cerebellar regions such as oculomotor vermis (vermal lobules VI-VII) and as well as fastigial nucleus [7]. Brainstem saccade generator receives projections from fastigial nucleus adjusting the saccadic amplitude [8].

Due to cerebellar lesions of various origins, the classic motor impairments are expressed in dysmetria of movements, oculomotor abnormalities, ataxic gait, tremor, muscle weakness and dysarthric speech, as well as disorders of non-motor functions (cognitive and affective) [7, 9]. One of the most informative clinical test for ataxia estimation is tandem gait test used when conducting neurological examinations to quantify the severity of impairments [10, 11]. Tandem gait implies walking heel to toe in a straight line, resulting in conditions of limited support and difficult maintenance of balance [12]. In normal clinical use, the task completion time and the number of steps and errors are recorded, but at the moment, research options are being developed using the registration of biomechanical parameters by motion capture systems [13].

Cerebellar oculomotor disorders include nystagmus, unstable fixations, saccadic intrusions and oscillations, impairments of smooth pursuit, saccadic dysmetria [14, 15]. In our previous research we showed saccadic hypermetria (when inaccurate saccade overshoots the target) could be considered as one of the most prominent symptom of cerebellar disorder [16]. Hypermetric saccades often followed by corrective saccades of smaller amplitude which return the gaze to the target. Eye tracking is useful non-invasive tool which allows to investigate saccadic functions in patients.

Various studies have shown common gait and saccadic regularities in healthy subjects and abnormalities in patients with neurodegenerative diseases [17–20]. In most of them, the parameters of locomotion and eye movements were recorded separately. For example, in Parkinson’s disease the step length and saccades tend to be hypometric, freezing of gait relates to increased saccadic latency [18]. In patients with cerebellar ataxia predictable results were given: dysmetric saccades occur during stepping [19]. It should be noted that more studies have recently appeared with simultaneous registration of gait and eye movements [20].

Cerebellar dysfunction can be caused by tumor process and its treatment. Among pediatric types of cancer, posterior fossa tumors (medulloblastoma, astrocytoma, ependymoma etc.) make up 50% of all brain cancer and represent a serious problem in neuro-oncology [21]. They mostly occur at an early age and lead to disability of the child for the rest of his life. While treatment approaches have been recently developed and provide high survival rate, pediatric neuro-oncology requires new rehabilitation methods for improving recovery process and reducing the consequences of disability. To assess the effectiveness of the rehabilitation process, it is necessary to use high-precision technological solutions, e.g. objective methods of motion capture and eye tracking.

Considering this, aim of our study was to establish the relationships between measures of tandem gait and saccades in patients survived cerebellar tumors for accurate diagnostics of ataxia symptoms. In addition, we wanted to test how systems of gait and eye movements correspond to system of postural control and the child's overall motor development using standardized classical methods of stabilometry and Bruininks-Oseretsky Test of Motor Proficiency.

2 Methods

Research was conducted on 15 patients (8 males, 9–17 years old, $M = 13.4 \pm 2.5$) who survived cerebellar tumor. Most of patients were diagnosed with medulloblastoma (7) and pilocytic astrocytoma (5) and single cases represented other tumors (ganglioma – 1, ependymoma – 1, neurocytoma – 1). Subjects didn't suffer from severe mental, neurological and ophthalmological deficits. They were staying at Clinical Research Rehabilitation Center (Chechov, Russia) and receiving rehabilitational course after finishing of treatment (including the chemotherapy) for at least six months. The experiment was approved by the Ethics Committee of Dmitry Rogachev National Medical Research Center of Pediatric Hematology, Oncology and Immunology (protocol number 8e/13–17 of 27.10.2017) and was conducted according to the principles of the Declaration of Helsinki.

The experimental design consisted of two main digital (motion capture and eye tracking) and two supplemental classical methods (stabilometry and Bruininks-Oseretsky Test of Motor Proficiency, BOT-2).

We used optical system Optitrack Motion Capture (12 cameras Flex 13, 120 Hz) for estimating kinematics of tandem gait. A set of 26 reflective markers were placed on anatomical landmarks of subject's body (Fig. 1). Subjects were asked to walk 4.5 m with eyes open, heel-to-toe, without spaces between feet along the straight line marked on the floor. Data from one marker on heel and from virtual marker represented center of mass position was registered. Estimated parameters were: (1) step length (m) - the length of two feet (40–60 cm, including mistakes); (2) step amplitude (height, m) – abduction of the leg to the side; (3) gait variability – the ratio of step length to the amplitude of step; (4) the trajectory of center of mass (CoM trajectory) from virtual marker (m). For further analysis, the coefficients of variation (CV) of step length, step amplitude and gait variability were used. The higher is the CV of gait variability – the more variable (inefficient) is the gait. CoM trajectory represents the real distance covered, taking into account the deviations from the given path.

Eye movements were evaluated in visually-guided saccades test and recorded by eye tracker Arrington 60 Hz. Standard 9-point calibration algorithm was used. Patients were asked to perform 24 visually guided saccades to the tops of the square demonstrated on the monitor. Saccadic amplitudes were obtained. Estimated parameters were: (1) percent of hypermetric saccades (whose amplitude exceeds the given by more than 10%); (2) percent of corrective saccades (followed after hyper- or hypometric saccades); (3) scanpath (°) - the total amplitude of the executed saccades according to the square's trajectory.

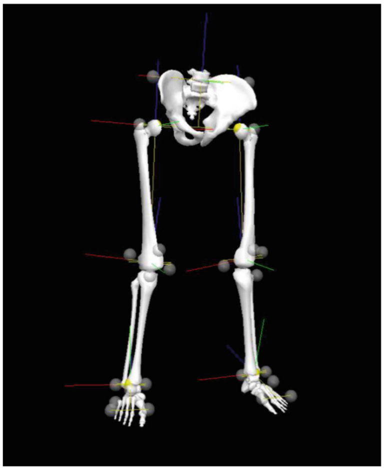

Fig. 1. Multisectional model of the lower extremities using 26 markers located on anatomical landmarks. The image is obtained from Visual 3D.

Stabilometry was performed using Stabilan-01–2® device (ZAO OKB "Ritm", Taganrog, Russia) for estimation of postural balance (in Romberg Pose with eyes opened). The estimated parameter was mean velocity of center of pressure moving (V of CoP, mm per sec).

Child's overall motor development was evaluated by BOT-2. This test sums up the performance of tasks for gross and fine motor skills, coordination, strength and dexterity [22]. The estimated parameter was general motor score.

All assessments described above were performed once and separately during the course of rehabilitation for each patient.

The statistical analysis was processed with STATISTICA 13 for Windows. Spearman's rank correlations were used for obtaining the relationships between parameters of motion capture, eye tracking, stabilometry and BOT-2.

3 Results

Our investigation of locomotor and oculomotor systems revealed significant relationships between gait variability level and saccade performance in patients (Table 1). Thus, high percent of hypermetric saccades was strongly associated with high CV of gait variability and increased CoM trajectory. Elongate scanpath was related to elongate CoM trajectory and to increased CVs of step amplitude and gait variability. High percent of corrective saccades tended to be associated with CV of gait variability ($p = 0.061$) and CoM trajectory ($p = 0.062$).

We also compared obtained parameters of locomotor and oculomotor systems with standardized indicators of postural stability and overall motor development for their verification (Table 2). Negative correlations of BOT-2 test execution are associated with the inverse relationship of the indicators of other tests because higher scores of BOT-2 mean better motor child's development in contrast to all other indicators. It should be noted

Table 1. Relationships between measures of tandem gait and saccade performance. Spearman's rank correlation coefficients (*r*) are given.

	% of hypermetric saccades	% of corrective saccades	Scanpath
CV of step amplitude	0.403	0.403	0.544*
CV of gait variability	0.552*	0.432	0.596*
CoM trajectory	**0.697****	0.453	0.530*

$^{*}p < 0.05$; $^{**}p < 0.01$

that standardized tests showed significant relationships between balance functions and general motor skills.

V of CoP and general motor score correlate with almost all the parameters we have deduced. It should be emphasized, that CV of step amplitude and gait variability are highly reliable correlated to stabilometry. It could be caused by moving the CoM during gait as well as during deviations in postural stability.

Table 2. Relationships between measures of tandem gait, saccade performance and stabilometry and BOT-2. Spearman's rank correlation coefficients (*r*) are given.

	V of CoP (stabilometry)	General motor score (BOT-2)
% of corrective saccades	0.541*	−0.612*
Scanpath	0.510*	−0.402
CV of step amplitude	**0.912*****	−0.614*
CV of gait variability	**0.752*****	−0.673**
V of CoP		−0.572*

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

4 Discussion

In our study, we identified objective measures of tandem gait and saccades and revealed their interconnections with each other and with indicators of postural stability and overall motor development in patients survived cerebellar tumors. Lesions of the cerebellum, as a structure of integration of these systems, determine revealed relationships [3]. The prominent sign of cerebellar disorder expresses in dysmetria of movements and saccades [5, 7]. Dysmetria of movements is presented by increasing of distance covered because of searching foot movements to return to a stable state. High gait variability (CVs) and elongate CoM trajectory evidence atactic gait. Dysmetria of saccades is presented by occurring of hypermetric (in contrast to previous research where hypometric saccades were revealed [19]) and corrective saccades, also reminiscent of the return of the eye to a stable state. Such oculomotor behavior may be pointed as an "ataxia of eyes" [23].

Thus, considering disturbances in postural stability, we revealed manifestations of ataxia in working mechanisms of human motor systems.

5 Conclusion

Our findings demonstrate the possibility of application high-precision methods of motion capture and eye tracking to comprehensively characterize the severity of ataxia and divide patients for further rehabilitation based on the results obtained. Moreover, deduced indicators could be useful for detailed diagnostics of reducing ataxia's manifestations after completing a rehabilitation course. The proposed approach may also be applied in the diagnosis of motor disorders provoked by a number of other CNS diseases (Parkinson‘s disease, stroke, traumatic brain injury, etc.).

References

1. Gibson, J.J.: Visually controlled locomotion and visual orientation in animals. Br. J. Psychol. **49**(3), 182–194 (1958). https://doi.org/10.1111/j.2044-8295.1958.tb00656.x
2. Patla, A.E.: How is human gait controlled by vision. Ecol. Psychol. **10**(3–4), 287–302 (1998). https://doi.org/10.1080/10407413.1998.9652686
3. Srivastava, A., Ahmad, O.F., Pacia, C.P., Hallett, M., Lungu, C.: The relationship between saccades and locomotion. J. Mov. Disord. **11**(3), 93–106 (2018). https://doi.org/10.14802/jmd.18018
4. Koeppen, A.H.: The neuropathology of the adult cerebellum. Handb. Clin. Neurol. **154**, 129–149 (2018). https://doi.org/10.1016/B978-0-444-63956-1.00008-4
5. Salman, M.S., Tsai, P.: The role of the pediatric cerebellum in motor functions, cognition and behavior: a clinical perspective. Neuroimaging Clin. N. Am. **26**(3), 317–329 (2016). https://doi.org/10.1016/j.nic.2016.03.003
6. Zhang, X.Y., Wang, J.J., Zhu, J.N.: Cerebellar fastigial nucleus: from anatomic construction to physiological functions. Cerebellum Ataxias **3**(1), 9 (2016). https://doi.org/10.1186/s40673-016-0047-1
7. Manto, M., Bower, J.M., Conforto, A.B., Delgado-García, J.M., Da Guarda, S.N.F., Gerwig, M., Molinari, M.: Consensus paper: roles of the cerebellum in motor control—the diversity of ideas on cerebellar involvement in movement. Cerebellum **11**(2), 457–487 (2012). https://doi.org/10.1007/s12311-011-0331-9
8. Scudder, C.A., Kaneko, C.S., Fuchs, A.F.: The brainstem burst generator for saccadic eye movements: a modern synthesis. Exp. Brain Res. **142**(4), 439–462 (2002). https://doi.org/10.1007/s00221-001-0912-9
9. Bodranghien, F., Bastian, A., Casali, C., Hallett, M., Louis, E.D., Manto, M., Mariën, P., Nowak, D.A., Schmahmann, J.D., Serrao, M., Steiner, K.M., Strupp, M., Tilikete, C., Timmann, D., van Dun, K.: Consensus paper: revisiting the symptoms and signs of cerebellar syndrome. Cerebellum **15**(3), 369–391 (2016). https://doi.org/10.1007/s12311-015-0687-3
10. Margolesky, J., Singer, C.: How tandem gait stumbled into the neurological exam: a review. Neurol. Sci. **39**(1), 23–29 (2018). https://doi.org/10.1007/s10072-017-3108-1
11. Cohen, H.S., Mulavara, A.P., Peters, B.T., Sangi-Haghpeykar, H., Kung, D.H., Moiser, D.R., Bloomberg, J.J.: Sharpening the tandem walking test for screening peripheral neuropathy. South. Med. J. **106**(10), 565–569 (2013). https://doi.org/10.1097/SMJ.0000000000000009

12. Cohen, H.S., Stitz, J., Sangi-Haghpeykar, H., Williams, S.P., Mulavara, A.P., Peters, B.T., Bloomberg, J.J.: Tandem walking as a quick screening test for vestibular disorders. Laryngoscope **128**(7), 1687–1691 (2018). https://doi.org/10.1002/lary.27022
13. Dozza, M., Wall Iii, C., Peterka, R.J., Chiari, L., Horak, F.B.: Effects of practicing tandem gait with and without vibrotactile biofeedback in subjects with unilateral vestibular loss. J. Vestib. Res. **17**(4), 195–204 (2007)
14. Kheradmand, A., Zee, D.S.: Cerebellum and ocular motor control. Front. Neurol. **2**, 53 (2011). https://doi.org/10.3389/fneur.2011.00053
15. Beh, S.C., Frohman, T.C., Frohman, E.M., Biousse, V., Galetta, S.: Cerebellar control of eye movements. J. Neuroophthalmol. **37**(1), 87–98 (2017). https://doi.org/10.1097/WNO.0000000000000456
16. Shurupova, M.A., Kasatkin, V.N., Anisimov, V.N., Latanov, A.V.: Influence of surgery-related cerebellar dysfunction on the saccadic system performance in children. Russ. J. Physiol. **106**(7), 866–879 (2020). https://doi.org/10.31857/S0869813920070079
17. Matthis, J.S., Barton, S.L., Fajen, B.R.: The biomechanics of walking shape the use of visual information during locomotion over complex terrain. J. Vis. **15**(3), 10 (2015). https://doi.org/10.1167/15.3.10
18. Nemanich, S.T., Earhart, G.M.: Freezing of gait is associated with increased saccade latency and variability in Parkinson's disease. Clin Neurophysiol. **127**, 2394–2401 (2016). https://doi.org/10.1016/j.clinph.2016.03.017
19. Marple-Horvat, D.E., Crowdy, K.A.: Direct visualisation of gaze and hypometric saccades in cerebellar patients during visually guided stepping. Gait Posture **21**, 39–47 (2005)
20. Stuart, S., Galna, B., Delicato, L.S., Lord, S., Rochester, L.: Direct and indirect effects of attention and visual function on gait impairment in Parkinson's disease: influence of task and turning. Eur. J. Neurosci. **46**(1), 1703–1716 (2017). https://doi.org/10.1111/ejn.13589
21. Kornienko, V.N., Pronin, I.N.: Diagnostic Neuroradiology. Springer, Heidelberg (2009). https://doi.org/10.1007/978-3-540-75653-8
22. Deitz, J.C., Kartin, D., Kopp, K.: Review of the Bruininks-Oseretsky test of motor proficiency, (BOT-2). Phys. Occup. Ther. Pediatr. **27**(4), 87–102 (2007). https://doi.org/10.1080/J006v27n04_06
23. Orzechowski, C.: De l'ataxie dysmétrique des yeux: Remarques sur l'ataxie des yeux dite myoclonique (opsoclonie, opsochorie). J. Psychol. Neurol. **35**, 1–8 (1927)

Histone Deacetylase Inhibitor Prevents Memory Impairment by Methiothepin

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Abstract. The role of histone acetylation in memory reinstatement after its disruption by antimnemonic drugs has been shown recently. It is known that a normally functioning serotonergic system is required for successful reconsolidation of context memory in terrestrial snails Helix lucorum. In the present study, using the nonselective antagonist of serotonergic receptors methiothepin and the histone deacetylase (HDAC) inhibitor sodium butyrate, we studied the role of histone acetylation in the maintenance and restoration of context memory after its impairment with methiothepin. The results obtained clearly demonstrate that memory impaired by methiothepin during reconsolidation is not restored later under conditions of an increased level of histone acetylation due to administration of sodium butyrate, both with weak memory reactivation (reminder of context) and with strong memory reactivation (electric shock). However, simultaneous administration of HDAC inhibitor sodium butyrate and a blocker of serotonin receptors methiothepin under conditions of memory reactivation prevented the impairment of context memory. The data obtained demonstrated that histone acetylation is a regulatory component for memory maintenance and reconsolidation.

Keywords: Sodium butyrate · Context memory · Histone acetylation · Methiothepin · Epigenetics

Abbreviations

5-HT	Serotonin
HDAC	Histone deacetylase
MET	Methiothepin
NaB	Sodium butyrate
PKMζ	Protein-kinase Mζ
ZIP	Zeta Inhibitory Peptide

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1 Introduction

To date, a large amount of experimental material demonstrated connection between the effects of serotonin (5-HT) in the nervous system of mollusks and the ability to learn [1–5]. It was shown that disruption of serotonergic system using the neurotoxin 5,7-dihydroxytryptamine or P-Chlorphenylanine during reminder leads to a weakening of the consolidated memory [6, 7]. It was also found that serotonergic reinforcing neurons change their activity during learning [6]. There are now several demonstrations that chromatin modifying mechanisms such as histone acetylation may underlie following memory processes: consolidation, reconsolidation, and extinction [8–18]. Numerous studies demonstrated that histone deacetylases (HDAC) inhibitors are able to rescue memory deficits [8, 13, 19, 20] and reinstate previously impaired memory [21–23]. In addition, it was established that increased serotonin concentration after serotonin precursor 5-hydroxytryptophan administration can reinstate the impaired context memory [24].

An increasing array of findings supports the connection of serotonin-histone regulation of physiological and behavioral responses. Recently, it was shown that a broad-spectrum HDAC inhibitor, trichostatin A, enhances the function of 5-HT neurons in organotypic raphe slice cultures [25]. Detailed analysis performed in this study showed that inhibition of HDACs increases the 5-HT synthesis and release by epigenetic mechanisms, and that the 5-HT release is mediated by the enhancement of AMPAR-mediated excitatory inputs and CaMKII signaling [25]. Activation of the 5-HT2A receptor by the endogenous serotonin repressed the promoter activity of the histone deacetylase 2 gene in mouse [26]. The link between serotonin and histone acetylation was demonstrated in *Aplysia* californica: administration of serotonin providing long-term facilitation of synaptic strength increased the acetylation of histone H3K14 and histone H4K8 [27]. Moreover, authors explored chromatin structure in Aplysia neuronal cultures in the context of learning-related synaptic plasticity. Chromatin immunoprecipitation assays showed that serotonin induced the downstream gene C/EBP by activating CREB1, which recruits CBP for histone acetylation [1, 27]. Another mechanism underlying serotonin-histone relations may be histone serotonylation. The ability of serotonin to covalently bind to its protein targets inside the cell was described in 2003 [28]. This protein modification is catalyzed by the enzyme transglutaminase 2. It has been shown that stimulation of serotonergic receptors through the G protein, leading to the activation of phospholipase C, the production of IP3 and the release of calcium from the endoplasmic reticulum, regulates the activity of the enzyme transglutaminase 2 and stimulates serotonylation [29, 30]. Recently, an article was published in which it was shown that in the nucleus serotonin covalently binds to histone H3 via transglutaminase 2 [31].

Given the importance of serotonin role, histone acetylation in different memory processes, and their ability to affect each other functioning, here we examined the regulatory role of histone acetylation in reinstatement and maintenance of context memory impaired with nonselective antagonist of serotonergic receptors methiothepin. The results obtained clearly demonstrate that memory impaired by methiothepin during reconsolidation is not later restored under conditions of an increased level of histone acetylation upon administration of sodium butyrate, both with weak memory reactivation (with reminder) and with strong memory reactivation (with electric shock). However, the simultaneous administration of histone deacetylase inhibitor sodium butyrate and a blocker of serotonin receptors methiothepin under conditions of memory reactivation prevents the weakening of context memory in mollusks. The effects of HDAC involvement in regulation of the serotonin system are clearly demonstrated.

2 Materials and Methods

2.1 Animals

Experiments were carried out in adult *Helix lucorum taurica* L. All animals for these experiments were comparable in weight (15g ± 5). The snails were kept in a wet environment and fed with carrots. Three to 5 days before training sessions, the experimental animals were deprived of food in order to keep them in active state of food-searching. The experimental procedures were in compliance with the Guide for the Care and Use of Laboratory Animals published by the National Institute of Health, and the protocol was approved by the Ethical Committee of the Institute of Higher Nervous Activity and Neurophysiology RAS. All behavioral test sessions were performed between the hours of 08:00 and 15:00h, animals were randomly assigned to treatment conditions and blind-tested in counterbalanced order.

2.2 Behavioral Experiments: Context Conditioning Paradigm

Behavioral experiments were conducted as described in our previous behavioral studies of context conditioning [32]. We used two different contexts, in one of which (a ball floating in water – context 1, Fig. 1a) the animals were shocked, while the second context (flat glass – context 2, Fig. 1b) was used as a control context, in which the animals did not receive shocks. Thus, differences in the responses of animals to the test tactile stimuli in two contexts indicated the presence of context memory. In context 1, the snails were tethered by their shell in a manner allowing them to crawl on a ball that rotated freely in water containing 0.01% NaCl. The ball was covered with aluminum foil to complete an electrical circuit between the animal's foot and a carbon electrode placed in the water. Electric shocks were delivered using 1 to 4mA, 1sec current through a macroelectrode applied to the dorsal surface of the snail's foot. Behavioral responsiveness was tested in both contexts using a tactile stimulation with calibrated hairs 0.2 mm tip diameter with pressure 25 gr/mm^2.

The amplitude of ommathophores (posterior tentacles) withdrawal in response to the moderate intensity tactile stimulation of the head skin 4–5 mm behind the posterior tentacles normally was 5–15% of the maximal withdrawal in untrained animals. To quantify and average the results, we video-recorded all responses, analyzed the distance between tip and base of the tentacle off-line for each trial, and scored the withdrawal amplitude as a percentage of the pre-stimulus length of the tentacle in each trial.

Before training, each snail was exposed to the experimental setup for 30 min daily for two days. Then the first test session (T0) was performed for all groups. Blind testing was performed for each snail in two randomly alternating contexts. After obtaining the pre-training scores, each group of snails received at least two electrical shocks per day with 20–30 min intervals for 10 days in Context 1 alone. No testing was performed during the training sessions. One day of rest after completion of the training session was given; animals were allowed to feed during the rest periods in terrarium. The order in which the animals were tested in each context was randomized. To reduce possible effects of recent handling, the test was administered no sooner than 5 min after the subjects were placed in the environment. Only actively moving animals were tested, because an animal in the inactive state (passively attached to the ball, no locomotion, with partial retraction of tentacles) may demonstrate an inadequate response to tactile stimulation.

The first group of experiments was devoted to finding out whether sodium butyrate is able to reinstate long-term context memory after its disruption with serotonergic receptor antagonist methiothepin. 24 h after the second test session (T1) (for details see a protocol on Fig. 2a) the snails were injected with methiothepin (groups G2-G4) or vehicle (sterile Ringer saline; group G1). Next day the third test session (T2) was carried out for all groups. Twenty-four hours later the snails were injected with vehicle (groups G1, G2) or sodium butyrate (group G3) with memory reactivation (20 min on a ball = reminder). Group G4 was injected with sodium butyrate and then once shocked on a ball. Next day the fourth test session (T3) was carried out for parallel groups with testing in two different contexts without any drug injections.

The second group of experiments was devoted to finding out whether the simultaneous blockade of serotonergic receptors with methiothepin and histone deacetylases with sodium butyrate would prevent the disruption of long-term context memory. 24 h after the second test session (T1), all groups G1-G3 were reminded of training by placing for 20 min in the same context where they were previously shocked (Context 1) and then immediately injected with vehicle (G1), methiothepin (G2), sodium butyrate and methiothepin (G3). Next day snails were tested (the third test session, T2).

2.3 Drugs and Injections

Methiothepin (MET) (Sigma, St. Louis, USA), 5 μg/g of body weight was dissolved in a sterile Ringer saline (in mM: 100 NaCl, 4 KCl, 7 $CaCl_2$, 5 $MgCl_2$, and 10 Tris-HCl buffer (pH 7.8)). Sodium butyrate (NaB) (Sigma, St. Louis, USA) at a final dosage 4.8 μg/g of body weight was dissolved in sterile saline. Estimated final concentration in the hemolymph of free behaving animals of methiothepin was $1.4\text{x}10^{-5}$M, sodium butyrate - $4.4\text{x}10^{-5}$M. These concentrations are required to produce the effects of chosen chemical substances. Control animals received an injection of the same volume of vehicle (sterile Ringer saline). 0.1 ml of the drug solutions were injected into the hemocoel of the animal. The specific timing at which the intracoelomic injections were made is indicated in the protocols. Intracoelomic injections were performed in an actively moving animals with a fine needle inserted in the low-sensitive part of the foot skin normally hidden under the shell.

2.4 Data Analysis

All data are presented as the mean ± S.E.M. Additionally, each scored value is shown as a dot at each figure. Statistical analyses were performed using StatSoft Statistica version

10. The data were analyzed using two-way ANOVA with one repeated measure (test), followed by post-hoc comparisons using Bonferroni test. Significance was set at $p < 0.05$.

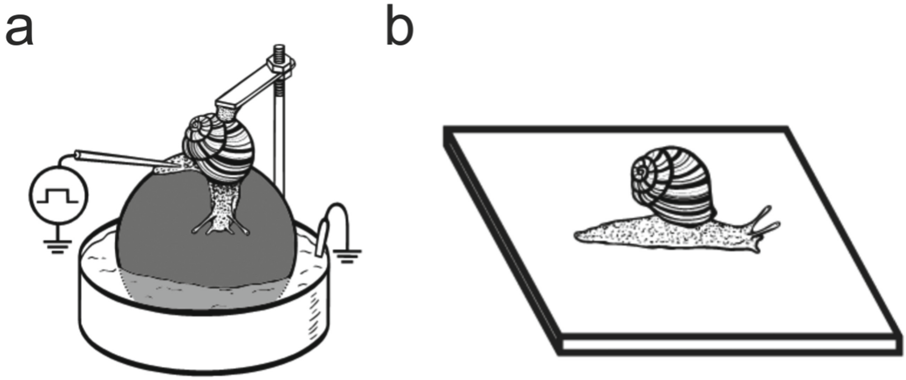

Fig. 1. Schematic representation of two contexts in behavioral experiments: a - context 1 (ball), b - context 2 (flat glass).

3 Results

In the first series of experiments, we tested whether the histone deacetylase inhibitor sodium butyrate would restore context memory impaired due to blockade of the serotonergic system with methiothepin during reconsolidation. After training, all groups of snails demonstrated a significant increase in the amplitude of tentacle contraction on ball (Fig. 2a, T1, G1, $n = 10$, 62.6 ± 6.6%, G2, $n = 5$, 76.8 ± 7.1%, G3, $n = 12$, 61.3 ± 3.7%, G4, $n = 7$, 68.7 ± 6.3%) relative to responses on flat glass (Fig. 2a, T1, G1, 5.3 ± 1.1%, G2, 7.6 ± 2.1%, G3, 7.6 ± 1.2%, G4, 6.9 ± 0.3%, $F_{1,60} = 368.4$, $p < 0.001$, context effect). The day after T1 testing session, groups G2, G3, G4 were injected with methiothepin immediately after being reminded (20 min on a ball without exposure to electric shock). Group G1, which served as a control, was injected with Ringer saline (see protocol on Fig. 2a). Testing next day (T2) showed that the methiothepin administration significantly worsened the context memory in groups G2-G4 (Fig. 2a, T2, ball reaction, G2, 9.2 ± 1.4%, G3, 8.9 ± 2.6%, G4, 11.5 ± 4.3%) compared with the control group G1 (67.3 ± 4.4%) (group effect: $F_{3,60} = 13.719$, $p < 0.001$). The next day, groups G1-G2 were injected with Ringer saline followed by a reminder; group G3 was reminded immediately after sodium butyrate injection; group G4 received a single training session (shock on a ball) immediately after sodium butyrate injection. When tested 24 h after drug administration (Fig. 2a, test T3), ANOVA revealed a significant main effect of the group (T3, $F_{3,60} = 181.77$, $p < 0.001$). Post-hoc comparisons showed that the percentage of tentacles contraction on the ball of groups G2 (6.4 ± 1.3%), G3 (6.6 ± 1.5%), and G4 (12.9 ± 2%) did not differ in the test session T3 ($p > 0.05$). The control group G1 showed a significantly bigger response of the tentacle contraction on the ball (70.2 ± 3.1%) compared to the groups G3 ($p < 0.0001$) and G4 ($p < 0.0001$), which received sodium butyrate injections during memory reactivation. In addition, the withdrawal responses of the G2-G4 groups did not differ on the ball and on the flat glass ($p > 0.05$). The results obtained clearly demonstrate that memory impaired by methiothepin during reconsolidation is not restored under conditions of increased histone acetylation due to administration of sodium butyrate, both with weak memory reactivation (with reminder) and with strong memory reactivation (with electric shock).

In the second series of experiments, we investigated whether the increased histone acetylation due to administration of sodium butyrate would prevent the disruption of long-term memory by methiothepin during reactivation. We injected methiothepin and sodium butyrate simultaneously after memory reactivation (see the protocol on Fig. 2b), not sequentially with 48 h interval as in the previous experiment (see the protocol on Fig. 2a). After training, all groups of snails demonstrated a significant increase in the reaction of the tentacle contraction on ball (Fig. 2b, T1, G1, $n = 7$, 66.6 ± 6.3%, G2, $n = 5$, 75.5 ± 8.3%, G3, $n = 8$, 72.3 ± 5.8%) relative to flat glass (Fig. 2b, T1, G1, 5.1 ± 1.4%, G2, 6.6 ± 0.5%, G3, 7, 5 ± 0.6%, $F_{1,34} = 296.9$, $p < 0.001$, context effect). The day after T1 testing session, group G1 was injected with Ringer saline immediately after the reminder (20 min on a ball without shock), group G2 was injected with methiothepin immediately after the reminder, group G3 was injected with methiothepin and sodium butyrate simultaneously and immediately after the reminder. When tested 24 h after drug administration (T2 test), ANOVA revealed a significant main group effect (Fig. 2b, T2, $F_{2,34} = 9.9378$, $p < 0.001$). Post-hoc comparisons showed that the percentage of tentacle contraction on the ball of G2 group (13.4 ± 3.8%) with methiothepin was significantly lower than that in the control animals receiving saline (G1, 69.3 ± 6.6%) ($p < 0.0001$) and animals of G3 group (70.5 ± 5.6%; $p < 0.0001$) with simultaneous administration of methiothepin and sodium butyrate. Post-hoc analysis did not reveal any differences between withdrawal reactions on the ball of G1 and G3 groups. In addition, the withdrawal responses of G2 group did not differ on the ball and on the flat glass ($p > 0.05$) while the withdrawal responses of G3 group were significantly different. Thus, we have shown that memory reactivation under blockade of serotonergic system with methiothepin led to a significant decrease in the tentacle contraction response in mollusks, while administration of the histone deacetylase inhibitor sodium butyrate during memory reactivation under blockade of serotonergic system prevented weakening of the context memory.

4 Discussion

To date, most studies on histone acetylation have focused on the function of histone acetylation in acquisition, reconsolidation, and extinction of long-term memory [8–18]. Here, we examined the role of histone acetylation in memory impairment and reinstatement in snails. Consistent with a previous study in mollusks [6], we revealed that the reinforcing serotonin neurotransmitter system is necessary for successful repeated reconsolidation of context memory in terrestrial snails *Helix lucorum* (Fig. 2a, 2b): methiothepin injections immediately after a reminder disrupted the context memory. These data are also consistent with earlier studies, where it was shown that methiothepin disrupts acquisition of both sensitization of defensive reaction in snails [33] and

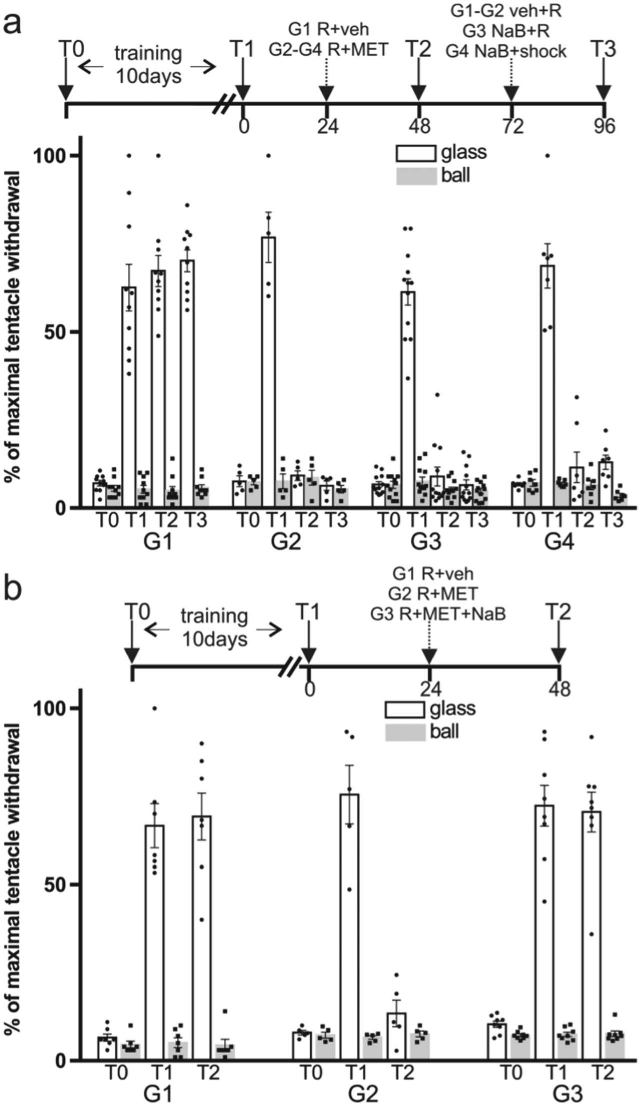

Fig. 2. Averaged data on the effects of the histone deacetylase inhibitor sodium butyrate (NaB) on the maintenance and impairment of context memory. a. The context memory impaired due to the methiothepin injection was not restored under conditions of increased histone acetylation, both after weak memory reactivation (R, reminder) and after strong memory reactivation (with electric shock). b. The administration of methiothepin simultaneously with sodium butyrate and reminding prevented weakening of the conditioned reflex response. Data are presented as mean ± S.E.M.

consolidation of associative reflexes [34]. Retrieval of methiothepin-impaired context memory followed by the HDAC inhibitor sodium butyrate administration did not induce significant strengthening of impaired memory trace (Fig. 2a, G3, G4). At the same time, we showed that the amnesic effect of methiothepin inhibition can be rescued by enhancing histone acetylation level with sodium butyrate if methiothepin and sodium butyrate applied together (Fig. 2b, G3). These results are consistent with literature data on the ability of histone deacetylase inhibitors to prevent various amnestic effects. For example, it has been reported that inhibition of protein-kinase Mζ (PKMζ) erases different types of memories in different species [32, 35–41]. Ko with colleagues [22] demonstrated that enhanced histone acetylation levels can rescue memory erasure induced by PKMζ inhibition: when sodium butyrate was co-infused with PKMζ inhibitor Zeta Inhibitory Peptide (ZIP), memory impairment was not observed. It is necessary to stress that sodium butyrate did not enhance in our experiments the withdrawal reactions in the safe context (glass), in other words, the responsivity to the tactile stimuli in the non-reinforced context was not changed. So we can conclude that sodium butyrate effects were absolutely specific for the memory. These findings demonstrate that the HDAC inhibitor sodium butyrate by itself does not affect the basal synaptic functions, what is consistent with the literature [8, 15, 21, 42].

Obtained results suggest that the serotonergic system participate in maintenance of memory upon reactivation, and possibly via its role in histone acetylation. Previously it was shown in *Aplysia californica* that administration of serotonin providing long-term facilitation of synaptic strength increased the acetylation of histone H3K14 and histone H4K8 [27]. Moreover, chromatin immunoprecipitation assays showed that serotonin by activating the transcription factor CREB1 induced the downstream gene C/EBP, which recruits CBP for histone acetylation [1, 27]. Results obtained in our experiments can be regarded at least partly as effects of serotonin on epigenetic regulation. Increased histone acetylation at memory formation was also reported in a number of other studies [15, 43–45]. In the current study, memory erasure through methiothepin was rescued by enhancing histone acetylation levels. Based on these data we can propose a hypothesis that serotonin after a reminder (or behavioral training) upregulates the histone acetylation level. When we block serotonergic receptors with methiothepin, serotonin cannot bind with its receptors and the upregulation of histone acetylation does not happen. When we apply the HDAC inhibitor sodium butyrate, we mimic the serotonin effects on histone acetylation.

The changes in histone acetylation that accompany a reminder procedure may occur rapidly as it happens at learning [15]. When we block serotonergic receptors with methiothepin while increasing histone acetylation by the HDAC inhibitor sodium butyrate during reminding, we mimic the serotonin effect on histone acetylation and thus we manage to maintain the existing memory. Methiothepin administration without sodium butyrate during reminding does not lead to increased histone acetylation. It is known that increased histone acetylation is associated with transcription of memory-related genes that is necessary for changes in synaptic plasticity [17, 46–49]. As transcription of reconsolidation-related genes does not occur properly under methiothepin exposure, the reminding procedure causes memory impairment. Subsequent administration of the HDAC inhibitor sodium butyrate does not rescue the impaired memory, suggesting that memory was damaged drastically, as the result the memory trace does not persist or it is too weak after serotonergic system blockade. Thus, histone acetylation-mediated neuroplasticity is not sufficient for rescue of remote memories impaired by methiothepin.

The latter fact is of important difference from our earlier data [23]. We showed that the HDAC inhibitors sodium butyrate and trichostatin A reinstated the memory impaired during reconsolidation under protein synthesis blockade or "memory molecules" (PKMζ) blockade with peptide inhibitor ZIP. Trichostatin A was also used by Chen with colleagues [21] who showed that memory can be reinstated with the inhibitor of HDAC following inhibition of protein-kinase Mζ and impairment of the memory. It is most likely that sodium butyrate and trichostatin A-mediated memory reinstatement occurred due to the presence of the "priming trace" [50], remained after memory disruption [21, 23]. Probably, in the current study, such trace did not exist or was too weak after methiothepin administration during reconsolidation and that is why the HDAC inhibitor sodium butyrate had no effect.

Overall, the data obtained has provided evidence that histone acetylation plays a crucial role in memory processes. Despite the fact that HDAC inhibitors have a powerful effect on histone acetylation, these inhibitors are not always able to affect memory. Our findings provide new insights into understanding of the physiological mechanisms of memory reinstatement by providing a link between epigenetic mechanisms such as histone acetylation and serotonergic system.

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Competing Interests.. The authors declare that they have no conflict of interest.

Author Contributions. The authors contributed equally. All authors read and approved the final manuscript.

Ethical Approval: All applicable international, national, and/or institutional guidelines for the care and use of animals were followed. All procedures performed in studies involving snails were in accordance with the ethical standards and approved (#011 from 10.10.2019) by Ethical Committee of the Institute of Higher Nervous Activity and Neurophysiology of Russian Academy of Sciences.

References

1. Alberini, C.M., Kandel, E.R.: The regulation of transcription in memory consolidation. Cold Spring Harb. Perspect. Biol. **7**, a021741 (2014). https://doi.org/10.1101/cshperspect.a021741
2. Balaban, P.M., Vehovszky, A., Maximova, O.A., Zakharov, I.S.: Effect of 5,7-dihydroxytryptamine on the food-aversive conditioning in the snail Helix Lucorum L. Brain Res. **404**, 201–210 (1987). https://doi.org/10.1016/0006-8993(87)91371-0
3. Balaban, P., Bravarenko, N.: Long-term sensitization and environmental conditioning in terrestrial snails. Exp. Brain Res. **96**, 487–493 (1993). https://doi.org/10.1007/BF00234116
4. Balaban, P.M.: Cellular mechanisms of behavioral plasticity in terrestrial snail. Neurosci. Biobehav. Rev. **26**, 597–630 (2002). https://doi.org/10.1016/s0149-7634(02)00022-2
5. Kandel, E.R., Schwartz, J.H.: Molecular biology of an elementary form of learning: modulation of transmitter release by cuclic AMP. Science **218**, 433–443 (1982). https://doi.org/10.1126/science.6289442

6. Balaban, P.M., Vinarskaya, A.K., Zuzina, A.B., Ierusalimsky, V.N., Malyshev, A.Y.: Impairment of the serotonergic neurons underlying reinforcement elicits extinction of the repeatedly reactivated context memory. Sci. Rep. **6**, 36933 (2016). https://doi.org/10.1038/srep36933
7. Deryabina, I.B., Muranova, L.N., Andrianov, V.V., Gainutdinov, K.L.: Impairing of serotonin synthesis by P-chlorphenylanine prevents the forgetting of contextual memory after reminder and the protein synthesis inhibition. Front. Pharmacol. **9**, 607 (2018). https://doi.org/10.3389/fphar.2018.00607
8. Alarcón, J.M., Malleret, G., Touzani, K., Vronskaya, S., Ishii, S., Kandel, E.R., Barco, A.: Chromatin acetylation, memory, and LTP are impaired in CBP+/− mice: a model for the cognitive deficit in Rubinstein-Taybi syndrome and its amelioration. Neuron **42**, 947–959 (2004). https://doi.org/10.1016/j.neuron.2004.05.021
9. Bredy, T.W., Wu, H., Crego, C., Zellhoefer, J., Sun, Y.E., Barad, M.: Histone modifications around individual BDNF gene promoters in prefrontal cortex are associated with extinction of conditioned fear. Learn. Mem. **14**, 268–276 (2007). https://doi.org/10.1101/lm.500907
10. Bredy, T.W., Barad, M.: The histone deacetylase inhibitor valproic acid enhances acquisition, extinction, and reconsolidation of conditioned fear. Learn. Mem. **15**, 39–45 (2008). https://doi.org/10.1101/lm.801108
11. Hemstedt, T.J., Lattal, K.M., Wood, M.A.: Reconsolidation and extinction: Using epigenetic signatures to challenge conventional wisdom. Neurobiol. Learn. Mem. **142**, 55–65 (2017). https://doi.org/10.1016/j.nlm.2017.01.007
12. Itzhak, Y., Anderson, K.L., Kelley, J.B., Petkov, M.: Histone acetylation rescues contextual fear conditioning in nNOS KO mice and accelerates extinction of cued fear conditioning in wild type mice. Neurobiol. Learn. Mem. **97**, 409–417 (2012). https://doi.org/10.1016/j.nlm.2012.03.005
13. Korzus, E., Rosenfeld, M.G., Mayford, M.: CBP histone acetyltransferase activity is a critical component of memory consolidation. Neuron **42**, 961–972 (2004). https://doi.org/10.1016/j.neuron.2004.06.002
14. Lattal, K.M., Barrett, R.M., Wood, M.A.: Systemic or intrahippocampal delivery of histone deacetylase inhibitors facilitates fear extinction. Behav. Neurosci. **121**, 1125–1131 (2007). https://doi.org/10.1037/0735-7044.121.5.1125
15. Levenson, J.M., O'Riordan, K.J., Brown, K.D., Trinh, M.A., Molfese, D.L., Sweatt, J.D.: Regulation of histone acetylation during memory formation in the hippocampus. J. Biol. Chem. **279**, 40545–40559 (2004). https://doi.org/10.1074/jbc.M402229200
16. Si, J., Yang, J., Xue, L., Yang, C., Luo, Y., Shi, H., Lu, L.: Activation of NF-κB in basolateral amygdala is required for memory reconsolidation in auditory fear conditioning. PLoS ONE **7**, e43973 (2012). https://doi.org/10.1371/journal.pone.0043973
17. Vecsey, C.G., Hawk, J.D., Lattal, K.M., Stein, J.M., Fabian, S.A., Attner, M.A., Cabrera, S.M., McDonough, C.B., Brindle, P.K., Abel, T., Wood, M.A.: Histone deacetylase inhibitors enhance memory and synaptic plasticity via CREB:CBP-dependent transcriptional activation. J. Neurosci. **27**, 6128–6140 (2007). https://doi.org/10.1523/JNEUROSCI.0296-07.2007
18. Villain, H., Florian, C., Roullet, P.: HDAC inhibition promotes both initial consolidation and reconsolidation of spatial memory in mice. Sci. Rep. **6**, 27015 (2016). https://doi.org/10.1038/srep27015
19. Barichello, T., Generoso, J.S., Simões, L.R., Faller, C.J., Ceretta, R.A., Petronilho, F., Lopes-Borges, J., Valvassori, S.S., Quevedo, J.: Sodium butyrate prevents memory impairment by re-establishing BDNF and GDNF expression in experimental pneumococcal meningitis. Mol. Neurobiol. **52**, 734–740 (2015). https://doi.org/10.1007/s12035-014-8914-3
20. Hu, Y.T., Tang, C.K., Wu, C.P., Wu, P.C., Yang, E.C., Tai, C.C., Wu, Y.L.: Histone deacetylase inhibitor treatment restores memory-related gene expression and learning ability in neonicotinoid-treated Apis Mellifera. Insect Mol. Boil. **27**, 512–521 (2018). https://doi.org/10.1111/imb.12390

21. Chen, S., Cai, D., Pearce, K., Sun, P.Y., Roberts, A.C., Glanzman, D.L.: Reinstatement of long-term memory following erasure of its behavioral and synaptic expression in Aplysia. ELife. **3**, e03896 (2014). https://doi.org/10.7554/eLife.03896
22. Ko, H.G., Kim, J.I., Sim, S.E., Kim, T., Yoo, J., Choi, S.L., Baek, S.H., Yu, W.J., Yoon, J.B., Sacktor, T.C., Kaang, B.K.: The role of nuclear PKMζ in memory maintenance. Neurobiol. Learn. Mem. **135**, 50–56 (2016). https://doi.org/10.1016/j.nlm.2016.06.010
23. Zuzina, A.B., Vinarskaya, A.K., Balaban, P.M.: Histone deacetylase inhibitors rescue the impaired memory in terrestrial snails. J. Comp. Physiol. A Neuroethol. Sens. Neural Behav. Physiol. **206**, 639–649 (2020). doi: https://doi.org/10.1007/s00359-020-01422-w
24. Zuzina, A.B., Vinarskaya, A.K., Balaban, P.M.: Increase in serotonin precursor levels reinstates the context memory during reconsolidation. Invert. Neurosci. **19**, 8 (2019). https://doi.org/10.1007/s10158-019-0227-9
25. Asaoka, N., Nagayasu, K., Nishitani, N., Yamashiro, M., Shirakawa, H., Nakagawa, T., Kaneko, S.: Inhibition of histone deacetylases enhances the function of serotoninergic neurons in organotypic raphe slice cultures. Neurosci. Lett. **593**, 72–77 (2015). https://doi.org/10.1016/j.neulet.2015.03.028
26. Holloway, T., González-Maeso, J.: Epigenetic mechanisms of serotonin signaling. ACS Chem. Neurosci. **6**, 1099–1109 (2015). https://doi.org/10.1021/acschemneuro.5b00033
27. Guan, Z., Giustetto, M., Lomvardas, S., Kim, J.H., Miniaci, M.C., Schwartz, J.H., Thanos, D., Kandel, E.R.: Integration of long-term-memory-related synaptic plasticity involves bidirectional regulation of gene expression and chromatin structure. Cell **111**, 483–493 (2002). https://doi.org/10.1016/s0092-8674(02)01074-7
28. Walther, D.J., Peter, J.U., Winter, S., Holtje, M., Paulmann, N., Grohmann, M., Vowinckel, J., Alamo-Bethencourt, V., Wilhelm, C.S., Ahnert-Hilger, G., Bader, M.: Serotonylation of small GTPases is a signal transduction pathway that triggers platelet α-granule release. Cell **115**, 851–862 (2003). https://doi.org/10.1016/s0092-8674(03)01014-6
29. Dai, Y., Dudek, N.L., Patel, T.B., Muma, N.A.: Transglutaminase-catalyzed transamidation: a novel mechanism for Rac1 activation by 5-hydroxytryptamine 2A receptor stimulation. J. Pharmacol. Exp. Ther. **326**, 153–162 (2008). https://doi.org/10.1124/jpet.107.135046
30. Dai, Y., Dudek, N.L., Li, Q., Muma, N.A.: Phospholipase C, Ca2+, and calmodulin signaling are required for 5-HT2A receptor-mediated transamidation of Rac1by transglutaminase. Psychopharmacology **213**, 403–412 (2011). https://doi.org/10.1007/s00213-010-1984-7
31. Farrelly, L.A., Thompson, R.E., Zhao, S., Lepack, A.E., Lyu, Y., Bhanu, N.V., Zhang, B., Loh, Y.-H.E., Ramakrishnan, A., Vadodaria, K.C., Heard, K.J., Erikson, G., Nakadai, T., Bastle, R.M., Lukasak, B.J., Zebroski, H., 3rd., Alenina, N., Bader, M., Berton, O., Roeder, R.G., Molina, H., Gage, F.H., Shen, L., Garcia, B.A., Li, H., Muir, T.W., Maze, I.: Histone serotonylation is a permissive modification that enhances TFIID binding to H3K4me. Nature **567**, 535–539 (2019). https://doi.org/10.1038/s41586-019-1024-7
32. Balaban, P.M., Roshchin, M., Timoshenko, A., Zuzina, A.B., Lemak, M., Ierusalimsky, V.N., Aseyev, N.A., Malyshev, A.Y.: Homolog of protein kinase Mzeta maintains context aversive memory and underlying long-term facilitation in terrestrial snail Helix. Front. Cell. Neurosci. **9**, 222 (2015). https://doi.org/10.3389/fncel.2015.00222
33. Abramova, M.S., Nistratova, V.L., Moskvitin, A.A., Pivovarov, A.S.: Methiothepin-sensitive serotonin receptors are involved in the postsynaptic mechanism of sensitization of the defensive response in the common snail. Neurosci. Behav. Physiol. **36**, 589–596 (2006). https://doi.org/10.1007/s11055-006-0062-4
34. Solntseva, S.V., Nikitin, V.P.: Neurochemical mechanisms of food aversion conditioning consolidation in snail Helix lucorum. Ross. Fiziol. Zh. Im. I. M. Sechenova. **94**, 1259–1269 (2008)

35. Kwapis, J.L., Jarome, T.J., Lonergan, M.E., Helmstetter, F.J.: Protein kinase Mzeta maintains fear memory in the amygdala but not in the hippocampus. Behav. Neurosci. **123**, 844–850 (2009). https://doi.org/10.1037/a0016343
36. Kwapis, J.L., Jarome, T.J., Gilmartin, M.R., Helmstetter, F.J.: Intra-amygdala infusion of the protein kinase Mzeta inhibitor ZIP disrupts foreground context fear memory. Neurobiol. Learn. Mem. **98**, 148–153 (2012). https://doi.org/10.1016/j.nlm.2012.05.003
37. Migues, P.V., Hardt, O., Wu, D.C., Gamache, K., Sacktor, T.C., Wang, Y.T., Nader, K.: PKMzeta maintains memories by regulating GluR2-dependent AMPA receptor trafficking. Nat. Neurosci. **13**, 630–634 (2010). https://doi.org/10.1038/nn.2531
38. Pastalkova, E., Serrano, P., Pinkhasova, D., Wallace, E., Fenton, A.A., Sacktor, T.C.: Storage of spatial information by the maintenance mechanism of LTP. Science **313**, 1141–1144 (2006). https://doi.org/10.1126/science.1128657
39. Serrano, P., Friedman, E.L., Kenney, J., Taubenfeld, S.M., Zimmerman, J.M., Hanna, J., Alberini, C., Kelley, A.E., Maren, S., Rudy, J.W., Yin, J.C., Sacktor, T.C., Fenton, A.A.: PKMzeta maintains spatial, instrumental, and classically conditioned long-term memories. PLoS Biol. **6**, 2698–2706 (2008). https://doi.org/10.1371/journal.pbio.0060318
40. Shema, R., Sacktor, T.C., Dudai, Y.: Rapid erasure of long-term memory associations in the cortex by an inhibitor of PKM. Science **317**, 951–953 (2007). https://doi.org/10.1126/science.1144334
41. Yao, Y., Kelly, M.T., Sajikumar, S., Serrano, P., Tian, D., Bergold, P.J., Frey, J.U., Sacktor, T.C.: PKM zeta maintains late long-term potentiation by N-ethylmaleimide-sensitive factor/GluR2-dependent trafficking of postsynaptic AMPA receptors. J. Neurosci. **28**, 7820–7827 (2008). https://doi.org/10.1523/JNEUROSCI.0223-08.2008
42. Yeh, S.H., Lin, C.H., Gean, P.W.: Acetylation of nuclear factor-kappaB in rat amygdala improves long-term but not short-term retention of fear memory. Mol. Pharmacol. **65**, 1286–1292 (2004). https://doi.org/10.1124/mol.65.5.1286
43. Bousiges, O., Vasconcelos, A.P., Neidl, R., Cosquer, B., Herbeaux, K., Panteleeva, I., Loeffler, J.P., Cassel, J.C., Boutillier, A.L.: Spatial memory consolidation is associated with induction of several lysine-acetyltransferase (histone acetyltransferase) expression levels and H2B/H4 acetylation-dependent transcriptional events in the rat hippocampus. Neuropsychopharmacology **35**, 2521–2537 (2010). https://doi.org/10.1038/npp.2010.117
44. Mahan, A.L., Mou, L., Shah, N., Hu, J.-H., Worley, P.F., Ressler, K.J.: Epigenetic modulation of Homer1a transcription regulation in amygdala and hippocampus with Pavlovian fear conditioning. J. Neurosci. **32**, 4651–4659 (2012). https://doi.org/10.1523/JNEUROSCI.3308-11.2012
45. Peleg, S., Sananbenesi, F., Zovoilis, A., Burkhardt, S., Bahari-Javan, S., Agis-Balboa, R.C., Cota, P., Wittnam, J.L., Gogol-Doering, A., Opitz, L., Salinas-Riester, G., Dettenhofer, M., Kang, H., Farinelli, L., Chen, W., Fischer, A.: Altered histone acetylation is associated with age-dependent memory impairment in mice. Science **328**, 753–756 (2010). https://doi.org/10.1126/science.1186088
46. Hebbes, T.R., Thorne, A.W., Crane-Robinson, C.: A direct link between core histone acetylation and transcriptionally active chromatin. EMBO J. **7**, 1395–1402 (1988)
47. Brownell, J.E., Allis, C.D.: Special HATs for special occasions: Linking histone acetylation to chromatin assembly and gene activation. Curr. Opin. Genet. Dev. **6**, 176–184 (1996). https://doi.org/10.1016/s0959-437x(96)80048-7
48. Gräff, J., Joseph, N.F., Horn, M.E., Samiei, A., Meng, J., Seo, J., Rei, D., Bero, A.W., Phan, T.X., Wagner, F., Holson, E., Xu, J., Sun, J., Neve, R.L., Mach, R.H., Haggarty, S.J., Tsai, L.H.: Epigenetic priming of memory updating during reconsolidation to attenuate remote fear memories. Cell **156**, 261–276 (2014). https://doi.org/10.1016/j.cell.2013.12.020

49. Levenson, J.M., Sweatt, J.D.: Epigenetic mechanisms in memory formation. Nat. Rev. Neurosci. **6**, 108–118 (2005). https://doi.org/10.1038/nrn1604
50. Pearce, K., Cai, D., Roberts, A.C., Glanzman, D.L.: Role of protein synthesis and DNA methylation in the consolidation and maintenance of long-term memory in Aplysia. Elife. **6**, e18299 (2017). https://doi.org/10.7554/eLife.18299

EEG-Correlates of Neuroinflammation and Neuroplasticity Processes in Patients with Depressive-Delusional Conditions

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Abstract. The processes of neuroinflammation and closely related to them the destructive and reparative processes of neuroplasticity play an important role in the pathogenesis of endogenous mental disorders. Structural damage of nerve cells dendrites, dendritic spines and synapses as well as of neural pathways caused by these processes inevitably disrupts the functioning of the brain neural nets and impairs cognitive functions, and should be reflected in the parameters of the brain electrical activity. However, there are only a few studies of the relationships between the parameters of immunity and EEG in neuropsychiatric disorders. In order to clarify the role of neuroimmunity interaction in pathogenesis of mental pathology a set of pre-treatment clinical, EEG and neuroimmunological parameters was analyzed in 25 female in-patients, aged 20–50, with depressive-delusional conditions. Certain correlations were revealed between values of EEG spectral power, immunological markers of neuroinflammation and neuroplasticity, and quantitative assessments of patients' clinical conditions. The structure of these correlations emphasize the role of demyelination in pathogenesis and EEG pattern in depressive-delusional conditions.

Keyword: Psychiatry · Depressive-delusional conditions · Quantitative EEG · Immunology · Neuroinflammation · Neuroplasticity

1 Introduction

Contemporary data demonstrate the important role of processes of neuroinflammation and closely related to them the destructive and reparative processes of neuroplasticity in pathogenesis of endogenous mental disorders, included depression [1–3] and schizophrenia [4–7]. In particular, it was shown that high enzymatic activity of leukocyte elastase (LE) and activity of its antagonist alpha-1 proteinase inhibitor (a-1_PI) reflect the activity of illness being associated with exacerbation of endogenous mental disorders, while in remission their activity decreased [5, 7, 8]. Appearance and increased levels of autoantibodies (AAB) to neuroantigenes (to common myelin protein – AAB_CMP and to nerve growth factor (protein S100b) – AAB_NGF) in serum reflect the damage of myelinated neural pathways. This is associated with the most severe and highly progredient forms

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of mental disorders caused by non-reversible changes in brain tissue [5]. Structural damage of nerve cells dendrites, dendritic spines and synapses as well as of neural pathways caused by these processes inevitably disrupts the functioning of the brain neural nets and impairs cognitive functions. This should be reflected in the parameters of the brain electrical activity. However, in the literature there are only a few studies of the relationships between the parameters of immunity and EEG in neuropsychiatric disorders [9].

The aim of the study was to identify the relationships between quantitative clinical, EEG, and neuroimmunological parameters to clarify the role of neuro-immune interaction in the pathogenesis of depressive-delusional states.

2 Methods

The study was carried out at the Laboratories of Neurophysiology and Neuroimmunology and the Department of Endogenous Mental Disorders and Affective Conditions of the Mental Health Research Centre (Moscow, Russia). The study followed the principles of biomedical ethics stipulated under the Helsinki Declaration 1964 and its subsequent amendments and approved by the local bioethics committee of the Mental Health Research Centre, Moscow, Russia (#16, Feb 12, 2019). Each patient signed the voluntary written informed consent to participation in the study.

2.1 Patients

The study included 25 female in-patients, aged 20–50 (mean age 36,3 ± 11,4 years old) with depressive-delusional conditions met the criteria of F20.01–02 и F25.1 of the International Classification of Diseases, 10th revision (ICD-10), admitted to clinic of the Mental Health Research Centre. The inclusion criteria were: the patient’s age from 20 to 50 years and the diagnosis of depressive-delusional conditions. Exclusion criteria included the patient’s age under 20 years old and elder than 50 years old, pregnancy or breastfeeding, the presence of signs of organic mental disorders and/or chronic somatic diseases at the stage of decompensation, as well as information about use of psychoactive substances.

The pre-treatment data of quantitative clinical, neurophysiological and immunological examinations of patients were analyzed.

2.2 Clinical Assessments

The depressive signs of patients were rated quantitatively by the Hamilton’s Depression Rating Scale (HDRS-17) [10]. Apart from the total sum of points on the HDRS-17 (HDRS-sum) the statistical analysis of these data took into account the values of the depression symptoms cluster (HDRS-depr), of the anxiety symptoms cluster (HDRS-anx), of the somatic symptoms cluster (HDRS-somat), and of ideation symptoms cluster (HDRS-ideat) of the HDRS-17 were calculated. The depression symptoms cluster (HDRS-depr) is the sum of points on items 1, 2, 3, 7 and 8 of the HDRS-17 scale. The anxiety cluster (HDRS-anx) is the sum of points on items 9, 10 and 11 of the HDRS-17 scale. The somatic symptoms cluster (HDRS-somat) is the sum of points on items

12, 13 and 14 of the HDRS-17 scale. The ideation symptoms cluster (HDRS-ideat) is the sum of points on items 2, 15, 16 and 17) of the HDRS-17 scale. Higher values of scores correspond to more pronounced symptoms.

Psychopathological signs of patients were assessed quantitatively using the Positive and Negative Syndrome Scale (PANSS) for schizophrenia [11] in which higher values of scores correspond to more severe symptoms. Total sum of PANSS scores (PANSS-sum), as well as sums of scores of positive syndromes subscale (PANSS-pos), of negative syndromes subscale (PANSS-neg), and of general psychopathological syndromes subscale (PANSS-gen) were calculated.

2.3 EEG Study

Multichannel recording of the background EEG was acquired before the beginning of the treatment course using a “Neuro-KM” EEG topographic mapping hardware (“Statokin”, Russia) and the “BrainSys” software (“Neurometris”, Russia) [12]. The patient was sitting in a comfortable chair in a state of quiet wakefulness with eyes closed. The monopolar EEGs were recorded from 16 Ag/AgCl electrodes (with impedances below 10 kΩ) positioned according to the International 10–20 system: F7, F3, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1 and O2 EEG leads with ipsilateral ear-lobes references A1 and A2, and ground electrode placed in between Fz and Fpz. EEG was acquired at 35 Hz bandpass, 0.1 time constant, with additional 50 Hz notch filter, and was recorded to computer hard disc at 200 Hz sample rate. Duration of EEG recordings was not less than 3 min. Artifact rejection was performed automatically using the built-in option of “BrainSys” software (at amplitude threshold 4 S.D.). Low-amplitude artifacts from slow eye movements were rejected manually taking into account their specific frontal-occipital amplitude gradient.

Then the Fast Fourier Transform (FFT) based spectral analysis of artifact-free EEG fragments (not less than 30 epochs of 4-s duration) was performed using “BrainSys” software. Absolute spectral power values (in μV^2) were calculated for 8 narrow frequency EEG sub-bands: delta (2–4 Hz), theta1 (4–6 Hz), theta2 (6–8 Hz), alpha1 (8–9 Hz), alpha2 (9–11 Hz), alpha3 (11–13 Hz), beta1 (13–20 Hz), and beta2 (20–30 Hz) from frontal (F3, F4), central (C3, C4), temporal (T3, T4), parietal (P3, P4), and occipital (O1, O2) EEG leads.

2.4 Immunological study.

Peripheral blood samples were taken in each patient on the day of clinical assessment and EEG recording. Four immunological parameters were measured: the enzymatic activity of leucocyte elastase (LE) and activity of its antagonist alpha-1 proteinase inhibitor (a-1-PI) as biomarkers of neuroinflammation, as well as serum levels of autoantibodies to common myelin protein (AAB-CMP) and to nerve growth factor (S100b protein – AAB-NGF) as biomarkers of neuroplasticity processes. The measurements were performed using enzymatic spectrophotometric method (for LE and a-1-PI), and by standard solid-phase Enzyme-Linked ImmunoSorbent Assay (ELISA) method [13] both realized in the frames of “Neuro-Immuno-Test” laboratory technology [14]. Measurements of these immunological parameters are relatively simple and less expensive in comparison with measurements of some other neuroinflammation and neuroplasticity markers (like interleukins).

2.5 Statistics

The relationships between pre-treatment clinical, EEG and immunological parameters were analyzed by the Spearman rank correlation method with Benjamini-Yekutieli corrections for multiple comparisons. When describing the results, only those correlations are presented that are significantly different from zero ($p < 0.05$).

3 Results

LE values correlated positively with the sums of scores of the HDRS-17 clusters of depression (HDRS-depr) and somatic disorders (HDRS-somat), and negatively – with the sum of points of anxiety cluster (HDRS-anx). As well LE values correlated positively with the sums of points of the subscales of positive (PANSS-pos), and with the sum of points of general psychopathological symptoms (PANSS-gen), and with the total score (PANSS-sum) of the PANSS scale. In addition, negative correlations were revealed between LE values and values of EEG spectral power in delta band in both occipital (O1 and O2) and in the left temporal (T3) leads, and values of alpha2 spectral power – in both occipital (O1 and O2), and values of beta1 spectral power – in the central (C3) and temporal (T3) leads of the left hemisphere.

The a1-PI values correlated positively with the sum of points of the HDRS-17 cluster of ideation symptoms (HDRS-ideat), with sum of points of the PANSS-gen and with PANSS-sum, as well as with values of theta2 spectral power in the left frontal (F3) and in the left central (C3) EEG leads.

The AAB-NGF values correlated negatively with the sum of scores of the HDRS-17 anxiety cluster (HDRS-anx), as well as with values of theta2 spectral power in the left frontal lead (F3) and with values of beta1 spectral power in the right temporal lead (T4), and correlated positively – with values of alpha2 spectral power in the left parietal lead (P3).

The largest number of significantly non-zero correlation coefficients were found for the AAT-CMP values. AAT-CMP values correlated positively with the sum of points of the HDRS-17 ideation symptoms cluster (HDRS-ideat), with the sum of points of PANSS-pos and with PANSS-sum. As well it correlated positively with values of delta spectral power in the left temporal lead (T3) and in the left occipital lead (O1), with values of theta1 spectral power in the left temporal lead (T3), with values of alpha1 spectral power in the right occipital lead (O2), with values of alpha2 spectral power in all EEG leads (except of right temporal lead T4), and with values of alpha3 spectral power in both occipital leads (O1 and O2).

4 Discussion

The presence of some correlations between neuroimmunological biomarkers of neuroinflammation (LE and a-1-PI) and neuroplasticity (AAB-CMP and AAB-NGF) and quantitative clinical assessments (by both HDRS-17 and PANSS rating scales), as well EEG spectral power values, confirms the participation of the processes of neuroinflammation and neuroplasticity in the pathogenesis of depressive-delusional conditions.

The structure of the correlations obtained, namely the largest number of significant correlation coefficients between the AAT-CMP values and EEG spectral power in the majority of narrow frequency sub-bands and in almost all EEG leads indicates that damage of the myelinated neural pathways, reflected in the increased values of AAT-CMP, determines the specialties of EEG patterns in patients with depressive-delusional conditions.

5 Conclusions

The data obtained confirm the participation of the processes of neuroinflammation and neuroplasticity in the pathogenesis of depressive-delusional conditions, and emphasize the role of demyelination in clinical manifestations and in the EEG patterns in these mental disorders.

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References:

1. Olie, J.-P., Macher, J.-P., Costa e Silva, J.A. (eds.): Neuroplasticity: A New Approach to the Pathophysiology of Depression. Science Press Ltd, London (2004). ISBN: 13–978–1858738291
2. Maes, M., Yirmyia, R., Noraberg, J., Brene, S., Hibbeln, J., Perini, G., Kubera, M., Bob, P., Lerer, B., Maj, M.: The inflammatory & neurodegenerative (I&ND) hypothesis of depression: leads for future research and new drug developments in depression. Metab Brain Dis **24**, 27–53 (2009). https://doi.org/10.1007/s11011-008-9118-1
3. Serafini, G.: Neuroplasticity and major depression, the role of modern antidepressant drugs. World J. Psychiatry **2**, 49–57 (2012). https://doi.org/10.5498/wjp.v2.i3.49
4. Müller, N., Schwarz, M.J.: Schizophrenia as an inflammation-mediated dysbalance of glutamatergic neurotransmission. Neurotox. Res. **10**, 131–148 (2006). https://doi.org/10.1007/BF03033242
5. Klyushnik, T.P., Zozulya, S.A., Androsova, L.V., et al.: Immunological monitoring of endogenous attack-like psychoses. SS Korsakov's J. Neurol. Psychiatry **114**, 31–35 (2014). (in Russian). https://doi.org/https://doi.org/10.17116/jnevro201411401131
6. Simonov, A.N., Klyushnik, T.P., Zozulya, S.A.: Evidence-based psychiatry: paraclinical diagnosis of asthenic dyndrome in schizophrenia based on the determination of leukocyte-inhibitory index. Psychiatry (Moscow) **18**, 6–12 (2020). (in Russian). https://doi.org/https://doi.org/10.30629/2618-6667-2020-18-2-6-12
7. Fond, G., Lançon, C., Korchia, T., Pascal Auquier, P., Boyer, L.: The role of inflammation in the treatment of schizophrenia. Front Psychiatry **11**, 160–168 (2020). https://doi.org/10.3389/fpsyt.2020.00160
8. Royall, D.R., Al-Rubaye, S., Bishnoi, R., Palmer, R.F.: Serum proteins mediate depression's association with dementia. PLoS ONE **12**, e0175790 (2017). https://doi.org/10.1371/journal.pone.0175790

9. Iznak, A.F., Iznak, E.V., Klyushnik, T.P., Kobel'kov, G.M., Damjanovich, E.V., Oleichik, I.V., Abramova, L.I.: Neurobiological parameters in quantitative prediction of treatment outcome in schizophrenic patients. J. Integr. Neurosci. **17**, 221–228 (2018). https://doi.org/10.3233/JIN-170054
10. Hamilton, M.Y.: A rating scale for depression. J. Neurol. Neurosurg. Psychiatry **23**, 56 (1960). https://doi.org/10.1136/jnnp.23.1.56
11. Kay, S.R., Fiszbein, A., Opler, L.A.: The positive and negative syndrome scale (PANSS) for schizophrenia. Schizophr Bull **13**, 261–276 (1987). https://doi.org/10.1093/schbul/13.2.261
12. Mitrofanov, A.A.: Computerized system for analysis and topographic mapping of brain electrical activity with neurometric EEG data bank (description and use). User's Manual, Moscow (2005).(in Russian)
13. Lequin, R.M.: Enzyme immunoassay (EIA)/enzyme-linked immunosorbent assay (ELISA). Clin. Chem. **51**, 2415–2418 (2005). https://doi.org/10.1373/clinchem.2005.051532
14. Klyushnik, T.P., Zozulya, S.A., Androsova, L.V., et al.: Laboratory Diagnostics in Monitoring of Patients with Endogenous Psychoses ("Neuro-Immuno-Test"). Medical Technology, MIA Publishers, Moscow (2014). (in Russian). ISBN: 978–5–9986–0279–5

Cognitive Robotics and Elements of AI

Cognitive Architecture for a Companion Robot: Speech Comprehension and Real-World Awareness

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Abstract. Companion robots should support natural communication with humans referencing the events in the environment and should respond with compound communicative reactions, reacting to incoming utterances, actions, gazes and other surrounding events. We represent a project of F-2 companion robot, where we implement unified representation types for (a) incoming speech semantics and (b) real events in the environment, registered by computer vision system. We rely of a classic linguistic notion of "case-frame" and represent each event as a predicate and a number of valencies: agent, patient, instrument, etc. Predicate and each valency refer to a referent ("id" of event or object) and is also represented by a list of semantic markers. These unified representations allow the robot to react to speech semantics and real events in a unified way. To simulate communicative reactions, we use a number of scripts (productions) which are activated by incoming case-frames, generate behavioral cues and get disactivated, once the cue is executed on the robot. The balance of activations allows the robot to select the most significant reactions or to simulate emotional behavior, expressively reacting to some minor stimulus. This architecture allows to eliminate the bottleneck on the stage of robot reactions, effectively process diverse incoming stimuli and simulate rich and compound communicative behavior on the robot.

Keywords: Emotional computer agents · Cognitive models · Semantic representation

1 Introduction

Companion robots should process incoming natural speech, recognize surrounding objects, and talk about their internal states, memory events and real-world situations, using speech and nonverbal cues. Robots should also remember the history of interaction and accumulate knowledge from different text sources: personal communication of incoming texts. The central point in the design of cognitive architectures for robots is the representation of semantic information (both from speech and visual sources) and its processing architecture, offering rich and believable behavior for the robot.

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Following classic approach by M. Minsky, an artificial cognitive architecture should consist of modules, competing or cooperating in various cognitive tasks [1]. Minsky has suggested, that basic processing should be performed by *proto-specialists*, each of those is a simple "agent" or procedure, designed to react to some dangerous or lucrative stimulus (external or internal), and thus, modelling a primary emotion (*fear, aggression*), reflex (*withdrawal*) or drive (*hunger*). The resolution of conflicts between the proto-specialists, active within the current moment of operation, constitutes current behavior of the agent – possibly, a mixture of expressive cues, suggested by diverse proto-specialists. We rely on further elaboration of this architecture, suggested within *Cognition and Affect Project – CogAff* model [2]. CogAff includes three levels of processing: (a) basic *reactive* level, withholding primary emotions and drives, (b) middle *deliberative* level, responsible for rational inferences and (c) upper *meta-management* level, engaged in reflexive processing. CogAff via SimAgent Toolkit has passed numerous experiments and is implemented in various artificial emotional agents. Although CogAff offers an extended view on the architecture of human cognitive processing, its internal cognitive representations are quite simple, as designed to represent simple events of virtual environments within SimAgent Toolkit. In our study we suggest an extended architecture, which implements the principle of script competition, typical for *proto-specialists* and *CogAff* architectures, but handles real speech semantics and representations of real objects and events, as recognized by computer vision modules.

2 F-2 Architecture

We represent a design of a cognitive architecture for a companion robot F-2. The architecture combines (a) an advanced speech processing system with morphological, syntactic and semantic levels, (b) visual recognition system, (e) central processor, which is operating with *scripts* or productions, and (d) robot controller, which manages speech synthesis and executes behavioral patterns on the real F-2 robot (Fig. 1).

The system is designed as a composition of modules (pipeline), which may run on the server without robot and computer vision (CV) subsystem and process daily news, blogs or novels to accumulate the extracted case-frames (facts) to a memory base. The system may also run on the robot to process (a) incoming written speech or oral speech after the external speech-to-text recognition and (b) the events from CV-subsystem. The processing is executed as the activation of *scripts* in the central processor module by the incoming representations. Scripts are subdivided into groups, sensitive to (a) emotional semantic representations (*d-scripts*, n = 79) and (b) rational semantic representations (*r-scripts*, n = 1600). In this sense, the distribution of scripts implements the two basic levels of CogAff architecture, while meta-management of reflexive processes are not covered. In case the system runs on the robot, the activated scripts send the corresponding behavioral patterns to the queue of the robot controller. These patterns can be executed depending on the activation of scripts and the availability of the robot's actuators. To describe the format of semantic representations within F-2 architecture we further examine the functions of speech processor and CV-subsystem as well as their integration within the component of scripts.

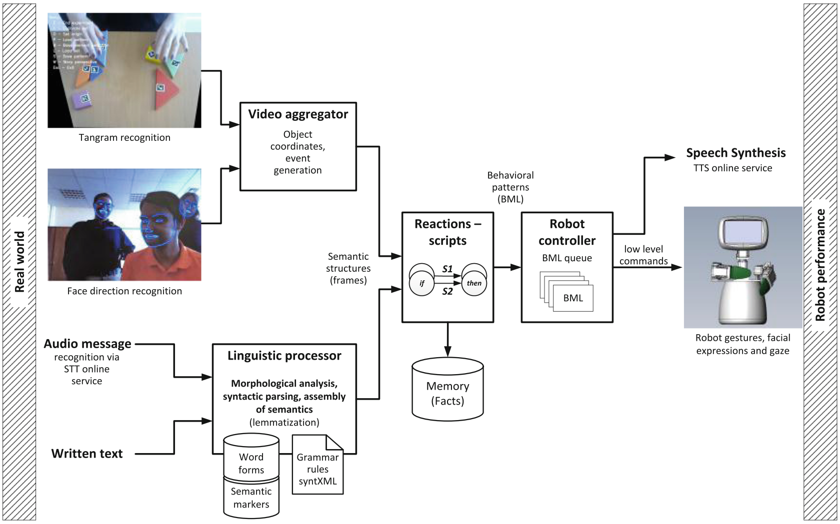


Fig. 1. General architecture of the F-2 companion robot.

3 Speech Processor

Speech processor is designed for the Russian language, but after the replacement of grammar and dictionary it may work with other languages, as the semantic representations will remain mostly intact. It receives written text or transcribed oral speech after a speech-to-text recognition service. The processor is based on traditional linguistic layered architecture with *morphological*, *syntactic*, and *semantic* processing levels. Wordforms are tagged with the help of a dictionary with 100,000 lemmata (1.5 mln wordforms), stored as a database. An automatic tagger (guesser) is used for unknown forms. Syntactic analysis relies on formal representation of the Russian grammar in SyntXML format [3]. The grammar contains over 600 syntactic rules, which define possible binding of two or more wordforms, or even virtual language segments. As for the output the syntactic component constructs a syntactic tree, as on Fig. 2, or a set of such trees with limited cardinality in case of lexical or syntactic ambiguity. Within a syntactic tree each noun (or pronoun) is assigned to a certain valency within the case-frame of the verb – as seen in SemVal variable in Fig. 2. The list of valencies is based on [4] and includes *agent* (**ag**), *patient* (**p**), *instrument* (**instr**) and other valencies (n = 22). A special *predicate* (**p**) meta-valency is assigned to verbs and predicatives; we assume, that this valency governs a predication, and with this assumption the semantics of a predication can be represented as a table (see Table 1). The semantic representation of each valency is a union of semantic markers for all the words within this valency (e. g. an *adjective* is joined with *noun*) retrieved from the semantic dictionary. Homonymy is marked by sub-division indexes (“1 1”, “1 2” etc.).

The semantic representation in this format is constructed for every clause for each of the homonymic syntactic trees. All the constructed representations arrive at the input of script component, which calculates distances between the semantic representations and

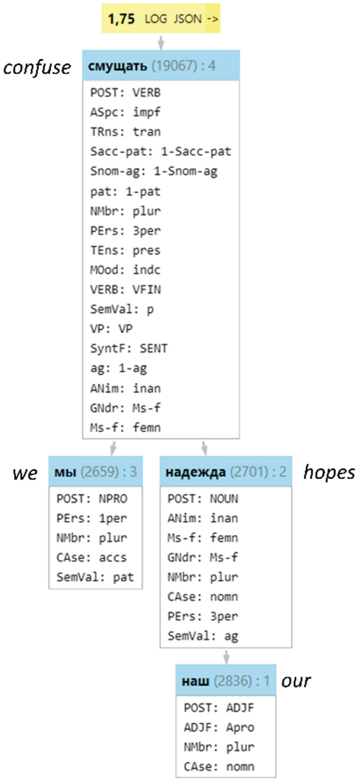


Fig. 2. Syntactic representation of a sentence *Our hopes confuse us.*

Table 1. Semantic representations of a sentence *Our hopes confuse us.*

P (*predicate*)	Ag (*agens*)	Pat (*patient*)
1 1 present tense 1 1 assertive 1 1 to cause emotions 1 1 to cause negative emotions 1 1 @to_ surprise 1 1 @5_VERB	1 1 many 1 1 abstract-goal 1 1 abstract 1 1 @wish_NOUN 1 1 @343_NOUN 1 1 own	1 1 somebody 1 1 egocentric – me 1 1 other person 1 1 physical object 1 1 principal – speaker 1 1 set of people

the premises of scripts. The tree with minimal average distance to scenarios is chosen for processing. A similar operation is executed for visual representations, that resemble text semantics but do not have homonymic variants.

4 Computer Vision Processor

Visual recognition subsystem should generate conceptual representations for the events, that are important enough to invoke the reactions of the robot. It also has to aggregate spatial information of the recognized events and objects, thus constructing the 3D-model of the robot's surrounding. The system consists of a set of CV modules and a *video aggregator*, which accumulates data from the modules and creates conceptual representations (events) for possible reactions of the robot. We assume, that personal interaction and communication regarding the problem space are the two most important areas for the CV-awareness. Thus, we use (a) face detection and face tracking modules to detect the aspects of personal communication and (b) tangram puzzle assembly submodule to detect operations in the problem space. The number of modules can be easily extended. The data on the recognized objects and events is transferred by each module into *video aggregator*, which constructs 3D-model of the environment and generates events for further processing by scripts (Fig. 3). These stimuli events of the visual recognition subsystem are represented as case-frames, similar to semantic representations from the speech processor.

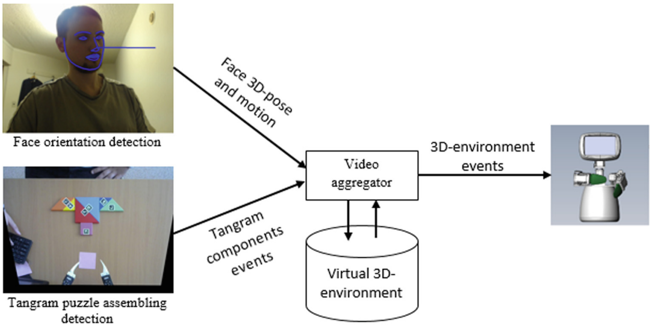


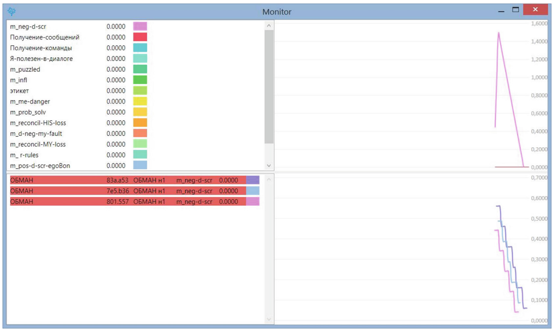
Fig. 3. Visual recognition subsystem principal scheme.

For face detection we apply pre-trained linear *SVM*-classifier in a sliding window within an image multiscale pyramid. This classifier uses advanced version of *HoG*-features [5] implemented in *Dlib* library [6]. We have decided to recognize user's face orientation as one of the key stimuli for user-robot interaction. In our experiments we assume the orientation of user's face as a rough evaluation of user's gaze or attention. The face orientation detection consists of two steps: (a) facial landmarks detection, (b) determination of relative 3D-position of the detected landmarks in the camera coordinate system. To detect facial landmarks, we apply an Ensemble of Regression Trees approach [7]. Then we associate these landmarks with 3D-points in an approximate face model and solve a Perspective-n-Point (PnP) problem to determine a 3D-orientation of the user's face in the camera coordinate system [8]. Video aggregator receives and updates the information on the location and orientation of the human face. It generates the events in the format as in Table 1, like, 'person (**ag**) looks at (**p**) you (**pat**)', to invoke a response from the robot, e. g. a response gaze. Also, it reports the current coordinates of the human face, so that the robot can update the angles of head and eyes, while trying to 'look at the person'.

To model the interaction with a user while solving a problem in the real world, we have chosen the Tangram puzzle, where a user has to construct a figure with a given shape with a help of 7 game elements. This game represents a good example of a task, where a human and a robot construct something together. The robot registers the position of game elements and user moves, gives emotional feedback and suggests the required actions. We have developed a recognition and game support library, which records movements and evaluates, whether a move is a step forward to any of the possible puzzle solutions (each game has multiple solutions). The data from this library is also accumulated by the aggregator which further generates events in a form, similar to Table 1, like 'Game element 5 (**pat**) has moved (**p**) to the correct position (**targ**) for the solution No 3 (**ben**)'. This allows the script component to react accordingly.

5 Competitive Processing

Upon the receipt of each input event in a form of a case-frame the script component calculates its distance to the premises of scripts. The preferring scripts are chosen (a) proportionally to the similarity between input event and the premise of the script, and (b) proportionally to the activation of microstate (current emotional state) for the corresponding script (only for the emotional *d-scripts*). In other words, each input is evaluated as relevant, if it corresponds to some known situation frame (for *r-scripts*) or to the emotive representation (*d-script*) of a prevailing emotion (microstate). The activated script transfers its behavioral pattern on Behavior Markup Language (BML) [9] to *robot controller* for possible execution. The BML is executed if the script activation is high enough, or if the corresponding body parts of the robot are free. This allows to simulate blending emotions, when two opposite emotions are combined in behavior [10], and even irony, when a strong negative reaction is substituted by an ironic positive response from the opposing script [11]. The competition of scripts allows the robot to combine the behavior from several scripts, e. g. 'head' and 'mouth' can be engaged to execute the direct speech reply, while the underlying anxiety is expressed with 'hands' though automanipulation or scratching. Script loses its activation upon the execution of the corresponding



```
m_neg-d-scr              0.0000
Получение-сообщений      0.0000
Получение-команды        0.0000
Я-полезен-в-диалоге      0.0000
m_puzzled                0.0000
m_infl                   0.0000
этикет                   0.0000
m_me-danger              0.0000
m_prob_solv              0.0000
m_reconcil-HIS-loss      0.0000
m_d-neg-my-fault         0.0000
m_reconcil-MY-loss       0.0000
m_ r-rules               0.0000
m_pos-d-scr-egoBon       0.0000
```

```
ОБМАН                    83a.a53  ОБМАН н1   m_neg-d-scr  0.0000
ОБМАН                    7e5.b36  ОБМАН н1   m_neg-d-scr  0.0000
ОБМАН                    801.557  ОБМАН н1   m_neg-d-scr  0.0000
```

Fig. 4. Competitive processing of scripts

BML. Figure 4 shows an example, where three incoming events (phrases) activate three instances of DECEPT (deception) d-script.

The instances compete in time, incrementally losing their activation, when the corresponding BMLs are executed (lower part of the screen), while the general microstate (negative emotional state) is activated by the sum of negative incoming events and loses its activation, following the expression of the scripts (upper part of the screen).

6 Conclusion

While the general architecture of F-2 robot inherits the classic concepts of *proto-specialists* and *CogAff*, it has been greatly extended to handle the semantics of natural texts and real events following CV recognition. In this respect the representation of semantics in the form of linguistic case-frames allows the robot to process semantic and visual information in a unified way. The competition of scripts on the reaction stage makes the architecture flexible, allowing the robot to react to incoming speech and visual events with diverse (and even contradictory) internal states and generate rich and compound communicative behavior, including blending emotional patterns and irony.

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References

1. Minsky, M.L.: The Society of Mind. Touchstone Book, New-York, London (1988)
2. Sloman, A., Chrisley, R.: Virtual Machines and Consciousness. J. Conscious. Stud. **10**(4–5), 133–172 (2003)
3. Kotov, A., Zinina, A., Filatov, A.: Semantic parser for sentiment analysis and the emotional computer agents. In: Proceedings of the AINL-ISMW FRUCT 2015, pp. 167–170 (2015)
4. Fillmore, C.J.: The Case for Case, Universals in Linguistic Theory, pp. 1–68. Holt, Rinehart & Winston, New York (1968)
5. Felzenszwalb, P.F., Girshick, R.B., McAllester, D., Ramanan, D.: Object detection with discriminatively trained part-based models. IEEE Trans. Pattern Anal. Mach. Intell. **32**(9), 1627–1645 (2010). https://doi.org/10.1109/TPAMI.2009.167
6. Dlib C++ Library – Image Processing (2019). https://dlib.net/imaging.html. Accessed 7 Dec 2019
7. Kazemi, V., Sullivan, J.: One millisecond face alignment with an ensemble of regression trees. In: 2014 IEEE Conference on Computer Vision and Pattern Recognition, Columbus, OH, pp. 1867–1874 (2014). https://doi.org/10.1109/CVPR.2014.241
8. Mallik, S.: Head Pose Estimation Using OpenCV and Dlib (2019). https://www.learnopencv.com/head-pose-estimation-using-opencv-and-dlib. Accessed 7 Dec 2019
9. Kopp, S., Krenn, B., Marsella, S., Marshall, A., Pelachaud, C., Pirker, H., Thórisson, K., Vilhjálmsson, H.: Towards a common framework for multimodal generation: the behavior Markup Language. In: Intelligent Virtual Agents, pp. 205–217 (2006)
10. Ochs, M., Niewiadomski, R., Pelachaud, C., Sadek, D.: Intelligent expressions of emotions. In: Tao, J., Tan, T., Picard, R.W. (eds.) ACII 2005, LNCS 3784, pp. 707–714. Springer-Verlag, Berlin, Heidelberg (2005)
11. Kotov, A.: Accounting for irony and emotional oscillation in computer architectures. In: Proceedings of International Conference on Affective Computing and Intelligent Interaction ACII 2009, pp. 506–511. IEEE, Amsterdam (2009)

Human Communicative Behavior While Solving Tangram Puzzles for Subsequent Transfer to a Robot

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Abstract. In a more general project, the present study is a part of, we apply natural communicative behavior to a robot in a situation where it acts as an assistant for a child while the child is solving a spatial problem – in our case, a Tangram puzzle. In order to find the key features of such tutoring behavior, we have arranged a natural situation with two people, helping each other to solve a puzzle. To date, 10 adult (5 pairs) men and women have been recorded. We analyzed the communication strategies that respondents use to effectively help in solving the task. We pay special attention to the emotional dynamics of the participants in each of the two dialogue positions: the assistant and the Tangram solver. We use the obtained data to develop deep and differentiated emotional model for the robot that is applicable to the situation of free assembly of the Tangram puzzle.

Keywords: Multimodal communication · Robot-to-human interaction · Affective robot tutors

1 Introduction

What makes a robot attractive? In natural communication, a person adjusts his behavior to the situation and actions of other people. Therefore, for the effective interaction with humans, robots also need to perform coordinated and timely actions based on the analysis of their social environment. A key feature of social robot behavior is the ability to adapt to the changing needs of the user [1]. Perceived adaptability affects the perceived utility of the robot, increases user's satisfaction from the interaction as well as the intention to use it in the future [2]. Robot's ability to respond to changes in the surrounding situation, to adapt its behavior and emotional expression to the users is an important factor to create a positive impression of interaction with a companion robot. It is important for robots to demonstrate emotional dynamics and expression depending on incoming events, such as reactions to successful or incorrect user's actions, user's questions, and user's gestures directed to the robot (for example, touching). The emotional model of companion robots might provide flexible and diverse behavior that underlies social interaction with humans.

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The robot's ability to simulate 'feelings' and express the variety of emotional reactions using expressive means (e. g. movements with eyes, head, and hands) is highly appreciated in learning [3–6]. Robots are used for teaching natural sciences [7], mathematics [8], music [9], and foreign language [10]. The use of robots might be also effective for developing children's cognitive skills [11, 12]. Social robots involve children in learning, increase their motivation and curiosity, as well as the number of emotional responses [3, 13, 14]. Robots can demonstrate various means of communication: using gestures, boy postures, and facial expressions, that also helps to increase the interest and motivation of users to learning. Thus, modeling complex emotional behavior is one of the key characteristics for educational robots.

So many researchers pay special attention to the development of an emotional robot model [15] in learning. For example, in [16] iCat robot plays chess with a child. The robot's emotional state and expression is affected by every move of the child. Children may interpret the robot's affective behavior and by that acquire additional information to better understand the game. The robot has empathic abilities, that also contributes to improving children's chess skills.

In our lab, we are developing a robot that acts as a child's assistant in solving puzzles. In this way, the robot controls the solution of the task: it introduces the puzzle to a child, gives instructions, and monitors the progress of the task.

2 F-2 Robot Platform for Experiments

2.1 Modeling of Multimodal Robot Behavior

We are developing the F-2 robot, which can be used as an experimental platform for the development of interaction models between humans and robots (Fig. 1). Robot's movements are modeled based on The Russian Emotional Corpus (REC) [17]. In this way, we model a complex robot behavior that is as close as possible to natural communication behavior. This behavior allows the robot to interact with people naturally and intuitively.

Numerous experimental studies have shown that complex nonverbal behavior of a robot has an effect on the attractiveness of the robot to the user. For example, in [18], we investigated the effect of complex robot eye movements on users. The experiment [19] evaluated the contribution of various means of communication (eye movements, facial expressions, gestures, speech) to the positive impression of the robot. It was shown that emotional gestures of the F-2 robot increase its attractiveness to the user, more than head movements and facial expression. Another experiment [20] investigated the effect of oriented robot gestures on users in spatial game situations. It was found that subjects implicitly prefer the robot that uses pointing gestures in its instructions. It is also shown that some participants in the experiment follow the robot's pointing gestures, without realizing it.

In a recent study [21], we test the effect of robot's emotional gestures and speech on participants in a game situation. In the experiment two identical robots helped children to complete the tangram puzzle. In the experiment two independent variables were varied, each of which had two levels: (a) robots demonstrated expressive (emotional) or neutral gestures, (b) robots could react with emotional or neutral statements. It was found that emotional gestures are the key factor that influences the attractiveness of the robot for

Fig. 1. The robot F-2

the child. In addition, children noted that the robot with emotional speech and gestures is more kind, empathic, it "has interesting words". In our experiment it was found that the robot F-2 successfully acts as a teacher, children like his assistance in solving spatial puzzles.

Previous simulations of game assistance were organized in the Wizard of Oz paradigm: the moves by the player were evaluated as successful or not by a remote human operator. Robot has been suggesting to complete the puzzle in a fixed order. As we develop an automatic system computer vision recognition system for Tangram puzzle, our attention is focused on the development of an extended emotional model of the robot with more complex system of robot responses with the optimal frequency of suggestions. The emotionality of gestures and speech should be more differentiated. On the one hand, when developing a model, it is necessary to focus on well-known classifications of emotions. For example, the robot must be able to look surprised, sad, happy, angry, frightened or fell shame. On the other hand, a qualitative analysis of the behavior of real people in identical situations is necessary. For example, in [22] the analyses of human-human interaction (HHI) has been suggested as the basis of multidisciplinary approach to the development of empathic robotic tutor. In [23] the Inter-ACT (INTEracting with Robots–Affect Context Task) corpus was presented, an affective and contextually rich multimodal video corpus containing affective expressions of children playing chess with the iCat robot.

2.2 Video Corpus

To develop a deeper and more differentiated emotional model, we need a qualitative analysis of behavior of real people in identical situations – in situations of assembling a puzzle. In our work, we create a corpus with recordings of pairs of people helping each other to solve a tangram puzzle. To date, 10 adults (5 pairs, average age 34.5 years) have been recorded. We analyze the communication strategies that respondents use to effectively assist in solving the problem and pay special attention to the emotional dynamics of the research participants in each of the dialogue positions (assistant and puzzle solver).

The participants helped each other solve a tangram puzzle by suggesting the right moves. Each subject had to solve and to explain 4 figures: two from a single set of Tangrams (7 elements), two from a double set (complex figures, made of 14 elements). In total, solutions to 40 Tangram tasks were recorded. Before the beginning of each session, the solver received the outer contour of the figure to the solved, and the assistant received the detailed composition of the figure – one of the possible solutions. The assistants were not limited to follow a specific strategy – it was important to create the situation of free assembly to select the appropriate strategies for the robot. The respondents could use pointing gestures, but they were not allowed to touch the figures and the target place for the game element. The experiment was recorded on a video camera (Fig. 2).

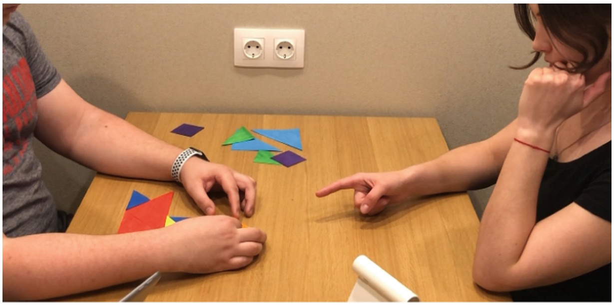

Fig. 2. The experimental situation

Following the analysis of video recordings, we have identified the main assisting strategies. The strategy in which the assistant focuses on the actions of the solver was called "**Helping**". It is characterized by the increased time for requesting a hint, adjustment of hints to the current arrangement of elements on the field, a general orientation towards the behavior of the puzzle solver. The strategy, in which assistants insistently try to impose their strategy on the solver, was called "**Dominant**". Study participants used both strategies depending on the complexity of the task and the previous interaction experience. The average waiting time for a hint or comment for the *Helping* strategy is about 3–10 s, for the *Dominant* – 1–2 s. Consequently, while assisting a human, a robot must wait for a hesitation pause of variable duration to give an advice, so as not to look intrusive and not deprive the subjects of the opportunity to solve complex problems without assistance.

The analysis of video recordings revealed the types of instruction used by the study participants:

1. Instruction about specific operations with a single game element.
2. Instruction about the decision procedure.
3. Instruction about the general structure of the figure or a general instruction.

These types of instructions can be initiated by the assistant before the puzzle solver begins the corresponding actions – this is typical for the *dominant* strategy. Instructions can also be offered when the puzzle solver meets the difficulties, in response to the solver's request, which is usually typical of a *helping* strategy. When assembling a tangram puzzle, respondents balance between different types of prompts, develop the most optimal strategy for interacting with each other.

After analyzing the corpus, it was also found that participants in the experiment demonstrate complex behavioral patterns for emotions of different "depths". The emotional expressions can be divided into *push emotions* (internal or experienced) and *pull emotions* (external or expressed).

According to the data obtained, half of the subjects experienced great difficulties not in assembling itself, but rather in assisting. The respondents began to get nervous, when the solver misinterpreted the advices, tried to hide their irritation, got upset because of the lack of mutual understanding in the pair, etc. Informants often intentionally used exaggerated expressions of fatigue or surprise to indicate the opponent's wrong action – e. g. behavioral patterns corresponding to the statements: *I can't stand your mistakes anymore!* or *Why is it so hard?* Such emotions were demonstrated to make the assessment of the interlocutor's actions more explicit. In other words, if a person wants to describe the interlocutor's action as incorrect, he can imitate emotion and broadcast a message about the interlocutor's incorrect actions not only through a direct statement (*Wrong*), but also through an emotional pattern.

The identified patterns can be interpreted based on K. Scherer's concept of *push* and *pull* emotions (experienced and expressed emotions) [24]. Based on experimental and corpus studies, Scherer showed that *push-emotions* are experienced internally by a person, while their external expression is suppressed as much as possible. This is typical for those emotions that are not approved in society (aggression, disgust, gloating). At the same time, *pull-emotions* can be experienced by a person relatively poorly, but their external expression is significantly exaggerated, for example, this is typical for empathy and guilt – for emotions in which the expression is associated with social approval.

Implementing such emotional dynamics on a robot will allow us to design complex emotional responses. The obtained data is considered when developing the emotional model.

3 Formal Model of Emotional Dynamics

To develop a formal emotional model, we proceed from the following requirements:

1. The robot should process most of incoming stimuli, giving preference to the correct and incorrect movements of the user.
2. The robot can take the initiative and give advice to the user.
3. The choice of communication strategy (as in points 1 and 2) depends on (a) the significance of the stimulus, (b) simulated personal characteristics of the robot – the emotional profile, and (c) the general simulated emotional state of the robot.

The robot control system allows us to combine the robot's facial and gesture responses from various behavioral packages (in BML format). The robot can express negation or irritation with head movements and at the same time compensate for them with hand movements (for example, automatic manipulation). The architecture allows us to model complex behavioral patterns of emotions of different "depths".

We also develop an emotional model that simulates short-term (within a single communicative reaction) emotional dynamics using an inventory of expressed emotions (pull-emotions), as well as long-term (within an interval of several reactions) communicative dynamics using an inventory of experienced push-emotions (Fig. 3).

For combinations of emotions, the following response pattern is used:
input from the user: <user action>
output from the robot: <patterns of communicative functions of expressed emotions><robot utterance><patterns of communicative functions of experienced emotions>

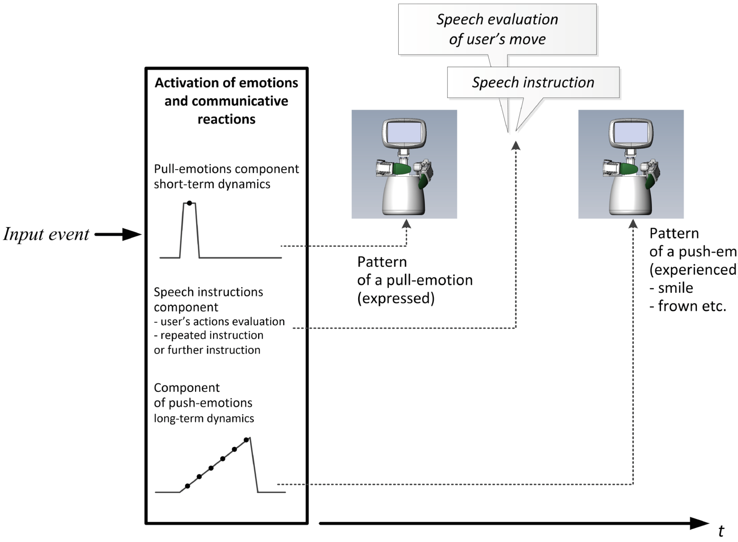

Fig. 3. Activating the emotional model

With a correct or incorrect user action, the proximity of the event to the stimulus patterns of expressed and experienced emotions is calculated. The level of emotion activation is calculated and updated. After that, an outgoing message is generated, at the beginning of which the patterns of expressed emotions are executed. First of all, these are emotional signs focused on feedback – the user must understand whether the robot evaluates his last action positively or negatively. An incoming event also changes the activation of experienced emotions, which are shown rather weakly.

4 Conclusions

Our goal was to develop the communicative behavior of the robot for a situation in which it acts as a tutor in solving a tangram puzzle. For this, the corpus was collected and analyzed, which includes video recordings of the puzzle assembly during the interaction of two adults. Analysis of video recordings allowed us to identify key features that need to be implemented in robot's communicative behavior: types of assistance advices, the strategies of their requests and offers. In addition, we found that participants in the experiment demonstrated complex behavioral patterns for emotions of different "depths". Their emotions can be divided into internal (experienced or *push-emotions*) and external (expressed or *pull-emotions*). Based on the data obtained, we develop a flexible emotional robot model that adapts to a variety of communication situations.

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References

1. Heerink, M., Krose, B., Evers, V., Wielinga, B.: Assessing the acceptance of assistive social agent technology by older users: the Almere model. Int. J. Soc. Rob. **2**(4), 361–375 (2010)
2. Broadbent, E., Stafford, R., MacDonald, B.: Acceptance of healthcare robots for the older population: review and future directions. Int. J. Soc. Rob. **1**, 319–330 (2009)
3. Kanda, T., Hirano, T., Eaton, D., Ishiguro, H.: Interactive robots as social partners and peer tutors for children: a field trial. Hum.-Comput. Interact. **19**(1–2), 61–84 (2004)
4. Alemi, M., Meghdari, A., Ghazisaedy, M.: Employing humanoid robots for teaching English language in Iranian junior high-schools. Int. J. Humanoid Rob. **11**(03), 1450022 (2014)
5. Belpaeme, T., Kennedy, J., Ramachandran, A., Scassellati, B., Tanaka, F.: Social robots for education: a review. Sci. Rob. **3**(21), eaat5954 (2018). https://doi.org/10.1126/scirobotics.aat5954
6. Dautenhahn, K.: Socially intelligent robots: dimensions of human–robot interaction. Phil. Trans. Roy. Soc. B Biol. Sci. **362**(1480), 679–704 (2007)
7. Shiomi, M., Kanda, T., Howley, I., Hayashi, K., Hagita, N.: Can a social robot stimulate science curiosity in classrooms? Int. J. Soc. Rob. **7**(5), 641–652 (2015)
8. Brown, L.N., Howard, A.M.: The positive effects of verbal encouragement in mathematics education using a social robot. In: IEEE Integrated STEM Education Conference, pp. 1–5 (2009)
9. Han, J.H., Kim, D.H., Kim, J.W.: Physical learning activities with a teaching assistant robot in elementary school music class. In: 2009 Fifth International Joint Conference on INC, IMS and IDC, pp. 1406–1410 (2009)
10. van den Berghe, R., Verhagen, J., Oudgenoeg-Paz, O., van der Ven, S., Leseman, P.: Social robots for language learning: a review. Rev. Educ. Res. **89**(2), 259–295 (2019)
11. Park, H.W., Rosenberg-Kima, R., Rosenberg, M., Gordon, G., Breazeal, C.: Growing growth mindset with a social robot peer.: In: Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction, pp. 137–145 (2017)
12. Cook, A., Encarnação, P., Adams, K.: Robots: assistive technologies for play, learning and cognitive development. Technol. Disabil. **22**(3), 127–145 (2010)
13. Gordon, G., Breazeal, C., Engel, S.: Can children catch curiosity from a social robot?: In: Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction, pp. 91–98 (2015)
14. Wainer, J., Feil-Seifer, D.J., Shell, D.A., Mataric, M.J.: The role of physical embodiment in human-robot interaction. In: ROMAN 2006-The 15th IEEE International Symposium on Robot and Human Interactive Communication, pp. 117–122 (2006)

15. Cuadrado, L.E.I., Riesco, Á.M., de la Paz López, F.: FER in primary school children for affective robot tutors. In: International Work-Conference on the Interplay Between Natural and Artificial Computation, pp. 461–471. Springer, Cham (2019)
16. Leite, I., Pereira, A.: iCat, the affective chess player. In: Proceedings of the Systems Demonstrations. Second International Conference on Affective Computing and Intelligent Interaction (ACII 2007), pp. 29–33 (2007)
17. Kotov, A., Zinina, A.: Functional analysis of non-verbal communicative behavior. In: Computational Linguistics and Intellectual Technologies: Proceedings of the International Conference "Dialog 2015", vol. 14, no. 21, pp. 308–322 (2015)
18. Zinina, A., Arinkin, N., Zaydelman, L., Kotov, A.: Development of communicative behavior model for f-2 robot basing on «REC» multimodal corpora [Razrabotka modeli kommunikativnogo povedeniya robota f-2 na osnove mul'timodal'nogo korpusa «REC»]. In: Computational Linguistics and Intellectual Technologies: Proceedings of the International Conference "Dialog 2018", vol. 17, no. 24, pp. 831–844 (2018)
19. Zinina, A., Zaydelman, L., Arinkin, N., Kotov, A.: Non-verbal behavior of the robot companion: a contribution to the likeability. In: Procedia Computer Science. Postproceedings of the 10th Annual International Conference on Biologically Inspired Cognitive Architectures, BICA 2019 (Tenth Annual Meeting of the BICA Society), pp. 800–806. Elsevier (2019). https://doi.org/10.1016/j.procs.2020.02.160
20. Zinina, A., Arinkin, N., Zaydelman, L., Kotov, A.: The role of oriented gestures during robot's communication to a human. In: Computational Linguistics and Intellectual Technologies: Proceedings of the International Conference "Dialogue 2019", vol. 18, no, 25, 800–808 (2019)
21. Zinina, A., Zaydelman, L., Arinkin, N., Kotov, A.: Emotional behavior of robots during of the spatial puzzle solving with children. In: Computational Linguistics and Intellectual Technologies: Proceedings of the International Conference "Dialogue 2020", vol. 19, no. 26, pp. 811–826 (2020)
22. Jones, A., Küster, D., Basedow, C.A., Alves-Oliveira, P., Serholt, S., Hastie, H., Castellano, G.: Empathic robotic tutors for personalised learning: a multidisciplinary approach. In: International Conference on Social Robotics, pp. 285–295. Springer, Cham (2015)
23. Castellano, G., Leite, I., Pereira, A., Martinho, C., Paiva, A., Mcoan, P.W.: Multimodal affect modeling and recognition for empathic robot companions. Int. J. Humanoid Rob. **10**(01), 1350010 (2013)
24. Scherer, U., Helfrich, H., Scherer, K.R.: Internal push or external pull? determinants of paralinguistic behavior. In: Giles, H., Robinson, P., Smith, P. (eds.) Language: Social Psychological Perspectives, pp. 279–282. Pergamon, Oxford (1980)

Towards Constructing an Autonomous Agent-Scientist

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Abstract. This work analyzes approaches to the construction of models of autonomous agents that would be capable to discover by themselves the laws of nature. The importance of the concept of "the internal model of the external world" is emphasized; an autonomous agent could have such a model. Such models can be compared with scientific theories, which can also be considered as models of the external world. A specific model of the evolution of a population of autonomous agents of two types is also constructed and analyzed. This model considers the following agents' types: 1) ordinary agents and 2) smart agents with profound cognitive abilities. The characteristics of the evolution of the population of the considered agents are analyzed by means of computer simulation.

Keyword: Cognitive agent · Cognition of nature · Model of the evolution of the population of agents

1 Introduction

The goal of this work is to analyze approaches to the design of an autonomous agent that is capable to discover the laws of nature. The general idea of the work is close to a new scientific direction: modeling of cognitive evolution. This direction devotes to investigate cognitive biological evolution that led to the formation of human thinking, which is used in scientific cognition of nature [1].

A similar approach was proposed in the work [2]. In that work, the principles of constructing of an autonomous agent-physicist were proposed. Such an agent could discover the laws of the external world and, ultimately, could discover the physical laws of nature. At constructing the agent-physicist, we can use the cognitive methods and features of Isaac Newton, who developed the laws of mechanical physics.

Rather simple models of the autonomous agent's cognition of causal relationships in the external world [3, 4] could also support the designing of the agent-scientist. It is important that these models were developed using the analysis of the concept of causality by David Hume [5]. These models demonstrate that in the process of evolution, agents with the ability to cognize causal relationships have a selective advantage over agents that are not able to cognize causal relationships.

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2 Approaches to Modeling of Autonomous Agents with Profound Cognitive Abilities

This paper analyzes approaches to designing models of agents with better cognitive abilities than the abilities of agents of the works [3, 4]. An important concept that we will use is the concept of an internal model of an agent. We will consider two types of internal models of the agent: 1) the cognitive model of the external world (that is independent on the agent), 2) the model of the agent's interaction with the external world.

Models of the external world are close to scientific theories. Many scientific theories can be considered as models. For example, we can talk about a model of quantum mechanics and about a model of the theory of relativity. Models of the agent's interaction with the external world can use models of the first type, i.e. the models of the external world.

We can consider the hierarchy of these models and the evolution of these models in agents with different cognitive abilities. For example, similar to the work of Valentin Turchin [6], we can consider the improvement of agent's internal models through analogs of metasystem transitions, i.e. transitions to higher levels of the hierarchy of models. Note that Turchin emphasized an important transition to a new level of the hierarchy; namely, a transition to critical thinking. In critical thinking, various forms of thought processes are mentally analyzed and compared, and, ultimately, the most perfect form from those thought processes is selected. According to Turchin [6]:

> "Critical thinking considers each explanation (linguistic model of reality) alongside other competing explanations (models) and it is not satisfied until it is shown that the particular explanation is better than its rivals".

Let us emphasize that critical thinking played an important role in the formation of the axiomatic method in mathematics and the corresponding proofs in ancient Greece. Turchin underlines [6]:

> "Neither in Egyptian nor in Babylonian texts do we find anything even remotely resembling mathematical proof. This concept was introduced by the Greeks, and is their greatest contribution".

The transition to a higher level of the hierarchy can be illustrated as follows. At a low level, particular problems are solved; at a higher level, a general axiomatic theory is built, which includes these particular solutions as consequences of the general theory.

Note that the functional systems (FS) of Petr Anokhin [7] can be considered as models of the second type, namely, models of the agent's interaction with the outside world. Vityaev and Demin [8, 9] analyzed in detail the possibilities of modeling the FS of agents taking into account the hierarchy of FS.

Note that the agent's model of predictions of future situations [4] can be considered as the simplest model of the external world. The model for using these predictions [3] can be considered as a model of the agent's interaction with the external world. Further, based on these models, we will construct and analyze a specific computer model of the evolution of a population of agents that can have and use internal models of the external world.

3 Model Description

The current model describes the general characteristics of the evolving population of cognitive agents. The model is similar to models of the works [3, 4]. We believe that there are two types of agents in the evolving population. Agents of the first type have ordinary cognitive abilities and use only intuitive ideas about the external world. Agents of the second type have knowledge about the external world (such as models of the external world) and can use this knowledge. We denote the number of agents of the first and second types by N_1, N_2, respectively. We will also refer to agents of the first type as ordinary agents and agents of the second type as smart agents.

We believe that time is discrete: $t = 1, 2, \ldots$ Each agent has its own life resource R. To maintain its knowledge, its cognitive abilities, an agent of the second type spends a certain resource ΔR_2 each time step.

We assume that every time step the agents encounter a difficult situation. The agent can handle this difficult situation. If the agent solves problems related to this situation, then the agent gets a reward: it obtains a rather large addition ΔR_S to its resource. When an agent receives this addition, it adds ΔR_S to its resource R. The probability of solving problems related to a complex situation and getting an addition to the resource is different for agents of different types. For agents of the first and second types, this probability is equal to P_1 and P_2, respectively. Naturally, we assume that $0 \le P_1 < P_2 \le 1$.

If an agent's resource exceeds a certain threshold R_{TH}, then that agent can give birth to a child. When a child is born, the parent agent gives the half of its resource to the child agent. Usually, the type of the child agent is the same as the type of the parent agent. However, "mutational" transitions from agents of the first type to agents of the second type and reverse transitions with probabilities P_{12} and P_{21}, respectively, are also possible.

In addition, we assume that each agent spends a certain resource to maintain its life: each time step the agent spends a certain portion of its resource, i.e. its resource value is multiplied by the coefficient k_D, $0 \le k_D \le 1$.

The model was investigated by means of computer simulation.

In computer simulation, we believed that the size of the total population of agents N_T is limited: $N_T \le N_{MAX}$. $N_T = N_1 + N_2$. If the population size has reached the value N_T, then new agents cannot be born. We also assume that the initial number of agents in the population N_0 is significantly less than N_{MAX}, i.e. there is a possibility of increasing the population size in the process of evolution. The types of agents were chosen randomly into the initial population, with equal probability for both types.

4 Results of Computer Simulation

Initially, a computer simulation was carried out for the reference version of the model with natural simulation parameters. In this case, the "mutational" transitions between the types of agents during reproduction were not taken into account, i.e. it was assumed that $P_{12} = P_{21} = 0$. After this, the influence of the value of the addition to the resource ΔR_S received by the agent when solving a complex problem in the evolutionary process was considered. Further, the influence of "mutational" transitions between the types of agents during their reproduction was analyzed.

4.1 Reference Version of Modeling

In the reference version of the simulation, the following parameters were used. The maximum number of agents in the population was $N_{MAX} = 1000$. The initial number of agents in the population was $N_0 = 10$. The increase in the agent's resource at the successful solution of a complex problem was $\Delta R_S = 2$. This value was the same for both types of agents. However, the probabilities of solving the problem by agents were different: smart agents (agents of the second type) solved a complex problem with probability $P_2 = 1$, ordinary agents (agents of the first type) solved a complex problem with probability $P_1 = 0.1$. The resource consumption of a smart agent for maintaining its cognitive abilities was $\varDelta R_2 = 1$. The probabilities of "mutational" transitions between agents of different types during reproduction in this version of the simulation were zero: $P_{12} = P_{21} = 0$. The value of the agent's resource, which is necessary for the birth of a descendant, was $R_{TH} = 10$. The resource consumption of each agent required to maintain its life corresponded to the coefficient $k_D = 0.9$.

The simulation results for the reference version are shown in Figs. 1, 2 and 3. Figure 1 shows the dependences of the number of ordinary (N_1) and smart (N_2) agents, as well as the total population size N_T on the time t. Note that after a short transition period (about 10 time steps) the number of ordinary agents becomes almost constant. The number of smart agents does not change at all. The dynamics of the population-average resource of both types of agents are shown in Fig. 2. The dependences of the number of born agents of both types on time are shown in Fig. 3.

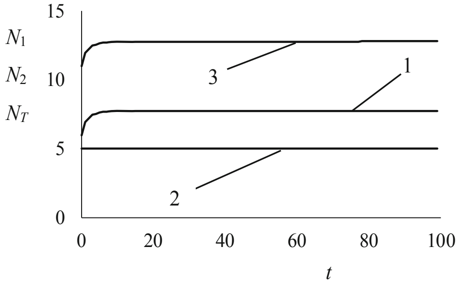

Fig. 1. Dependences of the number of ordinary (curve 1) and smart (curve 2) agents, as well as the total population size (curve 3) on time. $\Delta R_S = 2$, $P_{12} = P_{21} = 0$. The results are averaged over 1000 different calculations.

Note that the established number of ordinary agents is higher than the number of smart agents. Although the resource of smart agents is higher than that of ordinary agents. Smart agents do not give birth to offsprings at all, since they do not have enough resources for this (the resource of each smart agent is equal to 9.97). The absence of sufficient resource for duplication of smart agents is due to the fact that these agents spend a large amount of their resources to maintain their cognitive abilities. The resource of smart agents is less than the value R_{TH}, which is necessary for the birth of a child.

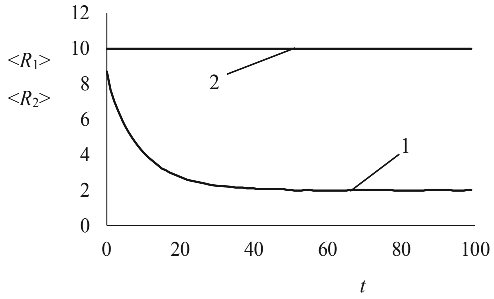

Fig. 2. Dependences of the population-average resource of ordinary (curve 1) and smart (curve 2) agents on time. $\Delta R_S = 2, P_{12} = P_{21} = 0$. The results are averaged over 1000 different calculations.

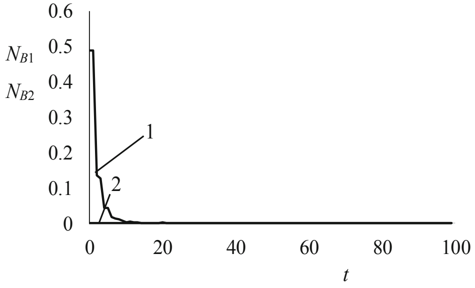

Fig. 3. Dependences of the number of births of ordinary (curve 1) and smart (curve 2) agents on time. $\Delta R_S = 2$, $P_{12} = P_{21} = 0$. The results are averaged over 1000 different calculations.

4.2 Influence of the Value of the Reward at Successful Problem Solving

In this version of the simulation, the increase of the agent's resource obtained by the agent after the successful solution of a complex problem was increased, the value of this reward was $\Delta R_S = 3$. All other parameters remained the same as in the reference version.

The dynamics of the number of agents, the population-average resource of agents, and the number of births of agents is shown in Figs. 4, 5 and 6. It is seen that in this version the number of smart agents and their resource grow. The total population size quickly reaches the maximal value N_{MAX}; after this reaching, new agents are not born. The number of smart agents becomes almost equal to N_{MAX}; the number of ordinary agents becomes equal to 12.8.

4.3 Influence of "Mutational" Transitions Between Types of Agents

In this version of the simulation, the value of the increase of the resource after a successful solution of the problem, as in the previous version, was $\Delta R_S = 3$. In addition, the "mutational" transitions between the types of agents were introduced. It was assumed that a smart agent with a high probability $P_{21} = 0.9$ gives birth to an ordinary agent,

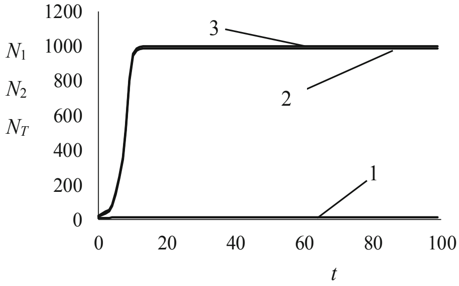

Fig. 4. Dependences of the number of ordinary (curve 1) and smart (curve 2) agents, as well as the total population size (curve 3) on time. $\Delta R_S = 3$, $P_{12} = P_{21} = 0$. The results are averaged over 1000 different calculations.

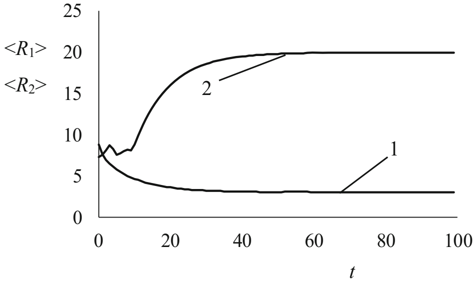

Fig. 5. Dependences of the population-average resource of ordinary (curve 1) and smart (curve 2) agents on time. $\Delta R_S = 3, P_{12} = P_{21} = 0$. The results are averaged over 1000 different calculations.

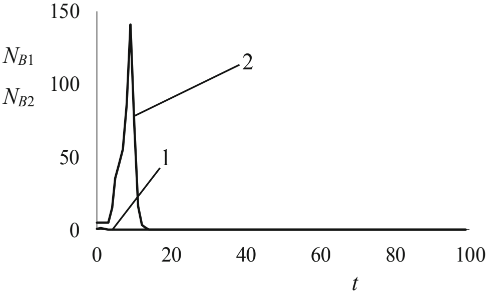

Fig. 6. Dependences of the number of births of ordinary (curve 1) and smart (curve 2) agents on time. $\Delta R_S = 3$, $P_{12} = P_{21} = 0$. The results are averaged over 1000 different calculations.

and the probability that an ordinary agent gives birth to a smart one is small: $P_{12} = 0.1$. The simulation demonstrates that the numbers of agents of the two types become close to each other, although the number of smart agents is somewhat larger than the number of ordinary agents. The dynamics of agents' resources and the number of agent births is qualitatively close to that of in the previous version.

5 Conclusion

Thus, the model of the evolution of a population of agents with different cognitive abilities has been built and analyzed. It is clear that this model is still very far from the models of agents capable to discover the laws of nature. Nevertheless, the model characterizes the features of the development of populations in which some of the agents have significantly more effective cognitive properties in comparison with other agents.

It is interesting that using this model, one can consider the evolution of people with different cognitive abilities in the human community. One can also consider the evolution of states with different levels of scientific development. Although, of course, such an interpretation of the results of the present model for human communities must be carried out with caution.

The further development of models of autonomous agents with effective cognitive abilities, the approaches outlined in the beginning of this article can be used. It is most appropriate to use the principles outlined in the works [1, 6].

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References

1. Red'ko, V.G.: Modeling of Cognitive Evolution: Toward the Theory of Evolutionary Origin of Human Thinking. URSS, Moscow (2018)
2. Red'ko, V.G.: Principles of functioning of autonomous agent-physicist. In: Chella, A., Pirrone, R., Sorbello, R., Johannsdottir, K.R. (eds.) Biologically Inspired Cognitive Architectures. Proceedings of the Third Annual Meeting of the BICA Society, pp 265–266. Springer, Heidelberg (2012)
3. Red'ko, V.G.: Modeling of feelings of causality. First results. Proceedings of NIISI RAS **9**(1), 66–68 (2019) (In Russian)
4. Red'ko, V.G.: Model of a feeling of causality. Proc. NIISI RAS **10**(2), 34–38 (2020). (in Russian)
5. Hume, D.: Philosophical Essays Concerning Human Understanding. A. Millar, London. (1748). See also: Hume, D.: Philosophical Essays Concerning Human Understanding. General Books LLC (2010)
6. Turchin, V.F.: The Phenomenon of Science: A Cybernetic Approach to Human Evolution. Columbia University Press, New York (1977)
7. Anokhin, P.K.: Biology and Neurophysiology of the Conditioned Reflex and its Role in Adaptive Behavior. Pergamon, Oxford (1974)
8. Vityaev, E.E.: Brain functioning principles, which are contained in the theory of functional systems by P.K. Anokhin and in the theory of emotions by P.V. Simonov. Neuroinformatics **3**(1), 25–78 (2008). (in Russian)
9. Demin, A.V., Vityaev, E.E.: Logical model of adaptive control system. Neuroinformatics **3**(1), 79–108 (2008). (in Russian)

Method for Automated Recognition of Frustration-Derived Aggression in Texts

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Abstract. The paper proposes a method for automatic recognition of reactions to frustration in texts. It also presents the results of a study that allows catching linguistic patterns for extrapunitive responses (E-reactions) aimed at protecting the "Self"; and shows the results of experiments with the Rosenzweig picture-frustration test protocols. We use a linguistic analyzer, "PCA Machine", which considers the wide range of multi-level features aggregated by the relational-situational model to process the texts with E-reactions to frustration. Then we developed a set of templates, which can catch the revealed linguistic patterns and use them together with machine learning models. This approach turns out to be new for modeling the reasoning of expert cognitive research. Experimental results show that in most cases, the templates allow detecting E-reactions. Moreover, the share of unrecognized reactions is small; however, to increase the recognition reliability, it is necessary to consider additional features, including the context of the analyzed text fragments.

Keywords: Reaction on frustration · Relational-situational analysis · Linguistic template · Rosenzweig picture-frustration study

1 Introduction

Rosenzweig defines extrapunitive reaction to frustration as a state of anger and indignation when one blames others for their fault [1]. His picture-frustration study (P-F study) has long been a useful research tool for assessing aggression as a reaction to frustration. In individual diagnostics, it is used to identify ways how a person responds to obstacles and accusations. Examples of typical answers are often used to define the test methodology.

However, until now, a systematic description of speech reactions to frustration in psychology has not appeared. On the one hand, this is because such research is interdisciplinary and requires a linguist; on the other hand, the very foundations of coding reactions in the methodology of P-F study are well described. Therefore psychologists intuitively understand the differences in responses of a particular type.

Natural language processing (NLP) methods make it possible to set new problems when creating new and modifying old psychodiagnostic methods. Simultaneously, identifying the linguistic foundations of Rosenzweig's types would also be in research interest

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because it opens up the possibility of professional reflection, discussing those linguistic features that psychologists are guided by when they rely on their expert intuition. Another motivation here is that recent studies show that frustration sometimes causes typologically definite shifts in speech; therefore it can be automatically detected [2].

In this paper, we identify and address the following open research question:

- Are there linguistic patterns of frustration response, and is it possible to hypothesize that the author of the text has frustration?

Furthermore, to address the question above, we have developed a software tool for the automatic classification of subjects' responses in the Picture-Frustration test, although there were technical issues:

1. Lexical richness, which means that there is much lexis to express particular ideas in speech. Besides, real texts are full of misspellings. We use a character-level word embeddings (FastText, [3]) to overcome this problem.
2. The frustration detection model should consider various linguistic features from morphology and lexemes to semantic roles and syntax dependencies.
3. The actual type of reaction in a text fragment often depends on the context. This leads to ambiguity, then we work with separate text fragments and means our approach has to be context-dependent.
4. Lack of training datasets. We propose to use a multistep approach to deal with the issue. Following the approach in the first step, we extract high-level features from text clauses with linguistic templates; then, we train a classification model with those features. In the final step, we use an additional set of simple context-dependent rules to disambiguate the classification results. This way, we can use a relatively simple machine learning model, which can be trained on a small labeled corpus without overfitting.

The rest of the paper is organized as follows. Section 1 provides an overview of related work. Section 2 contains a brief description of the experimental corpus and the methodology to build this corpus. Section 3 presents the proposed the revealed linguistic patterns and the method for the recognition of frustration-derived aggression in Russian texts. In Sect. 4, we analyze the experimental results and discuss the drawbacks and the directions of the future improvement of the method.

2 Related Work

The studies, which are the closest to this paper's topic, are devoted to sentiment analysis, aggression, and frustration detection in texts. For example, an article [4] presents a model, which has a sentiment analysis block to provide two-dimensional scores of emotion (valence and arousal), a market cognition analysis block based on context-dependent Hidden Markov Model (HMM). They also apply logistic regression model to reveal relationships between emotions in social networks and market cognition. This approach allows studying the effects of arousal in the market crash. The experimental results show that the increase of arousal emotions is related to the awareness of a market crash.

Similarly, paper [5] proposes a character level convolution neural network model that incorporates entity-specific sentiment information for efficient incivility detection. The model significantly outperforms other methods. In a result analysis, they also studied the behavioral aspects of the aggression targets and aggressors and tried to reveal the aggression reasons. Also, they have shown that there are patterns in aggressive behavior. Namely, they found a significant fraction of account holders who act as repeat offenders. They have mocked the targets more than ten times. Similarly, some targets get mocked multiple times. They found the targets to have higher reputation scores than the aggressors.

In [6], researchers analyzed more than 2 million messages, comparing discussion actors around neutral topics to those more likely to be hate-related. They use word embeddings, sentiment, and emotional indicators, lexis, and POS tags as features for classification and apply bidirectional LSTM [7] because the training dataset was quite big.

Several works tackle cognitive distortion detection. The main obstacle here is the lack of training datasets. For example, Shickel presents a relatively straightforward approach to that problem [8]. This approach involves detecting heterogeneous features for each text, which are then used to train separate logistic regression classifiers for predicting the label. They utilize n-grams, lexis, and word embeddings as features for the classification. Having a relatively small experimental dataset, he claims that the simplest text-based method is shown to provide the best performance. They also revealed the benefit of combining rigorous preprocessing with straightforward n-gram feature extraction and a simple linear classifier.

Similar results have been obtained in [9]. Namely, the researchers present a method to classify text into one of 15 distortion categories. They compared several machine learning-based approaches, such as Logistic regression, SVM, recurrent neural networks (Gated Recurrent Units) [10], gradient boosting on decision trees (XGBoost) [11]. The best-performing model is again logistic regression because the dataset was relatively small.

Paper [12] presents an HMM-based method for studying sentiment and user influence in social media networks. They model emotion-triggered impact and did analysis of emotion-influence causality and use relatively shallow features, such as keywords. The experiments show that the method can reveal influential users who express intense emotions of fear, anger, disgust, and sadness.

Agrawal with colleagues [13] propose a method that combines lexical features such as word and character n-grams with additional indicators like sentiment scores. Besides, they generate adult, offensive, and sentiment scores with neural models. With these features, the authors trained a Light-GBM model [14], which achieves better performance than deep-learning based models.

To sum the review up, some clues should be noted for the analysis of E-reactions in texts. Firstly, the lack of labeled corpora often leads to the situation; then, simple linear models show better quality scores than the deep-learning ones. Otherwise, if the training corpus is available, the standard approach is to use complex models for sequence labelings, such as recurrent neural networks and HMMs, since the context of the analyzed text fragments is crucial. Secondly, Agrawal with colleagues has shown that promising results can be obtained if one combines high-level features derived with some complex model, such as a deep neural network and a simple classification model, like Gradient Boosting.

3 Data Set of E-Reactions

We collected labeled dataset with text responses to frustration. Namely, we received pre-processed texts from 458 test subjects from Moscow and Kurgan, passed the P-F test, 1095 responses in summary. The test subjects are mainly university students and adult employees of several local companies. Those texts have all types and subtypes of reactions: extrapunitive, intropunitive, and impunitive ($E, E', e, M, M', m, I, I', i$).

Then, we separated those texts into fragments and performed the manual analysis by linguists. They studied the use of different-level linguistic units to express a specific type of response to frustration.

4 Aggression Classification Framework

The revealed and analyzed E-reaction patterns show five main communicative action groups in aggressive responses aimed at protecting the "Self".

1. Demand, often complicated by the illocutionary semantics of edification or reproach. The formal indicator of the performance of this action is the predicate expressed by:

   a) A verb in the imperative mood ("*Call your boss!*").
   b) Modal verbs "*can*", "*need*", "*have to*", "*should*" (rus: "*мочь*", "*должен*") in the subjunctive mood or an impersonal predicative word and an adjoining infinitive ("*You could have looked more attentively!*", "*You should look where you are going!*").

2. Sharp conviction of someone, negative assessment of someone's behavior, sometimes direct insult. The primary formal indicator of these actions is a predicate expressed by a noun or adjective of negative semantics ("*You are a liar*". "*Your accusations are disgusting*").
3. Confrontational denial of the partner's statements, rejection of his actions, sometimes with a tinge of reproach. In this case, the predicate uses the negative particle "*not*" (rus: "*не*"). ("*I don't even want to hear.*", "*You didn't keep your word*").
4. Outrage at something, expressed by a rhetorical question ("*And why should I wait another three hours?*", "*Why would I even know this?*").
5. Outraged mockery of the collocutor, expressed by an interrogative sentence with the idiom "*or what?*" (rus, part.: "*что ли?:*") ("*Are you talking to yourself, or what?*", "*Did you need to get the right, or what?*").

E-reactions can also be expressed by speech clichés of the corresponding semantics ("*Nothing of the kind!*" – denial of the collocutor's judgments. "*Are you out of your mind?*" – anger at one's behavior).

Figure 1 shows the aggression classification framework. In the first step, we apply MyStem [15] and UDPipe [16] to extract lexical, morphological features, and syntactic dependencies in the clauses. Then semantic role labeling is performed with the analyzer created at the FRC CS&C RAS [17] (PCA Machine). We use the relational-situational model of a text, a heterogeneous semantic network (HSN), to represent the extracted linguistic features. This model includes vertices (syntaxemes) and edges, which reflect the syntactic and semantic relationships between these vertices [18].

The second step consists of matching these network models (for each clause) with context-free templates, which contain a formalized description for multi-level linguistic features. The templates reflect features corresponding to particular groups of communicative actions. We created them to get higher recall than precision because it is hard to obtain high precision with any context-free approach.

In summary, there are 18 distinct templates of E-reactions. Each template itself is a fragment of a HSN. Vertices and edges in these fragments can be defined incompletely (for example, a vertex description can have part of speech or lexeme list only). Then we use a one-hot encoding approach and build high-level feature vectors, which hold information if a clause matches some templates.

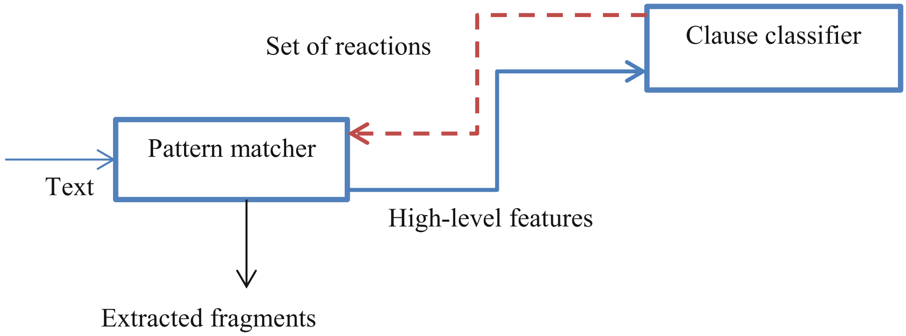

Fig. 1. Aggression classification framework

In the third step, we apply machine learning to train the models to classify the clauses. Since one clause can represent several reactions, we treat this classification problem as a multi-output one. Eventually, we have tested the following machine-learning methods:

1. Decision tree ensembles, such as a Random forest [19] and Gradient boosting on decision trees [14].
2. Linear SVM based classifier with L_2 regularization.

Since those models are single-output classifiers, we have trained an independent model for each output. We selected all the hyperparameters for the classifiers above with a grid search on 3 fold cross-validation. In the last step, we use a set of contextual templates, similar to those from step 2, to clarify the type of clauses, labeled with several classes. More precisely, these templates refer tokens from the clauses to distinct types of reactions.

5 Results and Discussion

We performed an experimental evaluation of the proposed method in pairs of texts containing E-reactions and texts containing all other types of reactions. We use standard scores to assess training reliability, which are precision, recall, and F1-score. Let describe them in more detail.

- *tp* is the number of correctly identified fragments containing E-reactions;
- *fp* is the number of fragments that do not contain E-reactions but are incorrectly assigned to this type by the classifier;
- *fn* is the number of the E-reaction fragments incorrectly assigned by the classifier to other types.

The precision (P) is the share of correctly identified fragments from all fragments marked by the classifier as E-reactions. Recall (R) - the proportion of correctly identified E-fragments and F1-score – harmonic mean of precision and recall.

$$P = \frac{tp}{tp + fp}, R = \frac{tp}{tp + fn}, F_1 = \frac{2PR}{P + R} \tag{1}$$

We use the statistical procedure of 3-fold cross-validation to evaluate the classification quality scores [20]. The XGBoost-based approach shows the best results, so we present the obtained scores for this classifier in Table 1.

Table 1. Results of detecting E-reactions among all other types of reactions

Reaction	F_1	P	R
E′	**0.81**	**0.68**	**0.99**
e	0.43	0.59	0.31
I	0.68	0.57	0.83
I′	**0.99**	**0.97**	**1.0**
M	**0.93**	**0.87**	**1.0**
M′	0.59	0.79	0.47
m	**0.90**	**0.83**	**1.0**
i	0.74	0.59	1.0

The high recall (*R*) shows that the created templates, in most cases, make it possible to identify E-reactions because the proportion of unrecognized reactions is small. Low precision (*P*) indicates that some context-dependent templates are needed after this step to consider additional features when classifying the types of responses. The creation of such templates is a topic of future research.

Therefore, the experiment shows that in most cases, the templates allow distinguishing between E-responses and other types of reactions, besides the share of unrecognized responses is small.

6 Conclusion and Future Work

In this study, we have revealed and validated some linguistic patterns of frustration E-response. Moreover, we built an automatic software tool, allows detecting this type of response.

For psychology, the proposed two-step text classification method can be considered, on the one hand, as an approach to professional self-reflection, and on the other, as a tool for verifying data of projective tests. It allows one to create a set of tools for automatic text psychodiagnostics (for example, discussions in social media). In linguistics, that approach builds a bridge from the categorical and grammatical meaning of an utterance to its psychological content. In cognitive research, it turns out to be a new method for modeling the reasoning of an expert evaluating texts.

However, the future revision of the proposed method is necessary. First of all, we are going to implement the last step of the framework and add context-dependent templates. Second of all, we admit that manual revealing of linguistic patterns is laborious; it reduces the scalability of the method. Therefore we are going to apply Transformer-based language models, which have been proved to emergent linguistic hierarchical structures while training [21]. With those models, one can significantly reduce a linguist's work from manual studying text corpora to examining template candidates provided by the network. Active learning also seems to be a perspective direction of future research because it simplifies creating the manual labeled corpora.

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References

1. Rosenzweig, S.: Types of reaction to frustration. J. Abnorm. Soc. Psychol. **29**(3), 298 (1934)
2. Kuznetsova, Y.M., Kuruzov, I.A., Smirnov, I.V., Stankevich, M.A., Starostina, E.V., Chudova, N.V.: Textual manifestations of social network user frustration. J. Medialinguistics **7**, 4–15 (2020)
3. Mikolov, T. Grave, E., Bojanowski, P., Puhrsch, C., Joulin, A.: Advances in pre-training distributed word representations. arXiv preprint arXiv:1712.09405 (2017)
4. Ge, Y., Liu, Z., Gu, W., Xu, L.: Beyond negative and positive: Exploring the effects of emotions in social media during the stock market crash. J. Inf. Process. Manage. **57**, 102218 (2020).
5. Maity, S.K., Chakraborty, A., Goyal, P., Mukherjee, A.: Opinion conflicts: AN effective route to detect incivility in Twitter. Proc. ACM Hum. Comput. Inter. **2**, 1–27 (2018)
6. Chatzakou, D., Leontiadis, I., Blackburn, J., De Cristofaro, E., Stringhini, G., Vakali, A., Kourtellis, N.: Detecting cyberbullying and cyberaggression in social media. ACM Trans. Web (TWEB). **13**(3), 1–51 (2019)
7. Hochreiter, S., Schmidhuber, J.: Long short-term memory. Neural Comput. **8**(9), 1735–1780 (1997)
8. Shickel, B., Rashidi, P.: Automatic triage of mental health forum posts. In: Proceedings of the Third Workshop on Computational Linguistics and Clinical Psychology, pp. 188–192 (2016)
9. Shickel, B., Siegel, S., Heesacker, M., Benton, S., Rashidi, P.: Automatic Detection and Classification of Cognitive Distortions in Mental Health Text. In: arXiv preprint arXiv:1909.07502 (2019)

10. Chung, J., Gulcehre, C., Cho, K., Bengio, Y.: Empirical evaluation of gated recurrent neural networks on sequence modeling. In: arXiv preprint arXiv: 1412.3555 (2014).
11. Friedman, J. H.: Greedy function approximation: a gradient boosting machine. J. Ann. Stat. **29**, 1189–1232 (2001)
12. Chung, W., Zeng, D.: Dissecting emotion and user influence in social media communities: an interaction modeling approach. J. Inf. Manage. **57**(1), 103108 (2020)
13. Agrawal, P., Suri, A.: NELEC at SemEval-2019 task 3: think twice before going deep. In: arXiv preprint arXiv:1904.03223 (2019).
14. Ke, G., et al.: Lightgbm: a highly efficient gradient boosting decision tree. J. Adv. Neural Inf. Process. Syst., 3146–3154 (2017)
15. Mystem analyzer. https://tech.yandex.ru/mystem/doc/index-docpage
16. Straka, M., Straková, J.: Tokenizing, pos tagging, lemmatizing and parsing ud 2.0 with udpipe. In: Proceedings of the CoNLL 2017 Shared Task: Multilingual Parsing from Raw Text to Universal Dependencies, pp. 88–99 (2017)
17. Shelmanov, A., Devyatkin, D.: Semantic role labeling with neural networks for texts in Russian. In: Computational Linguistics and Intellectual Technologies. Papers from the Annual International Conference "Dialogue", vol. 16, pp. 245–256 (2017)
18. Osipov, G.S., Smirnov, I.V., Tikhomirov, I.A.: Relational-situational method for text search and analysis and its applications. J. Sci. Tech. Inf. Process. **37**(6), 432–437 (2010)
19. Breiman, L.: Random forests. J. Mach. Learn. **45**(1), 5–32 (2001)
20. Flach, P.: Machine learning: the art and science of algorithms that make sense of data. Cambridge University Press (2012).
21. Manning, C.D., Clark, K., Hewitt, J., Khandelwal, U., Levy, O.: Emergent linguistic structure in artificial neural networks trained by self-supervision. J. Proc. Natl. Acad. Sci. **117**, 30046–30054 (2020)

Representation of "Natural" Concepts and Classes by a Hypernet Lattice of (Probabilistic) Formal Concepts

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Abstract. In previous works, a probabilistic generalization of formal concepts was developed that is resistant to noise and is capable of restoring formal concepts. In this paper, we show that probabilistic formal concepts have a deeper meaning than the restoration of formal concepts. Probabilistic formal concepts model "natural" concepts explored in cognitive sciences and "natural" classes explored in the "natural" classification. The hyper network of probabilistic formal concepts reflects the hierarchical structure of complex patterns – a hierarchy of secondary, increasingly complex features that are found as a result of deep learning. This hierarchy, obtained by logical-probabilistic methods, in addition to being "natural", is also explanatory, since it can give descriptions of its classes in logical-probabilistic terms. Thus, the hierarchy of probabilistic formal concepts discovered on complex images yields logical-probabilistic deep learning. The vertices of the hyper simplexes of the hyper network of probabilistic formal concepts reflect the content of "natural" concepts and classes, as they are inextricably linked with the underlying features. These vertices determine the meanings of "natural" concepts and classes, which are not reducible to the features that form them.

Keywords: Concept · Clustering · Hypernet lattice · Probabilistic formal concept

1 Hypernet of Probabilistic Formal Concepts

In Formal Concept Analysis [1], "formal concepts" are classification units that group data of the tables ("formal contexts") over a set of objects G and features M, in which rows are objects from G, and columns are attributes from M. Objects are grouped into classes in such a way that objects that have a maximum set of common attributes are included in the class, and this set of objects is maximum, i.e. no other object outside this class possesses the same set of attributes. The pairs (set of objects, set of features) obtained in this way can be naturally ordered by inclusion and represented as a complete lattice. Here is an example from the report of S.O. Kuznetsov.

In this example (Fig. 1) we have 4 objects for which 4 features a,b,c,d are defined. For these objects, 7 non-trivial formal concepts are defined, nested into each other by

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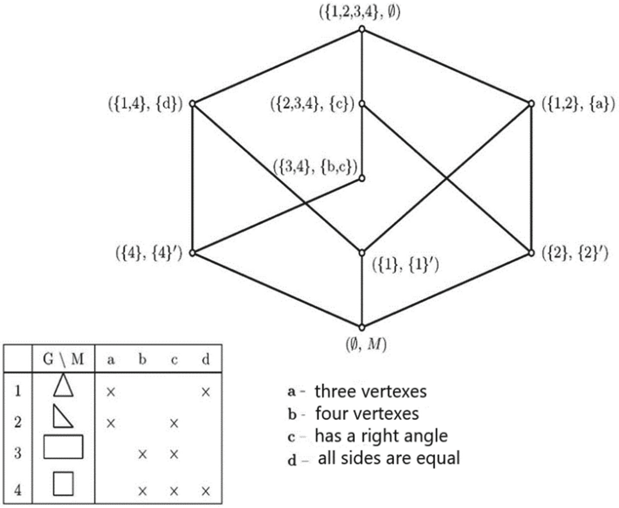

	G \ M	a	b	c	d
1	△	×			×
2	◺	×		×	
3	▭		×	×	
4	□		×	×	×

a - three vertexes
b - four vertexes
c - has a right angle
d - all sides are equal

Fig. 1. Lattes of formal concepts

inclusion ({4}, {4}′), ({1}, {1}′), ({2}, {2}′), ({1,4}, {d}), ({3,4}, {b, c}), ({1,2}, {a}), ({2,3,4}, {c}), where {4}′- all features of the object 4. Note that the definition of formal concepts is the same as that of a syndrome (a complex of organically related features). The syndrome includes all features common to the cases under consideration. However, the construction of the lattice of formal concepts is associated with the following problem: in the presence of noise (data distortions), the lattice of formal concepts is filled with noisy clones of the original classes-concepts, which leads to its exponential growth. In the works of [3–5] a probabilistic generalization of formal concepts is developed that is resistant to noise and is capable of restoring formal concepts.

The purpose of this work is to show that probabilistic formal concepts have a deeper meaning than the restoration of formal concepts under conditions of noise. Probabilistic formal concepts model "natural" concepts explored in the cognitive sciences. In works [6, 7] it is shown that "natural" concepts reflect a highly correlated structure of features of objects of the external world, which can be represented by "causal models" that are fairly accurately formalized by probabilistic formal concepts. The highly correlated structure of features of objects in the external world is also manifested in the "natural" classification. J. Stuart Mill [8] very accurately described "natural" classes as probabilistic formal concepts: "Natural groups… Are determined by features… However, this takes into account not only features that are certainly common to all objects included in the group, but the entire set those features, of which all are found in most of these objects, and most - in all". This definition, which J. Mill formulated back in 1843, differs from the definition of a formal concept only in that He says about most objects and features, which is precisely taken into account in the definition of probabilistic formal concepts.

The hypernetwork of probabilistic formal concepts reflects not only nesting according to features and objects, but also the natural "embeddedness" of objects of the external world, as J. Gibson wrote. Moreover, all complex images – faces, paintings, literary works contain a hierarchy of secondary, increasingly complex features. That is why Deep Learning methods have achieved impressive results. They organized hierarchical processing of information in neural networks that can capture this hierarchy of secondary features. Probabilistic formal concepts can reveal this hierarchy as a hierarchy of "natural" secondary features (concepts) and a hierarchy of "natural" classes. This hierarchy, obtained by logical-probabilistic methods, besides being "natural", is also "explainable", since it can give descriptions of its classes in logical-probabilistic terms. Thus, the hierarchy of probabilistic formal concepts discovered on complex images yields logical-probabilistic deep learning. Classes descriptions, obtained in this hierarchy automatically, are the vertices of the hyper-simplexes of the hypernetwork of probabilistic formal concepts that reflect the content of these "natural" classes. This vertex of the hypersimplex determines the meaning of the "natural" concept, which is not reducible to the content of the features that form it.

2 Probabilistic Formal Concepts

The precise definition of the probabilistic formal concepts is given in works [3–5]. Here we describe the process of probabilistic generalization of formal concepts in order to demonstrate its naturalness, although it is not mathematically trivial.

It consists in the following steps:

1. Define formal concepts as fixed points of implication [1].
2. Replace implications with probabilistic causality satisfying the following properties:
   a. Cartwright's definition of probabilistic causality [2]:
   If $\mathrm{R} = (\mathrm{H}_1\&...\&\mathrm{H}_k \Rightarrow \mathrm{H}_0)$, $\mathrm{R}^{\leftarrow} = \{\mathrm{H}_1, \ldots \mathrm{H}_k\}$, $\mathrm{R}^{\rightarrow} = \mathrm{H}_0$, then
   $\nu(R^{\rightarrow}/\&R^{\leftarrow}) > \nu(R^{\rightarrow}/\&(R^{\leftarrow}\backslash H))$, $\mathrm{H} \in \mathrm{R}^{\leftarrow}$.
   b. Satisfies the condition of maximal specificity, defined by Hempel [9]. Informally, this condition means that the probabilistic causal relationships must use maximum of available information.
   c. Define maximum specific probabilistic causality as probabilistic causality that satisfy conditions a,b.
3. Define probabilistic formal concepts as fix-points of these maximum specific probabilistic causalities.
4. Prove [10] that these fix-points are logically consistent and not contain some feature and its negation.
5. Define probabilistic formal concepts in terms of these fix-points.

Define "natural" classification and "natural" concepts as probabilistic formal concepts.

Let us consider the condition of maximal specificity in more details for the further definition of the neuron formal model that can learn maximum specific probabilistic causalities.

The condition of maximal specificity was defined by Hempel for solution of the statistical ambiguity problem. This problem rises in the field of the Inductive-Statistical (I-S) inference when inconsistent conclusions may be inferred from the consistent premises. Let us consider a traditional example. Suppose that we have the following statements:

- L1 Almost all cases of streptococcus infection clear up quickly after the administration of penicillin.
- L2 Almost no cases of penicillin resistant streptococcus infection clear up quickly after the administration of penicillin.
- C1 Jane Jones had streptococcus infection.
- C2 Jane Jones received treatment with penicillin.
- C3 Jane Jones had a penicillin resistant streptococcus infection.

These statements imply a contradiction by I-S inference. On the base of L1 and C1$\wedge$C2 one can explain why Jane Jones recovered quickly (E). The second argument with premises L2 and C2$\wedge$C3 explains why Jane Jones did not ($\neg$E). The premises of both arguments are consistent with each other, they could all be true. However, their conclusions contradict each other.

Hempel suggested to solve this problem by forcing all statistical laws in an argument to be maximally specific. In other words, they should contain all relevant information with respect to the domain in question. In our example the premise C3 invalidates the first argument L1, since it is not maximally specific with respect to all information about Jane Jones. So, we can only explain $\neg$E, but not E. The maximally specific statement instead of L1 must be "Almost all cases of streptococcus infection *that are not penicillin resistant* clear up quickly after the administration of penicillin".

We have proved that maximal specific causal relations solve the problem of statistical ambiguity [10] and I-S inference is consistent if it uses only maximally specific statements.

3 Formal Model of Neuron that Learn Maximal Specific Causal Relations. Probabilistic Formal Concepts as Cellular Ensembles

We formalize the conditional connection at the level of the neuron in such a way that it at first satisfies the Hebbian rule [11] and second can learn maximum specific probabilistic causalities. We developed a special semantic probabilistic inference [12] that learn such causalities.

By information, given to brain as «input», we mean all stimulus provided by afferent systems. Let us define information about a certain stimulus n, arising from an object (situation) a and transmitted by a nerve fiber, by a predicate $P_i(a)$, $i = 1, ..., n$, where a is a perceived object (situation). If this information transmitted on excitatory synapse, then it perceived by neuron as a truth of the predicate $P_i(a)$, and if this information transmitted on the inhibitory synapse, then it perceived as a negation of the predicate $\neg P_i(a)$. We define the excitation of neuron (its axon) in a situation (object) a by a special predicate $P_0(a)$. If neuron is inhibited in situation a, then we define this by a negation of this predicate $\neg P_0(a)$. We suppose, that each neuron is exciting by its receptive field, which is initial (before training) semantics of this predicate $P_0(a)$.

Predicates $P_i(a)$, $i = 1, \ldots, n$ and their negations are literals, which we denote as $a, b, c, \ldots \in L$. Let us introduce some definitions needed for the formal model.

The rule C $= (a_1\&\ldots\&a_n \Rightarrow c)$ is a *subrule* of the rule C$' = (b_1\&\ldots\&b_k \Rightarrow c)$ if $\{a_1\&\ldots\&a_n\} \subset \{b_1\&\ldots\&b_k\},\ n < k$.

By the *probabilistic law* we mean the rule C $= (a\&\ldots\&b \Rightarrow c)$, the conditional probability $(a\&\ldots\&b\&c)\big/(a\&\ldots\&b)$ of which is strictly greater than conditional probabilities of all its subrules. *Strongest Probabilistic Law* is a probabilistic law that is not a subrule of another probabilistic law.

Semantic probabilistic inference (Fig. 2) of a literal *c* is a sequence $C_1 \sqsupset C_2 \sqsupset \ldots \sqsupset C_n$ of probabilistic laws C$_i = (a_i\&\ldots\&b_i \Rightarrow c_i)$, such that C_i is a subrule of the rule C_{i+1} and probability of C_i is strictly less than the probability of $C_{i+1},\ i = 1, \ldots n-1$. C_n is the strongest probabilistic law.

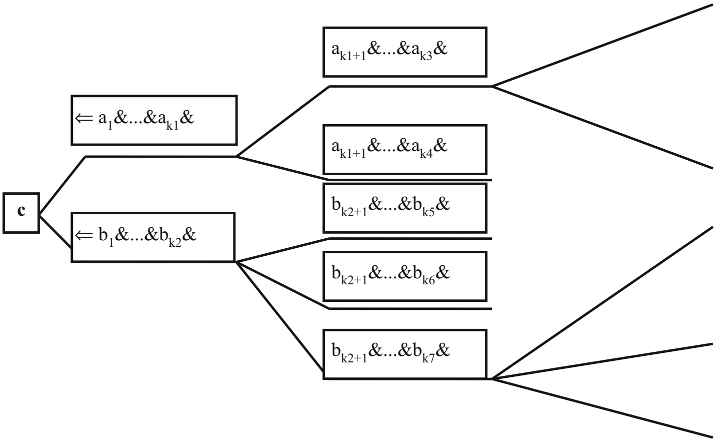

Fig. 2. Semantic probabilistic inference

A *maximally specific rule* MSR(c) for the inference of a literal *c* is a such Strongest Probabilistic Law of some *Semantic probabilistic inference* of a literal *c* that have maximum value of conditional probability.

Theorem [9] (solution of the statistical ambiguity problem). I-S inference and fix-points that use only MSR(c) rules are consistent.

Our formal model of a neuron (Fig. 3) is very similar to the structure of the semantic probabilistic inference (see Fig. 2) and it accurately implements the semantic probabilistic inference and thereby reveals the most specific causal relationships. Fix-points of these most specific causal relationships, produced by interconnected neurons, form cellular ensembles of self-excited neurons that form probabilistic formal concepts, reflecting a highly correlated structure of features of perceived "natural" objects.

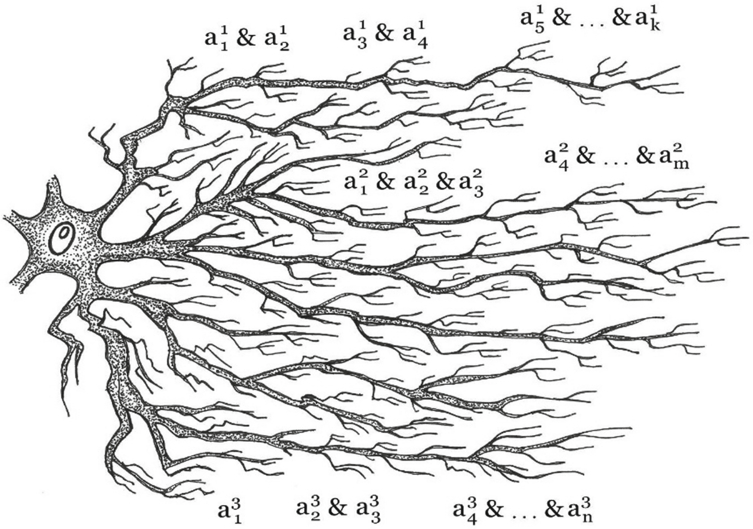

Fig. 3. Formal model of neuron

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References

1. Ganter, B., Wille, R.: Formal Concept Analysis - Mathematical Foundations. Springer, Heidelberg (1999)
2. Cartwright, N.: Causal laws and effective strategies. Noûs **13**, 419–437 (1979)
3. Vityaev, E., Demin, A., Ponomariov, D.: Probabilistic generalization of formal concepts. Program. Comput. Softw. **38**, 18–34 (2012). (in Russian)
4. Vityaev, E., Martynovich, V.: Probabilistic formal concepts with negation. In: Voronkov, A., Virbitskaite I. (eds.) Perspectives of System Informatics. LNCS, vol. 8974, pp. 385–399. Springer, Heidelberg (2015)
5. Martynovich, V., Vityaev, E.: Recovering noisy contexts with probabilistic formal concepts. In: Proceedings of the 2nd International Workshop on Soft Computing Applications and Knowledge Discovery. CEUR, Workshop Proceedings, vol. 1687, pp. 24–35 (2016)
6. Rosch, E.: Natural categories. Cogn. Psychol. **4**, 328–350 (1973)
7. Bob, R.: Categorization as causal reasoning. Cogn. Sci. **27**, 709–748 (2003)
8. Mill, J.: System of Logic. Ratiocinative and Inductive (1983)
9. Hempel, C.: Maximal specificity and lawlikeness in probabilistic explanation. Philos. Sci. **35**, 116–133 (1968)
10. Vityaev, E., Odintsov, S.: How to predict consistently? In: Cornejo Piñeiro, M.E., Kóczy, L.T., Medina, J., de Barros Ruano, A.E. (eds.) Trends in Mathematics and Computational Intelligence. Studies in Computational Intelligence, vol. 796, pp. 35–41. Springer (2019)
11. Hebb, D.: The Organization of Behavior. A Neurophysiological Theory. NY (1949)
12. Vityaev, E.: The logic of prediction. In: Goncharov, S., Downey, R., Ono, H. (eds.) Mathematical Logic in Asia 2005, Proceedings of the 9th Asian Logic Conference, pp. 263–276. World Scientific (2006)

Methodological Miscellania

Data-Driven Parametric Statistical Testing of Functional Connectivity Between Brain Sources Characterized by Activity with Close-to-Zero Phase Lags

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Abstract. One of the main methodological problems in evaluation of functional connectivity is the spatial leakage (SL) effect which occurs due to volume conduction and leads to false positives in coherence or phase-locking estimates. Several solutions have been already suggested, including the use of the imaginary part of coherency or cross-spectrum. Because these standard metrics are insensitive to zero-phase interactions, they prevent detection of false coupling, resulting from SL, but may underestimate true physiological interactions, characterized by close-to-zero phase lags. Due to the broad neurophysiological evidence, such interactions should not be excluded from consideration. The recently proposed method, referred as Phase Shift Invariant Imaging of Coherent Sources (PSIICOS), became the first implementation of the algorithm which reliably detects interactions for all the range of phase-lags by suppressing the power of SL subspace components of cross-spectrum. However, connectivity values obtained via PSIICOS are non-normalized by construction and depend on source power, so that uncoupled sources with high power profiles may become false positives. This limitation motivated us to develop a statistical test based on randomization of original time series or cross-spectrum in such a way that power distribution in source space is preserved, but phase interactions are eliminated. The generation of covariance matrices from Wishart distribution appeared to be the most reliable method, when applied to data from simulations. Thus, together with the proposed statistical test PSIICOS can be used as an effective instrument applicable to real EEG- or MEG-data in fundamental research or for clinical purposes.

Keywords: EEG · MEG · Connectivity · Cross-spectrum · Volume conduction · Wishart distribution · Statistical testing

1 Introduction

Despite the rapid development of neuroscience, the explanation of functional abilities of the brain is still a mystery that stirs up the minds of both theorists and methodologists. All the features that describe the brain would not contribute to its high computational

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capacities, if its elements did not possess a crucial property – the presence of functional connectivity [1].

The conclusive evidence suggests that connectivity, reflecting interactions between brain areas, underlies healthy brain functioning [2] and determines its dynamical properties [3]. Characterized by high temporal resolution, such non-invasive neuroimaging techniques as EEG and MEG, together with methods of source localization, make it possible to accurately estimate spatial, temporal and frequency characteristics of functional coupling. Nevertheless, the choice of robust methods and their improvement are still in great demand.

Within the scope of this paper, we operationalize functional connectivity as phase coupling. It represents engagement of neuronal oscillations at similar frequencies and reflects frequency-specific parameters of brain functioning [4]. In general, measures of phase coupling quantify the consistency of distribution of phase lags between signals by estimating the properties of cross-spectral density function – the frequency equivalent of cross-covariance function, which measures the joint variability of two signals at pairs of time points [5].

One of the main methodological problems in noninvasive evaluation of phase coupling is the spatial leakage (SL) effect which occurs due to volume conduction [6] and leads to false positive scalp correlations [7]. The standard metrics of phase coupling exploit the assumption that SL effects are instantaneous due to quasi-static approximation of the forward model [8–10]. The standard methods, such as imaginary coherence [10] or phase lag index [11] and their derivatives [12–15] exclude artifactual zero phase interactions together with true zero phase interactions. Besides, the majority of these methods reach the maximum of their sensitivity when the phase lag $\Delta\phi = \pi/2$ and approach zero when $\Delta\phi$ is close to zero. Thus, all standard metrics can underestimate true connectivity. Moreover, simulations illustrated that the presence of true interactions spreads the signal and produces ‘ghost’ false positive interactions between uncoupled sources. Ironically, these ‘ghost’ interactions are still detected by the algorithms based on exclusion of zero-phase coupling [16].

The importance of capturing zero or near-zero phase interactions is supported by empirical evidence: this type of coupling was reported in animal visual cortex [17, 18] as well as both visual and motor cortex [19] and was supposed to reflect sensory or visuomotor integration due to communication via reciprocal cortico-cortical connections. In humans, phase coupling with zero-centered distribution of lags was reported in subjects who viewed ambiguous visual stimuli and perceived faces rather than meaningless shapes [20]. Zero-phase rhinal-hippocampal coupling in gamma frequency range was registered [21] in patients with unilateral temporal lobe epilepsy as a result of successful declarative memory formation. In neocortex, near-zero phase interactions occur more often than zero phase coupling. The delays in neuronal interactions fall in the millisecond or submillisecond range [22]. These lags are consistent and may reflect, for example, visual stimulus orientation [23]. The major possible mechanisms that could underlie zero and near-zero phase phase synchronization include bidirectional communication between two areas [24]; the presence of common input – an area which drives two other areas into near-zero phase coupling [25]; or dynamical relaying [26, 27] via brainstem, hippocampus or thalamus [28]. Thus, all the metrics of phase coupling, based on exclusion of zero phase interactions make us blind in regard to a broad range of physiologically plausible functional coupling scenarios.

The recently proposed method, referred as Phase Shift Invariant Imaging of Coherent Sources (PSIICOS) [29], became the first implementation of the algorithm which reliably detects interactions for the entire range of phase-lags from the debiased sensor-space cross-spectrum resulting from suppression of SL power by the means of a projector operating in the linear space of cross-spectral matrices. However, connectivity values obtained via PSIICOS are non-normalized by construction and depend on source power, so that functionally uncoupled sources but powerful sources may be detected as coupled and thus generate false positives. This issue can be resolved by an appropriate statistical procedure on the basis of null distribution of cross-spectral coefficients. The development of such a statistical test defined the aim of the present study.

2 Material and Methods

2.1 Randomization Techniques

As it was previously stated, the aim of this study is to develop such a technique that allows for obtaining the distribution of cross-spectral coefficients under a null hypothesis of no coupling between sources. Two major approaches for construction of such a distribution are randomization of EEG or MEG time series, resulting in surrogate data, or randomization on the basis of already computed cross-spectrum.

Surrogate testing implies generation of multiple time series, which share the same statistical properties with the original one but lack the target property (in our case this target property is phase coupling). The values of interest (e. g. cross-spectral coefficients) obtained on the basis of that surrogate data form null distribution that can be compared to the observed value obtained from the original data. If the observed value statistically deviates from the surrogate distribution, one can conclude that the target property is present in the original data.

For surrogate testing we have chosen randomization of independent components obtained for the EEG or MEG data [30], AR-modeling and cyclic phase permutations of the source-space activity (CPP) [31].

2.2 Sampling from Wishart Distribution

Aside from surrogate testing, data-based parametric approaches can be used. The basic idea is to use a parametric distribution which represents the probability of observing a given covariance matrix. Note that a cross-spectral matrix that is instrumental in PSIICOS approach is simply a covariance matrix of Fourier coefficients at a specific frequency.

Let us consider a p × n random matrix

$$\mathrm{X} = (\mathrm{x}_1, \mathrm{x}_2, \ldots, \mathrm{x}_n) \sim N_{p\times n}(\mathrm{M}, \Sigma), \tag{1}$$

which consists of p-variate Gaussian random vectors with mean M and scale covariance matrix Σ. In this case $p \times p$ random matrix $\mathrm{S} = \mathrm{XX}^T$ has Wishart distribution [32] (a multivariate extension of χ^2-distribution) with scale matrix Σ and n degrees of freedom. We expect the cross-spectral estimates to be Wishart-distributed and therefore in order to model statistical properties of the cross-spectral matrices under null-distribution of no coupling we use Wishart distribution with S whose elements are determined from the data and spatial leakage properties encoded into the forward operator.

The standard way to obtain a random sample from Wishart distribution is Bartlett decomposition [33]. If orientations of the dipoles are not fixed, then the $i-$ th source is represented by the topographies of two orthogonally oriented equivalent current dipoles (ECDs) $g_i= [g_i^x g_i^y]$ in the tangential plane at the given $i-$ th vertex. In this case, by the means of traditional inverse mapping procedures, for a given pair of sources at fixed latency t we estimated the power of activation timeseries of the two orthogonal ECDs. These power components formed the diagonal of the scale matrix Σ. The off-diagonal terms reflected spatial leakage calculated using the forward model and notions of point-spread function. In order to obtain null distribution of cross-spectral values for sources with fixed orientations, the principal orientation angle was found by means of singular value decomposition (SVD) applied to the upper right 2×2 part of Wishart matrix.

The degrees of freedom of Wishart distribution were equated to the number of epochs in the data. Cross-spectral estimates used by PSIICOS exploit the cross-spectrum at all latency values within an epoch. In order to model this we build null Wishart distributions for each fixed latency and then perform Fisher's probability test to combine the results of individual tests from each latency. This gives the final p-value with regards to the averaged observed cross-spectral coefficient.

2.3 Material

The accuracy of the proposed approaches was evaluated on the basis of realistic simulation studies. We used a cortical surface with 15000 vertices and a high-resolution forward-model matrix.

The data consisted of 100 epochs, and the induced activity of coupled sources was modeled with two 10 Hz sinusoidal waveforms with random phase with respect to the start of each epoch. The phase jitter was drawn from a random distribution from the $[-\pi/2\ \pi/2]$ range. To simulate the close to zero phase coupling mean phase lag was established as $\phi = \pi/20$. The power spectrum density of the modeled brain noise matched the spectral characteristics of EEG or MEG data. The sources were projected into the sensor space using the forward matrix pre-computed with Brainstorm software.

In our simulations, each truly coupled network corresponded to the pair of nodes in the high-resolution cortical mesh. As for estimating source-space cross-spectral coefficients we used a sparser version of the cortical mesh, we considered a given pair of sources to be a true connection, if their coordinates fell into a given neighborhood around the original coordinates.

We tested the accuracy of our approaches in two conditions: the detection of three modeled networks and the detection of two modeled networks in the presence of one uncoupled network with high power characteristics. The latter condition was supposed to test the immunity of our statistical paradigms to the presence of false large cross-spectral estimates.

3 Results

The comparison of the proposed statistical approaches demonstrated that data-driven parametric testing outperforms surrogate testing. Using ICA-based surro-gate distribution results in constant sensitivity (true positive rate) TPR = 1, and the maximal specificity was equal to 0.67, which is unsatisfactory due to a larger number of pairs tested. CPP surrogates performed better and achieved for maximal sensitivity TPR = 1 was at higher specificity of 0.76. Statistical testing based on the AR modeling yielded for sensitivity TPR = 1 the specificity of 0.97, but was characterized by a very poor spatial distribution of the false positive source pairs. It should be stressed that truly coupled sources constitute just a small part of all possible connections and, consequently, sensitivity is expected to be large. Additionally, falsely detected pairs are to have spatially consistent structure and would ideally fall into the neighbourhood of the truly coupled sources. Thus, for the statistical test to be of a high accuracy we should consider only high specificity values along with low false alarm rate.

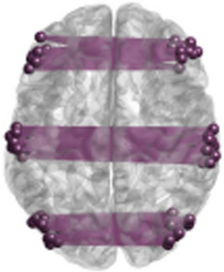

Fig. 1. The spatial structure of three modeled networks. In various conditions one of the networks was uncoupled and characterized by a high power resulting in large cross-spectral coefficients. The working statistical test was expected to detect only two truly coupled networks.

Parametric approach based on using the Wishart distribution as a null distribution, appeared to me more accurate. The viability of the proposed approach is supported by reasonable reconstruction of spatial structure of the modeled networks even in the presence of the highly powerful sources. Without statistical testing, these sources correspond to the largest cross-spectral coefficients and would produce the false positive detection of coupling. Since Wishart distribution implicitly captures interrelation between power components and covariances, it was demonstrated that even when the cross-spectral coefficients of the uncoupled sources exceed the ones from the coupled sources, they are correctly labeled as statistically insignificant (see Fig. 1 and Fig. 2).

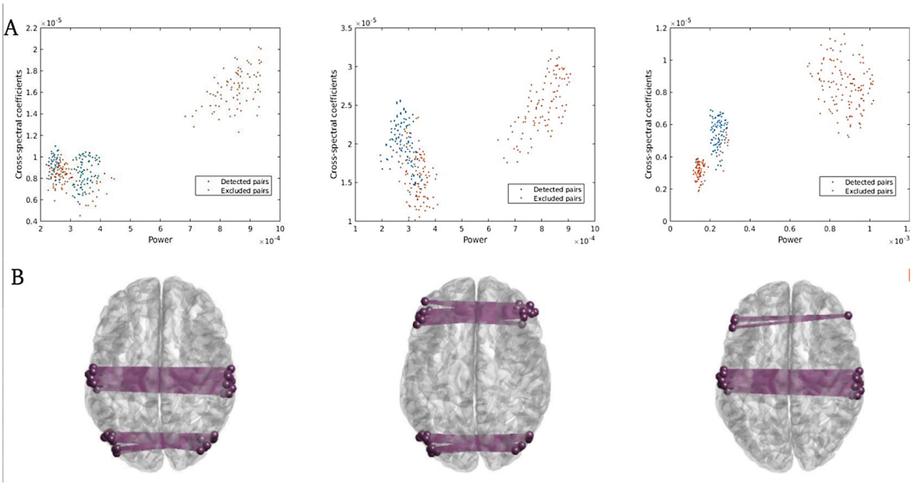

Fig. 2. The demonstration of the immunity of Wishart-based statistical test to the powerful but functionally uncoupled sources. (A) The dependence of cross-spectral coefficients and source power. The distinguishable cluster of points represents uncoupled pairs of sources. As evident from the plot, these pairs are successfully labeled as statistically insignificant ($p < 0.05$). (B) The spatial structure of the detected coupled networks.

4 Discussion

We have tested and evaluated several approaches of statistical testing in order to assess the statistical significance of cross-spectral estimates obtained after PSIICOS-projection [29], which allows us to overcome the artifacts of volume conduction and supports an accurate detection of zero and close-to-zero phase coupling. Using realistic simulations, we have compared the performance of the following methods that allowed us to form the null distribution of cross-spectral estimates and use it as a statistical criterion: random shifting of independent components, AR modeling of source activity, cyclic phase permutations (CPP) and sampling from Wishart distribution.

Parametric approaches based on Wishart distribution outperformed surrogate testing. ICA-based surrogate testing yielded too randomized data, although we expected such a surrogate distribution to be much more conservative due to the possibility of several coupled dipoles to contribute to the same component. CPP-based surrogates demand to be modified with respect to more accurate extraction of phase cycles. AR-based surrogate distribution as well as Wishart distribution were close to the empirically observed distribution of cross-spectral estimates from the simulation without synchronized activity. However, AR-based surrogate distribution being used as a statistical criterion failed to reconstruct spatial patterns of modeled networks. On the other hand, statistical testing based on Wishart distribution was immune to the presence of uncoupled networks with a high power profile.

5 Conclusion

Thus, with a high degree of certainty we can conclude that the proposed parametric approach based on Wishart distribution forms a viable basis for a statistical testing. This expands the capabilities and accuracy of PSIICOS technique. We conclude that the procedure can be useful in estimating genuinely low phase-lag coupled sources ubiquitously present in the empirical data.

References

1. Sporns, O.: The human connectome: a complex network. Ann. N. Y. Acad. Sci. **1224**(1), 109–125 (2011)
2. Greicius, M.: Resting-state functional connectivity in neuropsychiatric disorders. Curr. Opin. Neurol. **21**(4), 424–430 (2008)
3. Hutchison, R.M., Womelsdorf, T., Allen, E.A., Bandettini, P.A., Calhoun, V.D., Corbetta, M., Della Penna, S., Duyn, J.H., Glover, G.H., Gonzalez-Castillo, J., et al.: Dynamic functional connectivity: promise, issues, and interpretations. Neuroimage **80**, 360–378 (2013)
4. Siegel, M., Donner, T.H., Engel, A.K.: Spectral fingerprints of large-scale neuronal interactions. Nat. Rev. Neurosci. **13**(2), 121–134 (2012)
5. Bastos, A.M., Schoffelen, J.M.: A tutorial review of functional connectivity analysis methods and their interpretational pitfalls. Front. Syst. Neurosci. **9**, 175 (2016)
6. Nunez, P.L., Srinivasan, R., Westdorp, A.F., Wijesinghe, R.S., Tucker, D.M., Silberstein, R.B., Cadusch, P.J.: Eeg coherency: I: Statistics, reference electrode, volume conduction, laplacians, cortical imaging, and interpretation at multiple scales. Electroencephalogr. Clin. Neurophysiol. **103**(5), 499–515 (1997)
7. Westdrop, A.: Volume conduction effects on correlation analysis of EEG data. In: 1993 Proceedings of the Twelfth Southern Biomedical Engineering Conference, pp. 150–152. IEEE (1993)
8. Plonsey, R., Heppner, D.B.: Considerations of quasi-stationarity in electro-physiological systems. Bull. Math. Biophys. **29**(4), 657–664 (1967)
9. Stinstra, J., Peters, M.: The volume conductor may act as a temporal filter on the ECG and EEG. Med. Biol. Eng. Compu. **36**(6), 711–716 (1998)
10. Nolte, G., Bai, O., Wheaton, L., Mari, Z., Vorbach, S., Hallett, M.: Identifying true brain interaction from eeg data using the imaginary part of coherency. Clin. Neurophysiol. **115**(10), 2292–2307 (2004)
11. Stam, C.J., Nolte, G., Daffertshofer, A.: Phase lag index: assessment of functional connectivity from multi channel eeg and meg with diminished bias from common sources. Hum. Brain Mapp. **28**(11), 1178–1193 (2007)
12. Nolte, G., Ziehe, A., Nikulin, V.V., Schlögl, A., Krämer, N., Brismar, T., Müller, K.R.: Robustly estimating the flow direction of information in complex physical systems. Phys. Rev. Lett. **100**(23), 234101 (2008)
13. Pascual-Marqui, R.D., Lehmann, D., Koukkou, M., Kochi, K., Anderer, P., Saletu, B., Tanaka, H., Hirata, K., John, E.R., Prichep, L., et al.: Assessing interactions in the brain with exact low-resolution electromagnetic tomography. Phil. Trans. Roy. Soc. A Math. Phys. Eng. Sci. **369**(1952), 3768–3784 (2011)
14. Ewald, A., Marzetti, L., Zappasodi, F., Meinecke, F.C., Nolte, G.: Estimating true brain connectivity from eeg/meg data invariant to linear and static transformations in sensor space. Neuroimage **60**(1), 476–488 (2012)

15. Vinck, M., Oostenveld, R., Van Wingerden, M., Battaglia, F., Pennartz, C.M.: An improved index of phase-synchronization for electrophysiological data in the presence of volume-conduction, noise and sample-size bias. Neuroimage **55**(4), 1548–1565 (2011)
16. Palva, J.M., Wang, S.H., Palva, S., Zhigalov, A., Monto, S., Brookes, M.J., Schoffelen, J.M., Jerbi, K.: Ghost interactions in MEG/EEG source space: a note of caution on inter-areal coupling measures. Neuroimage **173**, 632–643 (2018)
17. Frien, A., Eckhorn, R., Bauer, R., Woelbern, T., Kehr, H.: Stimulus-specific fast oscillations at zero phase between visual areas v1 and v2 of awake monkey. NeuroReport **5**(17), 2273–2277 (1994)
18. Gray, C.M., König, P., Engel, A.K., Singer, W.: Oscillatory responses in cat visual cortex exhibit inter-columnar synchronization which reflects global stimulus properties. Nature **338**(6213), 334–337 (1989)
19. Roelfsema, P.R., Engel, A.K., König, P., Singer, W.: Visuomotor integration is associated with zero time-lag synchronization among cortical areas. Nature **385**(6612), 157–161 (1997)
20. Havenith, M.N., Zemmar, A., Yu, S., Baudrexel, S.M., Singer, W., Nikolić, D.: Measuring sub-millisecond delays in spiking activity with millisecond time-bins. Neurosci. Lett. **450**(3), 296–300 (2009)
21. Rodriguez, E., George, N., Lachaux, J.P., Martinerie, J., Renault, B., Varela, F.J.: Perception's shadow: long-distance synchronization of human brain activity. Nature **397**(6718), 430–433 (1999)
22. Fell, J., Klaver, P., Lehnertz, K., Grunwald, T., Schaller, C., Elger, C.E., Fernández, G.: Human memory formation is accompanied by rhinal– hippocampal coupling and decoupling. Nat. Neurosci. **4**(12), 1259–1264 (2001)
23. König, P., Engel, A.K., Roelfsema, P.R., Singer, W.: How precise is neuronal synchronization? Neural Comput. **7**(3), 469–485 (1995)
24. Chawla, D., Friston, K.J., Lumer, E.D.: Zero-lag synchronous dynamics in triplets of interconnected cortical areas. Neural Netw. **14**(6–7), 727–735 (2001)
25. Rajagovindan, R., Ding, M.: Decomposing neural synchrony: toward an explanation for near-zero phase-lag in cortical oscillatory networks. PLoS ONE **3**(11), e3649 (2008)
26. Fischer, I., Vicente, R., Buldú, J.M., Peil, M., Mirasso, C.R., Torrent, M., García-Ojalvo, J.: Zero-lag long-range synchronization via dynamical relaying. Phys. Rev. Lett. **97**(12), 123902 (2006)
27. Vicente, R., Gollo, L.L., Mirasso, C.R., Fischer, I., Pipa, G.: Dynamical relaying can yield zero time lag neuronal synchrony despite long conduction delays. Proc. Natl. Acad. Sci. **105**(44), 17157–17162 (2008)
28. Gollo, L.L., Mirasso, C., Villa, A.E.: Dynamic control for synchronization of separated cortical areas through thalamic relay. Neuroimage **52**(3), 947–955 (2010)
29. Ossadtchi, A., Altukhov, D., Jerbi, K.: Phase shift invariant imaging of coherent sources (PSIICOS) from meg data. Neuroimage **183**, 950–971 (2018)
30. Shahbazi, F., Ewald, A., Ziehe, A., Nolte, G.: Constructing surrogate data to control for artifacts of volume conduction for functional connectivity measures. In: 17th International Conference on Biomagnetism Advances in Biomagnetism–Biomag 2010, pp. 207–210. Springer, Heidelberg (2010)
31. Lancaster, G., Iatsenko, D., Pidde, A., Ticcinelli, V., Stefanovska, A.: Sur-rogate data for hypothesis testing of physical systems. Phys. Rep. **748**, 1–60 (2018)
32. Wishart, J.: The generalised product moment distribution in samples from a normal multivariate population. Biometrika **20A**, 32–52 (1928)
33. Smith, W., Hocking, R.: Algorithm as 53: wishart variate generator. J. Roy. Stat. Soc. Ser. C (Appl. Stat.) **21**(3), 341–345 (1972)

Performance Analysis of a Source-Space Low-Density EEG-Based Motor Imagery BCI

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Abstract. Brain-computer interfaces are considered as the next level of human-machine interaction. A bunch of approaches in decoding human states aims to achieve sufficient precision and accommodate a growing number of distinct states to decode. The following study investigates the capabilities of the EEG-based inverse modelling to improve the classification accuracy and provides a comparison between different inverse models. The computational pipeline of represented BCI includes clustering and dimension reduction of the forward model. The obtained results show the advantages of minimal norm estimate (MNE) inverse operator in comparison to the Beamformer, sLORETA. We have also observed that a motor imagery BCI based on the fully blown individual inverse model outperformed that based on Riemann geometry-based approaches, while the latter demonstrated performance superior to the approaches using band specific sensor space power distribution. The performance analysis was done using a 32 channel EEG data recorded during motor imagery of the four limbs.

Keywords: Brain-computer interface · Brain-machine interface · BCI · EEG inverse problem · Motor imagery BCI · Low-density EEG · EEG Riemannian approach · Minimal norm estimate · Beamformer

1 Introduction

Brain-computer interface is a developing interdisciplinary field of science and technology which is expanding the capabilities of human-computer interaction. Brain-computer interfaces prove their applicability in the task of motor rehabilitation [1], it also finds uses in psychiatry and psychology under the disguise of neurofeedback [2]. There is some non-medical usage of BCI in the gaming and control of daily routine [3].

Transformation of brain activity into the commands issued into the external environment results from a specific computational pipeline [4]. The proposed blocks include a range of statistical approaches, machine learning techniques and digital signal processing methods. Typically, EEG-based motor BCIs exploit desynchronization of sensorimotor rhythms in the two sets of frequency bands - alpha (7–13 Hz) and beta (13–30) [5] as quantitative features. It has been also shown that it is possible to use the inverse problem solution as an additional computational step that when performed correctly implicitly adds more information to the decoding process and improves the decoding accuracy [6]. This is because such a transition from the space of sensor signals to the space of

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neuronal sources allows us to partly counteract the volume conduction that smears the activity of individual sources into the EEG sensor timeseries. Here, we for the first time implement an inverse modeling-based motor BCI based on the low-density EEG and perform a detailed performance analysis of our solution to pinpoint the key aspects that influence it.

There are several approaches that decompose EEG-signal into source activations which can have non-adaptive and adaptive nature [7]. The first group does not use statistical properties of the recorded signal to form a decomposition matrix (inverse operator) to be applied to the incoming data. The inverse operators formed by this family of techniques are constant over time and depend only on the individual anatomy and the regularization approach used to solve the inverse problem. The most widely spread method is minimal norm estimate (MNE) that yields source distribution that describe the data and have minimal quadratic norm. This method relies on a system of linear equations that represents the initial signal as a linear combination of source activity. When we find its solution, we prefer the one which has minimal activity in sources [8]. One of the key parameters for the MNE algorithm is the regularization parameter that theoretically should reflect the signal-to-noise ratio (SNR) in the recorded signal. Variation of this parameter can produce a significant impact on quality of obtained source activity. The extension of MNE approach is standardized low resolution brain electromagnetic tomography (sLORETA) [9] that uses a different scaling matrix to compute the quadratic norm.

When it comes to adaptive algorithms the most widely used one is linearly constrained minimum variance beamformer (LCMV) [10]. For computation of the inverse operator, it uses correlation matrix of the recorded data and the forward model. Adaptive nature of this approach gives its superresolution property but makes it crucially depend on the forward model accuracy which can be compromised in practice.

2 Methods and Materials

The 32 channel EEG data were recorded at sampling frequency of 250 Hz from a subject executing motor movement of four states: left hand, right hand, legs, rest. The data were then filtered in the 1–40 Hz range with eye-movement components rejected via ICA-based spatial filtering. Also, the dataset included an MRI scan of the participant's brain used to construct the EEG forward model. Recorded EEG data were split into 2-s-long overlapping segments with 0.2 s step, so that each such segment referred to one motor state. The segments extracted from the first contiguous part of the recorded data was used for training and the rest was used for testing. The overall number of data slices made up 724 samples.

We calculated the EEG forward model using the 3-shell overlapping spheres of the source dipoles located in the nodes of the cortical mesh extracted from the individual MRI using the FreeSurfer software. Based on this forward model we produced three inverse operators: MNE, sLORETA, LCMV. The MNE inverse operator was constructed for a grid of the regularization parameter values. Only source-space corresponding to the sensory-motor regions was used. The selected region of interest (ROI) comprised 20 zones picked up using Desikan-Killiany atlas. The resulting ROI appeared to have

6765 voxels. We then used a K-means clustering procedure applied to the topographies (columns of the forward model matrix) of all ROI sources.

Prior to the clustering we performed dimension reduction. The given forward matrix consisted of triplets of dipoles for each source and was divided into three matrices for each dipolar orientation aligned with x, y, z coordinate axes. Each of the matrices was decomposed using singular value decomposition (SVD). We only kept the first singular components capturing 95% of the forward model variance. We have then projected the original forward matrix onto these principal directions and concatenated the obtained vectors for the three dipolar orientations.

K-means clustering was then applied to these reduced topography vectors. To determine the number of clusters we used the elbow approach based on the within-cluster sum of squares (WSS) metrics. The dimension reduction of the initial forward model matrix lets us to easily compute several clustering with different numbers of clusters to find the one which fits best the geometry of sources.

The final feature vector was created by computing mean band power values in alpha (8–12 Hz), beta (15–25 Hz), and theta (3–7 Hz) ranges using the time-series of 40 resultant clusters which resulted into 120 features per time unit. The final dataset contained 724 class-balanced samples each of which corresponds roughly to a 2-min long record. We trained the SVM classifier with radial basis function kernels using the first 600 samples without shuffling and used the rest of 124 samples for testing. The SVM classifier significantly outperformed Decision Tree, Linear regression and Random forest classifiers as compared using a 4-fold cross-validation procedure over the first 600 training samples. The SVM hyperparameters were also picked as identified using this cross-validation procedure. All models were developed using sklearn Python library, the hyperparameter values for all algorithms were tuned using GridSearch toolbox.

3 Results

Analysis of performance was done in several steps. Firstly, we have selected MNE regularization parameter $\lambda = 1/2000$ that yielded the best accuracy [11] of 0.73 on the balanced dataset with four classes, see Fig. 1.a. Then we compared the accuracy achieved by the BCI based on the MNE inverse solver to the BCI using sLORETA and adaptive beamformer based inverse solutions. As evident from Fig. 1.b the source-space MNE based BCI significantly outperformed the two other possible implementations whose performance was just slightly above chance. In the case of adaptive beamformer based inverse this observation can be due to the inaccuracy of the forward model which is critical for the beamformer approach.

Nevertheless, all inverse solver-based approaches outperformed the traditional sensor space methodology, including that based on the use of Riemann geometry approaches [12] and exploiting sensor-space covariance matrices as features. To implement this approach, we used a simple MDM-based decision rule with a Riemann distance as a metric of the distance between covariance matrices. This approach yielded a significant increase in classification accuracy, around 0.5 accuracy in our 4-state BCI as compared to the traditional FBCSP sensor-based approach. These results are summarized in Fig. 1.b.

Next we explored the dependence of the classification accuracy on the length of the time-window used for classification. As shown in Fig. 1.c the best accuracy was

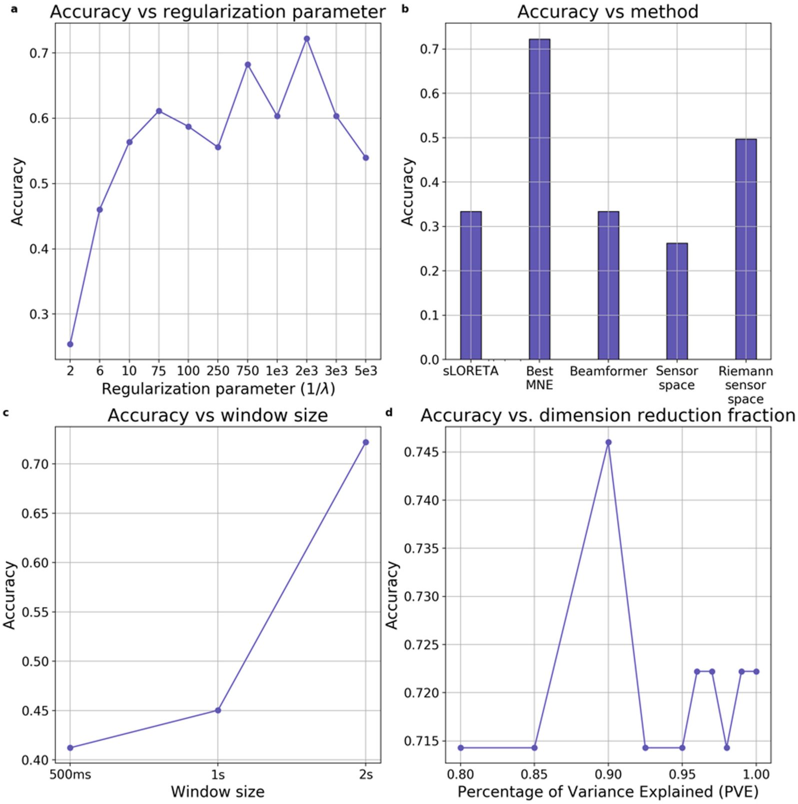

Fig. 1. BCI Performance analysis. (a) Accuracy score of MNE-based BCI with different regularization parameters (b) Accuracy score according to different inverse models and different sensors space approaches (c) Accuracy score as a function of time window duration (d) Accuracy score values that as a function of percentage of variance explained used during the dimension reduction step.

achieved using the longest (2 s) data window. One of the steps in our source-space MI BCI implementation is that of dimension reduction. In Fig. 1.d we explored the accuracy as a percentage of explained variance when attempting to reduce the feature space dimension. As our experiments demonstrated this step does not significantly affect the classification accuracy in our BCI.

4 Discussion

The transformation into source space gave significant enhancement in BCI performance. This improvement can be explained by the additional information about mixing of cortical sources brought into the solution by the inverse solver. Additionally, it is necessary to point out sensitivity of accuracy to value of λ, that illustrates the importance of signal to noise (SNR) estimation, because λ explains level of noise in sensor space signal. It might be relevant to make additional trials in the beginning of the BCI experimental paradigm that will allow us to make suggestions about SNR. Low classification accuracy when the LCMV beamformers are used as inverse solvers is likely associated with the imprecision of the forward model. Other methods might require additional tuning of parameters.

The best alternative for MNE-based BCI in terms of this study is sensor space decoder built on Riemann geometry approaches. Riemann shows a high prediction rate and can be accounted as a true competitor to source space decoder and also to a variety of spatial filtering techniques. Furthermore, we found that the accuracy critically depends on the length of the time window, we achieved the reported performance with the window length of 2 s. The described observations need further verification on a group of participants.

5 Conclusion

The obtained results emphasize the benefits of using the inverse solver in the EEG and MEG based BCIs. Given that the forward model accuracy is likely to affect the BCI performance we expect even greater benefits when dealing with MEG data. The Riemannian approach remains the best option if one does not want to explicitly inverse model the data.

References

1. Mane, R., Chouhan, T., Guan, C.: BCI for stroke rehabilitation: motor and beyond. J. Neural Eng. **17**(4), 041001 (2020)
2. Kim, S., Birbaumer, N.: Real-time functional MRI neurofeedback: a tool for psychiatry. Curr. Opin. Psychiatry **27**(5), 332–336 (2014)
3. Takabi, H., Bhalotiya, A., Alohaly, M.: Brain computer interface (BCI) applications: privacy threats and countermeasures. In: 2016 IEEE 2nd International Conference on Collaboration and Internet Computing (CIC). IEEE (2016)
4. Lebedev, M.A., Nicolelis, M.A.: Brain-machine interfaces: from basic science to neuroprostheses and neurorehabilitation. Physiol. Rev. **97**(2), 767–837 (2017)
5. Salenius, S., Schnitzler, A., Salmelin, R., Jousmäki, V., Hari, R.: Modulation of human cortical rolandic rhythms during natural sensorimotor tasks. Neuroimage **5**(3), 221–228 (1997)
6. Edelman, B.J., Meng, J., Suma, D., Zurn, C., Nagarajan, E., Baxter, B.S., He, B.: Noninvasive neuroimaging enhances continuous neural tracking for robotic device control. Sci. Robot. **4**(31), eaaw6844 (2019)
7. Sekihara, K., Nagarajan, S.S.: Adaptive Spatial Filters for Electromagnetic Brain Imaging. Springer, Heidelberg (2008)
8. Uutela, K., Hämäläinen, M., Somersalo, E.: Visualization of magnetoencephalographic data using minimum current estimates. Neuroimage **10**(2), 173–180 (1999)
9. Pascual-Marqui, R.D.: Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details. Methods Find Exp. Clin. Pharmacol. **24**(Suppl. D), 5–12 (2002)
10. Van Veen, B.D., Buckley, K.M.: Beamforming: a versatile approach to spatial filtering. IEEE ASSP Mag. **5**(2), 4–24 (1988)
11. Sokolova, M., Japkowicz, N., Szpakowicz, S.: Beyond accuracy, F-score and ROC: a family of discriminant measures for performance evaluation. In: Australasian Joint Conference on Artificial Intelligence, pp. 1015–1021. Springer (2006).
12. Congedo, M., Barachant, A., Bhatia, R.: Riemannian geometry for EEG-based brain-computer interfaces; a primer and a review. Brain Comput. Interfaces **4**(3), 155–174 (2017)

On the Structure of Conceptual Experience in a Model of Intelligence: Neural Network Modeling

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Abstract. The article presents the results of constructing a neural network modeling of the structure of conceptual experience in testing this block in the model of intelligence by senior school students M.A. Kholodnaya. The study involved 100 students (median is 15 years). Methodological base of the research: "Conceptual synthesis", "Conceptual generalization", "Semantic differential". The study results allow us to conclude that the accuracy of the resulting model is low, allowing 43.2197 errors, which is unacceptable for trusting the obtained model. Despite the low reliability of the constructed neural network model, the constructed neural network made it possible to argue for the correctness of the structure of the conceptual block of mental experience proposed by M.A. Kholodnaya. The findings encourage us to develop more appropriate analysis tools on the one hand and to develop the structural components of intelligence on the other.

Keywords: Neural network modeling · Conceptual experience · Intelligence

1 Introduction

The development of the mathematical apparatus and applied tools for processing and analyzing experimental data obtained in empirical research makes it possible to understand the essence of many phenomena and events, including the composition and structure of the activity's mental experience. As a basis for the analysis, we chose the structural model of intelligence proposed by M.A. Kholodnaya [5, p. 157], implying the inclusion of 6 blocks (Fig. 1):

Each of these blocks subdivides into several components. For the analysis in the presented work, we considered a block of conceptual experience in its components [6]:

- semantic abilities are mental properties that are related to the productivity of semantic processes and reveal themselves in the processes of operating with the content of verbal signs within the framework of the individual mental lexicon and in the speed of operational processing of semantic information;
- categorical abilities are mental properties related to the productivity of categorization processes and ensuring the assignment of the corresponding object to a specific category based on transformations in the system of categorical signs of varying degrees of generalization;

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Fig. 1. Structural model of intelligence.

- generative abilities are mental properties related to the productivity of conceptualization processes and providing the ability to generate some new mental contents missing in available information (identifying implicit connections and patterns, constructing metaphors, interpretation, modeling, thought experiment, etc.).

Following M.A. Kholodndya's scientific concept, all conceptual abilities have a hierarchical organization based on generalization and conceptualization of the mental content. So, at the base of the conceptual structure are semantic abilities, then categorical abilities follow, and conceptual abilities close this hierarchy of conceptual abilities.

Thus, there is reason to assume a specific complex of related mental formations that characterize the activity's conceptual experience. Accordingly, in the presented study, the structure of conceptual abilities is analyzed, suggesting conceptual, categorical, and semantic abilities as components of a neural network model of conceptual experience.

Purpose of the study: disclosing the specifics of the construct of conceptual experience in older adolescence using a statistical analysis of its components.

2 Material and Methods

2.1 Participants

To analyze the model, we carried out an empirical study and sampled 100 students of the 9th grade of school No. 1201 in Moscow at the age of 14–16 years (Fig. 2 and 3).

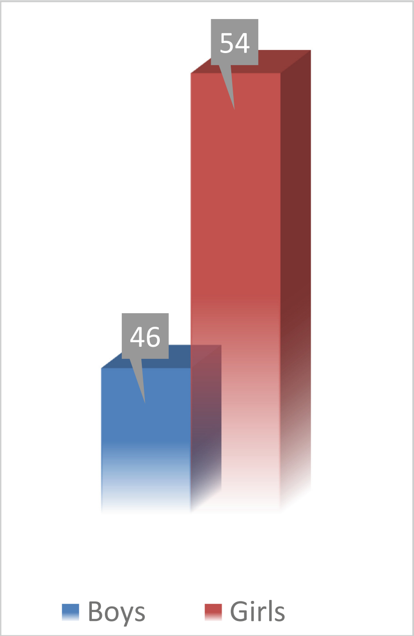

Fig. 2. Study participants. Sex differentiation.

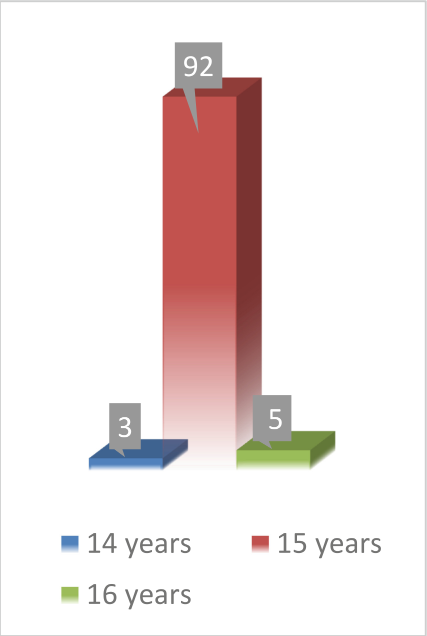

Fig. 3. Study participants. Age differentiation.

2.2 Materials

2.2.1 Methodology "Conceptual Synthesis" [6]

The material of the "Conceptual synthesis" methodology, which allows assessing the formation of conceptual abilities, aims to identify the ability to independently construct a semantic context based on three unrelated words while offering the maximum possible number of their combinations in the form of meaningful sentences.

Indicator: the sum of points characterizing the formation of conceptual abilities (ability to conceptual synthesis).

2.2.2 Methodology "Generalization of Three Words" [6]

The material of the "Generalization of three words" method provides an assessment of the ability to categorical generalization.

Indicator: the sum of points characterizing the level of formation of categorical abilities).

2.2.3 Modified Method "Visual Semantics" [2]

According to research by E.Yu. Artemieva [2], there is a mechanism that naturally "packs" the experience of human interaction with the world into some impressive structures, which E. Yu. Artemyeva called "semantic-perceptual universals" [2, p. 14].

We assessed two variables using this technique: semantic interpretations of indefinite visual forms and the ability to generate semantic features when describing indefinite visual forms.

Indicators (calculated for each subject): 1) the total number of semantic interpretations, denotations; 2) the total number of semantic features, signs (total number of joint ventures).

2.3 Procedures

- ***Methodology "Conceptual synthesis"*** **[6].**

A4-size forms have one triad of words in each form:

- shell - paper clip - thermometer
- computer - tornado - pin
- planet - electrical outlet - the hourglass.

We orally give the study participants instructions: to establish different variants of semantic connections between these three words and write down each variant in the form of one or two sentences. We presented three triads of words in total. The working time with each triad was 3 min.

Methodology "Conceptual synthesis" (PS) assesses the variable "conceptual abilities." Evaluation criteria for the answer: 0 points - no written proposals; only two words were used (for example, for the second triad of words – "I sat at home and watched a film about a tornado on the computer"); 1 point - simple listing of words in a sentence (for example, for the first triad of words – "A shell, a paper clip, and a thermometer were on my desk"); 2 points - creating a context within the description of a specific situation or specific circumstances (for example, for the third triad of words – "Previously, time on our planet was measured only with the help of an hourglass, and then electrical sockets and mechanical clocks appeared"); 3 points - a sentence using comparisons, metaphors, generalizing categories, or expanded causal relationships (for example, for the first triad – "A shell cut in half has curls that look like the bends of a paper clip, and if this shell is heated to 200°, it will melt and you will get a glass for a thermometer and other objects").

We summed up the points for all triads.

- ***Methodology "Generalization of three words"*** **[6].**

The material of the "Generalization of three words" method consists of 10 triads of words, each of which the researcher reads out to the research participants sequentially. Participants in the study should think about the common between the words they read and write down the answer with one or two words. The methodology gives 25 s to reflect and to write down the answer for each triad of words.

List of word triads:

1. article, flower bed, picture
2. newspaper, lighthouse, bonfire
3. hunting, playing, thinking
4. monument, bridge, antenna
5. icon, map, decoration
6. pulse, tide, spring
7. trap, fence, cork
8. soap bubble, vase, suitcase
9. umbrella, trench, stick
10. scale, beads, ladder

Evaluation of each answer for each of the ten triads according to the following criteria:

- 0 points - no answer; generalization of only two words; thematic generalization based on the spatial or temporal proximity of objects (for example, for the fourth triad – "city," "my yard");
- 1 point - analytical generalization; formal generalization without an exact meaningful specification (for example, for the fourth triad – "made by man," "metal");
- Two points - strict categorical generalization using generic concepts (for example, for the tenth triad – "sequence").

We summed up the points for all ten triads.

- ***The modified method, "Visual semantics"*** [2]**.**

The subject is shown a graphic image on a white A4 sheet in the upper part. There were two questions to be answered about each image. The first question is: "What is it? What does it look like?". Second question: "What properties do you feel are inherent in this object? What is it like?". Figure 4 presents five images from Artemyeva's set in total.

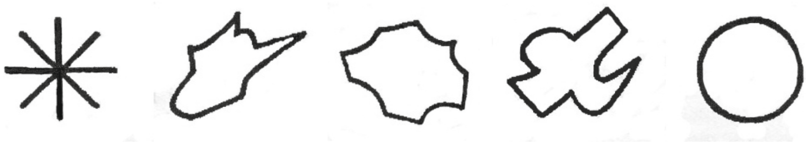

Fig. 4. Examples of graphic images in the method "Visual semantics" [2].

We use graph analysis and non-network analysis (STATISTICA 12 and SPSS 21.1 software) to process the results.

3 Results

Figures 5 and 6 show the response surfaces:

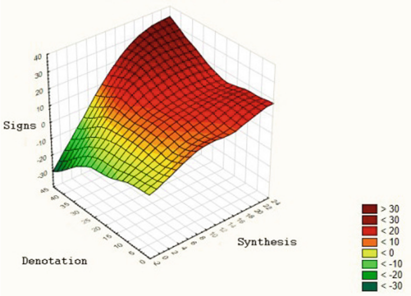

Fig. 5. The response surface of two different types of semantic abilities ("Denotation" and "Signs") and conceptual abilities.

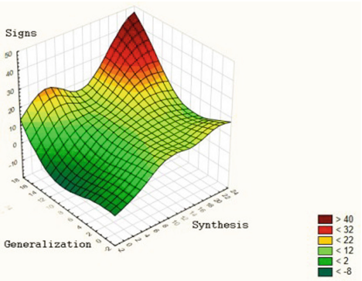

Fig. 6. Response surface of semantic, categorical, and generative abilities

Table 1. Neural network models of conceptual experience indicators (automated selection with attenuation).

№	Network architecture	Learning performance	Test performance	Control performance	Learning algorithm	Error function	Activation on the hidden layer	Activation of output neurons
6	RBF 20-5-1	56,78	37,27	42,86	BFGS 2	SOS	Hyperbolic	Identity

Table 2. Sensitivity analysis of the 6th neural network model of indicators of conceptual abilities.

Net	Sensitivity analysis (STATISTICA Spreadsheet. sta) Samples: train, test, validation			
	Generative abilities	Categorical abilities	Semantic abilities to generate features	Semantic abilities to generate interpretations
6. RBF 20-5-1	1,07	1,05	1,04	1,02

4 Discussion

Speaking about neural network modeling, we should first say that these methods bases on graph theory. Network models are precise and consider the object of research as a single complex of interrelated components. The used network model of the logical-mathematical description makes it possible to algorithmize the system parameters' calculations.

Network modeling of random measurements is an essential method for the analysis of multivariate random measurements. The network itself is a graph composed of nodes connected by edges. Accordingly, the variables of the network turn out to connect in the form of interdependent paths of transitions (edges) to each other (nodes) [1].

In general, there are two types of links that can be present in the network and represented as edges of the graph: - the edge can be directed, in which case it has an arrow at one end indicating a one-way effect, - or the link can be undirected, which indicates some mutual relationship. We use pairwise Markov random fields to model undirected networks [3]. A node represents each variable, and many edges connect the nodes. In these models,

Links between nodes are "weights" of the edges of the network, and the weight of an edge is always a nonzero number because zero weight indicates no edge. The sign of the edge weight (positive or negative) indicates the type of interaction, and the absolute value of the edge weight indicates the strength of the bond effect between nodes. The length of an edge in a network is reciprocal of the edge's weight. The distance between two nodes is equal to the sum of all edges' lengths on the shortest path between two nodes [7].

Scientists assess the importance of individual nodes in a network using the specialized Fruchterman Reingold algorithm [4]. Network visualization is an abstract representation of high-dimensional space in two dimensions. However, 2D rendering cannot correctly reflect the model's actual space since the metric distance between node placements in 2D space has no direct interpretation, for example, with multidimensional scaling. Graph theory has developed several methods to more objectively quantify, which node is the most central in a network [8]:

- The node strength, also called the degree in unweighted networks [7], adds the strength (weight) of all associated edges to the node; - if the network consists of partial correlation coefficients, the strength of the node is equal to the sum of the absolute partial correlation coefficients between this node and all other nodes.
- Closeness takes the reciprocal of all shortest paths between one node and all other nodes in the network.
- Strength of a node indicates how strongly a node is directly connected to other nodes in the network - proximity - how strongly a node is indirectly connected to other nodes.
- Betweenness tells how many of the shortest paths between two nodes to go through the node in question; - the higher the intermediate, the more critical is the node connecting other nodes.

Thus, we present the results of studying the network structure of conceptual experience in the context of semantic, categorical, and generative abilities through network modeling. Following the results presented in Fig. 5, we made a preliminary conclusion that the degree of abstraction and generalization of the concepts' information affects the strength of the connection between the components of conceptual experience. Thus, more abstract "Signs" of the circle's graphical variations are consistent with a highly organized conceptual ability profile than "Denotation," i.e., interpretation of the same graphic variations. Concerning categorical abilities ("Generalization"), it is not possible to make such an unambiguous conclusion (Fig. 6).

Neural network modeling of conceptual abilities gives us nine models (automated selection with damping). We trained the models with radial basis functions with interactive learning. The work done demonstrated a large learning error for the correction. We used multiple subsamples using radial basis functions but increasing the number of hidden neurons from 3 to 25 pieces—the program identifies only 1 model: RBF 20-5-1 (Table 1).

As can be seen from the obtained results of constructing a neural network model of conceptual experience indicators, the resulting model's accuracy is low, allowing 43.2197, which is unacceptable for trusting the obtained model. Considering the sensitivity analysis (Table 2), i.e., analyzing the importance of variables, the first place in terms of importance in the constructed model is occupied by conceptual abilities, the second. Accordingly, the less significant place belongs to categorical abilities, and semantic abilities to generate signs and interpretations follow the 3rd and 4th place.

5 Conclusion

Thus, we conclude that, although the low reliability of the constructed neural network model, nevertheless it made the possibility to argue the correctness of the structure of the conceptual block of mental experience proposed by M.A. Kholodnaya.

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References

1. Artemenkov, S.L.: Initiative-semantic model of divergent creativity. J. Psychol. Sci. Educ. **3**, 1–15 (2012). https://psyjournals.ru/en/psyedu_ej/2012/n3/55664.shtml
2. Artemyeva, E.Yu.: The Psychology of Subjective Semantics. Publishing house of Moscow University, Moscow (1980)
3. Epskamp, S., Rhemtulla, M.T., Borsboom, B.: Generalized network psychometrics: combining network and latent variable models (2017). https://arxiv.org/pdf/1605.09288.pdf
4. Fruchterman, T.M.J., Reingold, E.M.: Graph drawing by force-directed placement. Softw. Pract. Exp. **21**(11), 1129–1164 (1991). https://doi.org/10.1002/spe.4380211102
5. Kholodnaya, M.A.: Psychology of Intelligence: Research Paradoxes. Peter, St. Petersburg (2019). (in Russian)
6. Kholodnaya, M.A.: Psychology of Conceptual Thinking: From Conceptual Structures to Conceptual Abilities. Institute of Psychology RAS, Moscow (2012)
7. Newman, M.E.J.: Networks. An Introduction. Oxford University Press, Oxford (2010). https://doi.org/10.1162/artl_r_0006
8. Opsahl, T., Agneessens, F., Skvoretz, J.: Node centrality in weighted networks: generalized degree and shortest paths. Soc. Netw. **32**, 245–251 (2010). https://doi.org/10.1016/j.socnet.2010.03.006

Comparison of Simulated Macro- and Mesoscopic Cortical Traveling Waves with MEG Data

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Abstract. We simulated radial traveling waves of local currents on the folded surface of the human cerebral cortex. The magnetic fields on the surface of the head were calculated by individual MRI. Model MEGs were compared with experimental data using two-dimensional correlation. The maximum values of correlation coefficients were determined for traveling wave velocities of 0.2 m/s with epicenters in the occipital lobes of the brain, including V1 and V2. In these cases, a jump in the levels of maximum correlations in time and space took place. At a velocity of 6 m/s, the maximum values were lower, and the change in the level of correlations was smoothed out. The results of the study show the advantage of the intra-cortical hypothesis of the brain traveling waves.

Keyword: Cortical traveling waves · Intra-cortical hypothesis · MEG

1 Introduction

Traveling waves of local brain potentials have been experimentally found in animals from snails [1] to the higher apes [2] and man [3]. These waves can be recorded only using intra-cortical electrodes [4] or voltage-dependent dyes [5].

Macroscopic traveling waves observed in recording of EEG, MEG, and ECoG are visualized using interpolation and most likely reflect the effects caused by extracellular currents in the conductive volumetric environment of the brain, its shells, skull and head integuments. The visibility of macroscopic traveling waves is conditioned by the equivalent rotating dipoles formed due to the movement of cortical traveling waves along

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the complex folded surface of the brain [6, 7]. The validity of this approach based on experimental data was shown by us in a number of works [8, 9].

On the other hand, the hypothesis of macroscopic traveling waves, which has no direct experimental support, is used to interpret the results [10]. The propagation of excitation, creating mesoscopic traveling waves of local brain potentials, is due to the transverse processes of unmyelinated axonal fibers (the propagation speed of action potentials < 1 m/s), whereas macroscopic traveling waves explain the transmission of signals through the white matter of the brain having the propagation speed of action potentials >1 m/s. In this work, we evaluated the hypotheses about macro- and mesoscopic cortical traveling waves by simulating such waves on the three-dimensional model of the human brain cortical surface and reconstructing the MEG to compare the simulations with the experimental data.

2 Materials and Methods

We used one healthy right-handed subject for the MEG analysis. Registration was carried out with a 306-channel MEG using an Elekta Neuromag Vector View setup (Elekta Oy, Finland), which was located in a magnetically shielded room. The MEG recording was carried out for 9 min in the state of quiet wakefulness with closed eyes. A high-resolution structural MRI of the head was obtained using a Magnetom Verio 3 (Siemens) tomograph based on a T1-weighted sequence ($R = 1900$ ms, $E = 2.21$ ms, voxel size $1 \times 1 \times 1$ mm). According to the MRI data, a model of individual surfaces of the head and brain was built with the resolution of about 300 000 vertices. Each vertex was an epicenter, for which the distributions of the current density in the form of radial traveling waves with propagation velocities of 0.2 or 6 m/s and an average frequency of 11 Hz were calculated. The model waves propagated over the distances of 2 cm for the lower and of 20 cm for the higher velocity. We conditionally called the first model “mesoscopic”, because for it, a limited wave propagation of no more than 2 cm was assumed. In the second case, the model wave covered almost the entire surface, and in numerous works such traveling waves are called “macroscopic” [11].

The forward MEG problem was solved using the boundary element model separately for each hemisphere [12] in the Brainstorm software environment [13]. The technique is described in detail in our works [8, 9, 14].

As a result, we obtained 306 values of the magnetic field per 100 ms at the locations of the sensors, which were used to register the MEG in the experiment. Model MEGs were compared with the experimental data by calculating two-dimensional correlation (`corr2` function in MATLAB) each time shifting the analysis window by 2 ms. We found the maximum correlation value for each moment of time and the corresponding vertex on the simulating surface of the subject’s cerebral cortex. Thus, the MEG recording was analyzed for 5 min. The obtained set of correlation coefficients was analyzed in order to reveal advantage of one of the models.

We compared the growth of the maximum values of the correlation coefficients for each of the models separately for each hemisphere. We assessed the normality of the distribution of the correlation coefficients for each of the models and the differences in their mean values using ANOVA method. The difference between the maximum values of the correlations and their probability for each model were analyzed. We obtained the spatial distribution and the dynamics of changes in the positions of the traveling waves epicenters for two types of simulations with maximal similarities between the model and experimental MEG signals.

3 Results

In our analysis, we used model waves starting from 145885 epicenters for the left hemisphere and starting from 154674 epicenters for the right hemisphere for two velocities and two propagation distances. Two-dimensional correlations were calculated for 15 segments of 20 s between experimental and model signals. For each segment, 9950 correlation values were obtained per epicenter. Thus, 21 773 336 250 coefficients were obtained for the left hemisphere and 23 085 094 500 values for the right hemisphere for each propagation velocity and the same number of solutions for the second model. For each time interval of 2 ms, the epicenter with the maximum value of the correlation was found separately for each hemisphere of the brain.

The increase in the levels of correlations was significantly different for the compared models (Fig. 1).

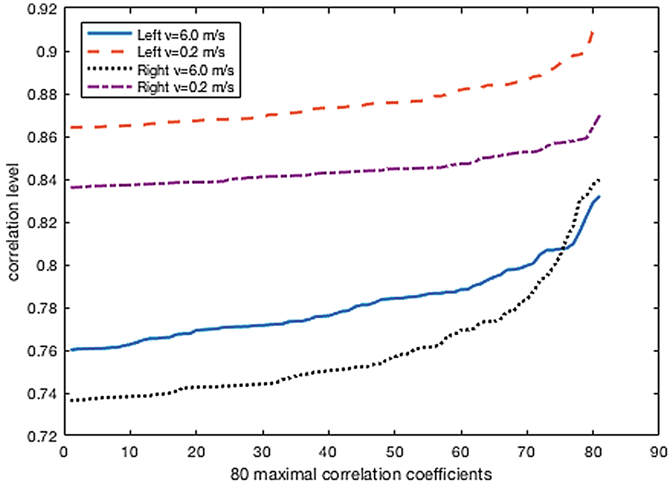

Fig. 1. Comparative increase in correlations for traveling wave models with velocities of 0.2 m/s and 6.0 m/s in the left and right hemispheres.

The level of maximum correlations at a certain moment of time for the simulations of traveling waves with the speed of 0.2 m/s was, on average, significantly higher ($p < 0.0001$) than for the simulations with the speed of 6.0 m/s for the both hemispheres (Fig. 2).

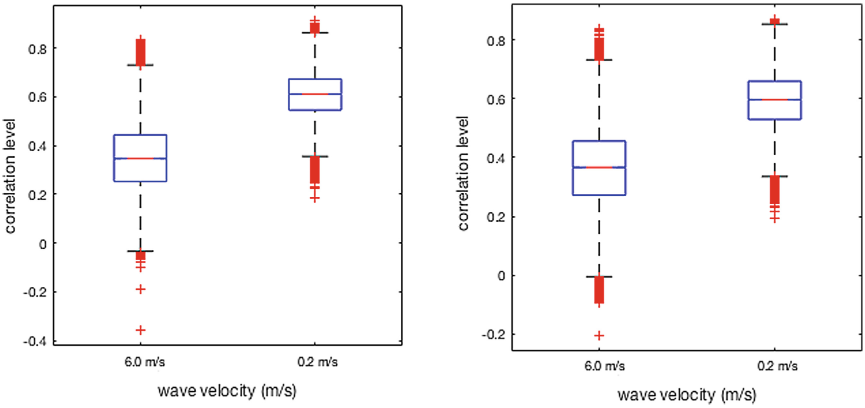

Fig. 2. Comparison of mean correlation values using ANOVA for traveling wave models with wave velocities of 6.0 m/s (1) and 0.2 m/s (2) in the left hemisphere (left) and the right hemisphere (right).

In the mesoscopic model, the mean correlations were 0.6079 for the left hemisphere and 0.5931 for the right. For the model of macroscopic waves in the right and left hemispheres, the average correlations were at the level of 0.3502 and 0.3635, respectively.

Epicenters for traveling wave velocities of 0.2 m/s were determined in the occipital and parietal lobes of the brain with levels $r > 0.7$. For a given velocity, 516 such waves were found in the left hemisphere. Most of these epicenters were located in the calcarine fissure and parieto-occipital fissure, which correspond to the areas of the visual cortex V1, V2 (Fig. 3). Epicenters arose in different places of these areas, mainly shifting by a distance of no more than 20 mm and a maximum distance of 70 mm (see “VideoJ02” in Supplementary Materials). At the velocity of 6 m/s, the maximum values were lower, and for the correlation level $r > 0.7$, only 84 epicenters were identified in the left hemisphere, which were evenly distributed between the frontal and occipital poles (Fig. 4). Position changes in most cases were either local, up to 5 cm, or remote, up to 15 cm, i.e. “jumped” between the frontal region and the occipital region (see “VideoJ60” in Supplementary Materials).

The dependence between the numbers of the traveling waves epicenters in the left hemisphere having the correlations with the MEG data, which is greater than a given threshold and the value of the threshold for the wave velocities $v = 6.0$ m/s and $v = 0.2$ m/s is presented in Fig. 5. The relation between these numbers of the epicenters as a function of the threshold correlation is displayed in Fig. 6.

Thus, in the left hemisphere, the number of epicenters of the traveling wave with the velocity of 0.2 m/s having a high correlation with the MEG data (i.e. $r > 0.75$) is at least 5 times higher than the corresponding number for the traveling wave velocity of 6.0 m/s. Moreover, by the correlation of 0.8, the number of mesoscopic traveling waves becomes almost 40 times higher than the number of macroscopic traveling waves.

For the right hemisphere, we obtained the results qualitatively similar to the results demonstrated in Fig. 3–6 for the left hemisphere.

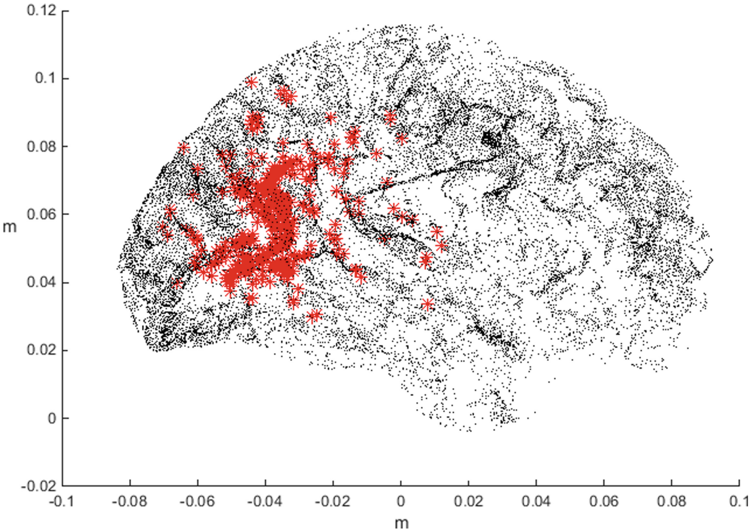

Fig. 3. The epicenters of mesoscopic traveling waves (asterisks) in the left hemisphere for $r > 0.7$, $v = 0.2$ m/s.

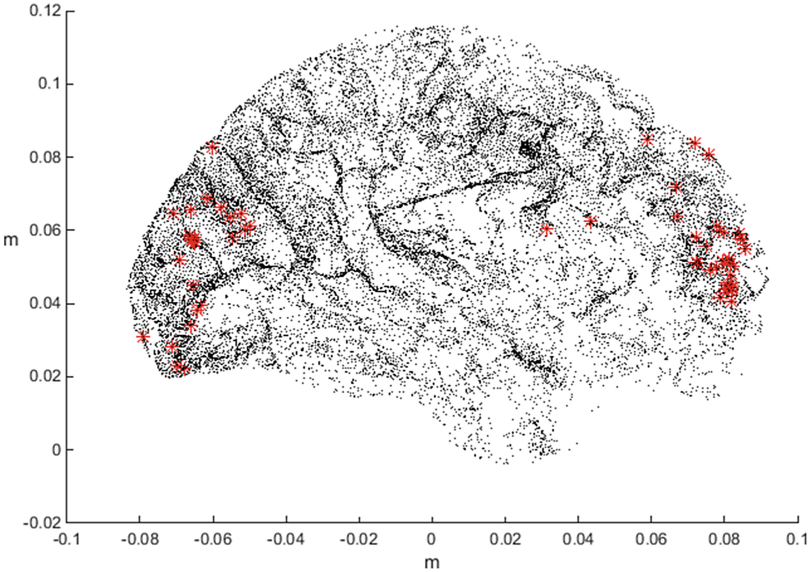

Fig. 4. The epicenters of macroscopic traveling waves (asterisks) in the left hemisphere for $r > 0.7$, $v = 6.0$ m/s.

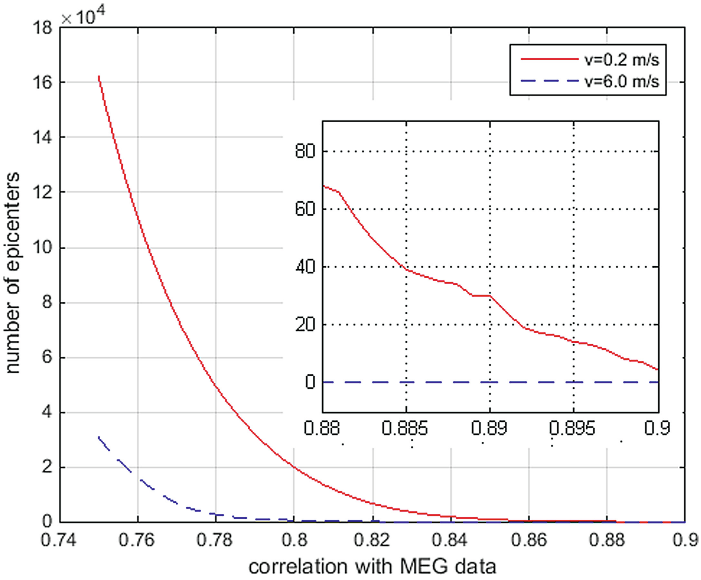

Fig. 5. The numbers of the epicenters of mesoscopic (solid line) and macroscopic (dashed line) traveling waves in the left hemisphere having the correlations greater than a given threshold as functions of the threshold.

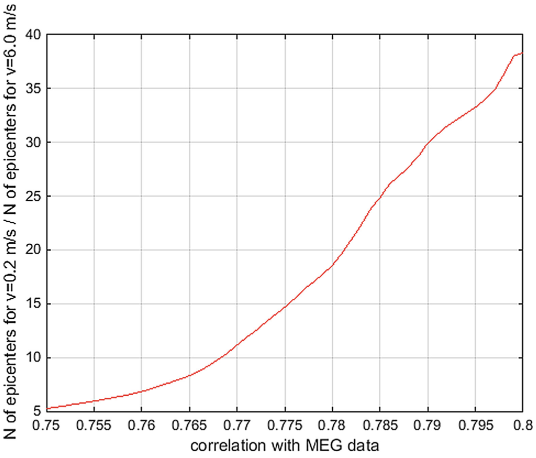

Fig. 6. The relation between the number of mesoscopic waves epicenters and the number of macroscopic waves epicenters in the left hemisphere having the correlations greater than a given threshold as functions of the threshold.

4 Discussion

Although we have not yet received absolute evidence in favor of the mesoscopic wave model, the advantage of this model is supported by the data given in Sect. 3. It must be admitted that both models give very similar magnetic field distributions on the head surface and the crucial experiment that will deny the existence of macroscopic cortical waves will be a joint analysis of ECoG records and microelectrode arrays [3] using our calculation methodology. The analysis using the mesoscopic paradigm, unfortunately, is still limited to one hemisphere, although it is known that the majority of waves arise in symmetrical regions of both hemispheres [6, 15]. The joint analysis of the hemispheres is possible, but it requires much more computational resources.

The localization of the traveling waves epicentres in the occipital cortex is clear, because we analyze the alpha rhythm that is associated with the visual cortex and has the largest amplitude in normal humans in comparison with other similar rhythms. The localization of the epicentres of the model macroscopic waves reflects the distribution of the magnetic field of the alpha rhythm observed in the occipital and posterior frontal regions. This distribution can also be explained by the presence of powerful current sources in the occipital cortex, which imitates macroscopic waves.

Traveling waves are associated with the mechanism of attention on a mental image. In addition, the brain compares sensory and mental images [16]. Earlier, we showed a special role of the visual cortical projection periphery in this process [17].

In our work, we observed chaotic “jumps” of the traveling waves epicenters in the visual cortex when the subject is at rest with his eyes closed. It is known from the literature that both evoked visual responses and saccadic eye movements are accompanied by traveling waves [18]. In this case, the amplitude of the EEG (EP) and MEG (EMF) is much less than that of the alpha rhythm. Typically, the perceived sensory image is projected onto the central cortical field of the retinotopic projection. Only in cases of lateral vision, the epicenter of the traveling wave appears at the periphery of the cortical projection of the visual field, which causes a noticeable effect of increasing the EEG amplitude [16].

5 Conclusions

We have shown the advantage of the mesoscopic traveling wave model for a spontaneous alpha rhythm. In this case, the epicenters of traveling waves arise in the primary and secondary fields of the visual cortex in the occipital lobes of the brain. This leads to the conclusion that traveling waves of the alpha rhythm propagate at speeds of the order of 0.2 m/s, which corresponds to the speed of the action potential in the non-meyline axons of neurons. The same results were obtained in experiments on animals when recording traveling waves with intra-cortical electrodes such as Utah arrays [19] or by optical methods [3]. The second important outcome of this our research is the observation of “jumping” epicenters or the appearance of foci of activation in different areas of the visual cortex, which may correspond to mental tracking by analogy with eye tracking and subjectively may be accompanied by wandering of the inner gaze with awareness of visual imaginary or recalled visual images.

6 Ethical Approval

Thus, the model of the evolution of a population of agents with different cognitive abilities has been built and analyzed. It is clear that this model is still very far from the models of agents capable to discover the laws of nature. Nevertheless, the model characterizes the features of the development of populations in which some of the agents have significantly more effective cognitive properties in comparison with other agents.

It is interesting that using this model, one can consider the evolution of people with different cognitive abilities in the human community. One can also consider the evolution of states with different levels of scientific development. Although, of course, such an interpretation of the results of the present model for human communities must be carried out with caution.

The further development of models of autonomous agents with effective cognitive abilities, the approaches outlined in the beginning of this article can be used. It is most appropriate to use the principles outlined in the works [1, 6].

7 Supplementary Materials

The "jumps" of the mesoscopic and the macroscopic traveling wave epicenters corresponding to Fig. 3 and Fig. 4 in the time interval of 5 min are presented in the time-scale 1:100 in the video files "VideoJ02" and "VideoJ60", respectively, that can be found in the archive "222Video" at the GitHub repository by the link https://github.com/BrainTravelingWaves/MentalTracking. The program codes in MATLAB for these videos as well as for the figures presented in the present paper can be also found by the link given above.

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References

1. Nikitin, E.S., Balaban, P.M.: Optical recording of responses to odor in olfactory structures of the nervous system in the terrestrial mollusk Helix. Neurosci. Behav. Physiol. **31**(1), 21–30 (2001). https://doi.org/10.1023/a:1026666012225. PMID: 11265810
2. Denker, M., Zehl, L., Kilavik, B.E., Diesmann, M., Brochier, T., Riehle, A., Grün, S.: LFP beta amplitude is linked to mesoscopic spatio-temporal phase patterns. Sci. Rep. **8**(1), 5200 (2018). https://doi.org/10.1038/s41598-018-22990-7
3. Martinet, L.E., Fiddyment, G., Madsen, J.R., Eskandar, E.N., Truccolo, W., Eden, U.T., Cash, S.S., Kramer, M.A.: Human seizures couple across spatial scales through travelling wave dynamics. Nat. Commun. **8**, 14896 (2017). https://doi.org/10.1038/ncomms14896
4. Le Van Quyen, M., Muller, L.E., Telenczuk, B., Halgren, E., Cash, S., Hatsopoulos, N.G., Dehghani, N., Destexhe, A.: High-frequency oscillations in human and monkey neocortex during the wake-sleep cycle. Proc. Natl. Acad. Sci. USA **113**(33), 9363–9368 (2016). https://doi.org/10.1073/pnas.1523583113
5. Muller, L., Reynaud, A., Chavane, F., Destexhe, A.: Thestimulus-evokedpopulation response in visual cortex of awake monkey is a propagating wave. Nat. Commun. **5**, 3675 (2014). https://doi.org/10.1038/ncomms4675

6. Verkhliutov, V.M.: A model of the structure of the dipole source of the alpha rhythm in the human visual cortex. Zh. Vyssh. Nerv. Deiat. Im. I.P. Pavlova **46**, 496–503 (1996). PMID: 8755052
7. Hindriks, R., van Putten, M.J.A.M., Deco, G.: Intra-cortical propagation of EEG alpha oscillations. Neuroimage **103**, 444–453 (2014). https://doi.org/10.1016/j.neuroimage.2014.08.027
8. Verkhlyutov, V., Sharaev, M., Balaev, V., Osadtchi, A., Ushakov, V., Skiteva, L., Velichkovsky, B.: Towards localization of radial traveling waves in the evoked and spontaneous MEG: a solution based on the intra-cortical propagation hypothesis. Procedia Comput. Sci. **145**, 617–622 (2018). https://doi.org/10.1016/j.procs.2018.11.073
9. Verkhlyutov, V.M., Balaev, V.V., Ushakov, V.L., Velichkovsky, B.M.: A novel methodology for simulation of EEG traveling waves on the folding surface of the human cerebral cortex. Stud. Comput. Intell. **799**, 51–63 (2019). https://doi.org/10.1007/978-3-030-01328-8
10. Alexander, D.M., Ball, T., Schulze-Bonhage, A., van Leeuwen, C.: Large-scale cortical travelling waves predict localized future cortical signals. PLoS Comput. Biol. **15**(11), e1007316 (2019). https://doi.org/10.1371/journal.pcbi.1007316. PMID: 31730613
11. Muller, L., Chavane, F., Reynolds, J., Sejnowski, T.J.: Cortical travelling waves: mechanisms and computational principles. Nat. Rev. Neurosci. **19**(5), 255–268 (2018). https://doi.org/10.1038/nrn.2018.20. PMID: 29563572
12. Kybic, J., Clerc, M., Abboud, T., Faugeras, O., Keriven, R., Papadopoulo, T.: A common formalism for the integral formulations of the forward EEG problem. IEEE Trans. Med. Imag. **24**, 12–28 (2005). https://doi.org/10.1109/TMI.2004.837363
13. Tadel, F., Baillet, S., Mosher, J.C., Pantazis, D., Leahy, R.M.: Brainstorm: a user friendly application for MEG/EEG analysis. Comput. Intell. Neurosci. **2011**, 879716 (2011). https://doi.org/10.1155/2011/879716
14. Verkhlyutov, V.M., Balaev, V.V.: The method of modeling the EEG by calculating radial traveling waves on the folded surface of the human cerebral cortex. bioRxiv, **242412** (2018). https://doi.org/10.1101/242412
15. Alamia, A., VanRullen, R.: Alpha oscillations and traveling waves: signatures of predictive coding? PLoS Biol. **17**(10), e3000487 (2019). https://doi.org/10.1371/journal.pbio.3000487
16. Lozano-Soldevilla, D., VanRullen, R.: The hidden spatial dimension of alpha: 10-Hz perceptual echoes propagate as periodic traveling waves in the human brain. Cell Rep. **26**, 374–380 (2019). https://doi.org/10.1016/j.celrep.2018.12.058
17. Verkhlyutov, V.M., Ushakov, V.L., Sokolov, P.A., Velichkovsky, B.M.: Large-scale network analysis of imagination reveals extended but limited top-down components in human visual cognition. Psychol. Russ. State Art **7**(4), 4–19 (2014). https://doi.org/10.11621/pir.2014.0401
18. Zanos, T.P., Mineault, P.J., Nasiotis, K.T., Guitton, D., Pack, C.C.: A sensorimotor role for traveling waves in primate visual cortex. Neuron **85**(3), 615–627 (2015). https://doi.org/10.1016/j.neuron.2014.12.043. PMID: 25600124
19. Davis, Z.W., Muller, L., Martinez-Trujillo, J., Sejnowski, T., Reynolds, J.H.: Spontaneous travelling cortical waves gate perception in behaving primates. Nature **587**(7834), 432–436 (2020). https://doi.org/10.1038/s41586-020-2802-y. PMID: 33029013
20. Red'ko, V.G.: Modeling of Cognitive Evolution: Toward the Theory of Evolutionary Origin of Human Thinking. URSS, Moscow (2018)

Selection of Functionally Homogeneous Human Brain Regions for Functional Connectomes Building Based on fMRI Data

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Abstract. In the current work we focused on the problem of identifying the mechanism of interaction of neural networks in the human brain in cognitive processes. An important step in solving this problem is to identify functionally homogeneous regions of the brain. In this paper, we present two methods which are needed to identify these regions and build maps of areas of the brain that work stable in time. We tested the developed methods on experimental resting-state fMRI data and showed that the brain areas identified with the proposed methods have greater functional homogeneity compared to established anatomical and functional brain atlases and thus could be considered more suitable for further connectome calculation.

Keywords: Functional connectome · Homogenous regions · FMRI data · Regions of interest

1 Introduction

Functional Connectome (FC) is a term used to refer to the whole variety of functional connections in the brain. One of the urgent tasks today is to construct the FC of the human brain at rest [1, 2]. One of the aspects of building a FC is its scale. This can be, for example, the scale of individual neurons, ensembles of neurons, or even entire macroscopic regions of the brain [3]. If fMRI data are used to construct a FC, then the unit of data is a volume of the order of 1 to several tens of cubic millimeters, called a voxel. At such a scale, the number of voxels in the human brain can exceed 100,000.

To reduce the dimensionality of the data, as well as to get rid of the influence of the noise introduced by the scanning process into the dynamics of individual voxels, several voxels are often combined into spatially connected functionally homogeneous regions (FHRs), in which all voxels have similar dynamics [4]. Since the dynamics of all voxels of one FHR are similar, each FHR is represented by its single characteristic time-series

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or region dynamics. As a result, the functional connectome includes connections not between individual voxels, but between the selected functionally homogeneous regions.

Currently, there are many approaches to the allocation of FHR [5], but there is no single generally accepted approach. Regions of anatomical atlases are often used as the FHR. But the regions of anatomical atlases are often very large and the dynamics of the voxels included in them are not always similar. For example, voxels that are formally included in one region according to anatomical atlases (for example, AAL), but located on opposite boundaries of the anatomic structure, may have a correlation close to zero. In this case, it would be incorrect to consider the selected regions as functionally homogeneous. And if the regions are not functionally homogeneous, then it is incorrect to take one "characteristic" dynamics from the region. One of the reasons for such heterogeneity of regions in the case of using anatomical atlases, as well as for many other existing approaches, is the complete division of the brain into regions, when each voxel is assigned to one of the regions. As a result, sharp boundaries between the regions are formed, and voxels lying near these boundaries and combining the dynamics of both regions are not taken into account correctly.

To solve the problems described above, we propose two new methods for creating FHR. One method is focused on identifying the FHR with a high level of connectivity between the voxel dynamics included in it, however, the configuration of the selected regions dynamically changes over time. The second approach relaxes the requirement for the strength of between voxel similarity within a region, but allows creating FHRs that are stable in time. An essential feature of the proposed approaches is the possibility of the presence of voxels that do not belong to any region.

In this work, we focus on testing and validating the presented methods. The structure of this work is the following: in Sect. 2 we describe the developed methods for creating FHRs, as well as methods for testing and validating them on simulated and experimental data; in Sect. 3 we present the results of testing, as well as some additional studies, such as, analysis of the stability of the results and the effect of autocorrelation in data on the result of identifying the FHRs.

2 Material and Methods

2.1 FHR Selection

We have developed two methods for FHR selection. One method is focused on identifying the FHR with a high connectivity strength between the voxel dynamics within the regions, but the location of the regions can change over time. The second method is focused on identifying the FHRs that are stable over time but the connectivity strength within each region might be reduced.

The first method, "Cluster Segmentation Method" (CSM), is based on the clustering of voxels dynamics. CSM includes the following simple steps:

1. Split the whole time interval T of the input fMRI data into overlapping intervals T_1, T_2, … T_N.

2. Cluster voxels dynamics in each time interval T_i (for example, using k-means clustering) based on correlation distance. Thus, we get N sets of clusters, where each set corresponds to one time window.
3. Select the sets of voxels clustered into the same clusters with a probability not less than given. We use probability of 80%.

CSM method uses 2 parameters: the time intervals length at step 1 and its overlap degree. The CSM method is described in details in [6].

The second method, "Functional Segmentation Method" (FSM) includes the following steps:

1. Select "Level of minimum correlation" (LMC). It is assumed that for each selected region there will be a reference dynamic having correlation with any voxel's dynamic in the region greater than this LMC value. So the LMC value characterizes the internal functional homogeneity of the identified regions.
2. Select an "Influence Area" (IA) for each voxel: a spatially connected area consisting of voxels that have correlation with the current voxel greater than the LMC value. The result of this step is many overlapping IAs.
3. Voxels redistribution between IAs: one voxel - to one IA. Large IAs are preferred.

The FSM uses 1 parameter: LMC value. The FSM method is described in details in [6].

An important feature of both proposed methods is the possibility of neutral voxels i.e. voxels that do not belong to any region.

2.2 Testing and Approbation

We tested the proposed methods both on simulated data and on experimental fMRI data obtained with a 3 T magnetic resonance imager Magnetom Verio.

Simulated Data. To check the correctness of the methods, we tested them on simulated data. The advantage of simulated data in contrast to experimental data is that the results of the methods can be compared with the model and we can get a numerical estimate of error.

We used models based on experimental data in which voxel dynamics were replaced with simulated time series of the same length. And the method of replacement depended on the specific model:

1. The "completely random model" involves replacing the dynamics of each voxel with a random time series with a uniform distribution of values.
2. The "random permutation model" involves replacing the dynamics of each voxel with a random time series, which is obtained from the time series of experimental data by arbitrary permutation of values.
3. The "ideal model" involves replacing the dynamics of each voxel in such a way that a perfect splitting is obtained: the entire brain is divided into regions, and in each

region all voxels have the same dynamics, different from the dynamics of voxels in any other region.

4. The “noisy model” is obtained from the “Ideal model” by adding white noise to the dynamics of each voxel, the amplitude of which depends on the amplitude of the signal. We used models with noise levels of 5, 15, and 25%

For each simulated data set, we identified the FHR using the CSM and FSM methods and compared it with ground truth data. To calculate the error, we took the resulting maps, determined the “one-to-one” correspondence between the selected FHR and the model ones, and then estimated the number of voxels that were included into the wrong regions.

Experimental Data. The experiment was carried out on 3 T MRI scanner Magnetom Verio (Siemens GmbH, Germany) at the National Research Centre "Kurchatov Institute". fMRI data were obtained with the following scan parameters: 42 slices, repetition time (TR) 2000 ms, echo time (TE) 20 mc, field of view (FOV) 192 × 192 mm^2, voxel size 3 × 3 × 3 mm^3. As part of the study, 1000 time samples were scanned for functional data, with a total duration of about 33.5 min. The total study acquisition time was 40 min. Functional and structural MRI data were processed using the SPM12 software package (available at [7]). After converting DICOM files to NIFTI format, all images were manually centered to anterior commissure for better template coregistration. The EPI images were corrected for magnetic field inhomogeneity using the FieldMap toolbox for SPM12 and recorded during expiremt session field mapping protocol. Then, the slice timing correction for fMRI data signals was conducted. Anatomical and functional data were normalized in the ICBM stereotactic reference system. T1 images were divided into 3 tissue maps (gray, white matter, and cerebrospinal fluid). Functional data was smoothed using a $6 \times 6 \times 6$ mm^3 FWHM Gaussian filter.

This study was approved by the ethics committee of the NRC Kurchatov Institute, ref. no. 5 (from 05.04.2017). All subjects signed an informed consent for participation in the study.

Testing and Approbation Methods. The experimental data were used both to obtain synthetic data and for additional testing:

1. We studied the characteristics of the FHR identified by the CSM and FSM methods on the experimental data, in particular: the total number of selected regions, the strength of the connection between voxels within the same region, the number of voxels distributed over regions, etc.
2. We studied the stability of the resulting FHR over the time:

    a. For the FSM we investigated how much the configuration of the allocated FHR changes over time. For this we split the experimental data set into overlapping time windows of length 300 with the intersection of 50 time samples. Then we identified the FHR in each time window using the FSM method. Next, we compared the FHR identified in the time windows with each other. For this we calculated the intersection percent.

   b. For the CSM we investigated the influence of the time window length on the resulting FHR location change. For this we identified the FHR for time windows of different lengths (from 50 to 400 with a step of 50). Then we calculated the intersection percent of the obtained FHR corresponding to different windows

3. FMRI data is known to have autocorrelation in it. Autocorrelation influences correlation-based methods. Since the developed methods use correlation as a metric of voxel connectivity we analyzed the effect of autocorrelation on the results of identifying the FHR. For this we removed autocorrelation from the data and compared the results of the proposed methods obtained on the original and cleaned data. To remove autocorrelation, we used the MATLAB function "ar" with parameter order equals 2.

3 Results and Discussion

3.1 Simulated Data

Testing on simulated data led to the following results:

1. "Completely random model" and "Random permutation model": both methods did not allocate a single region, as expected.
2. "Ideal model". Both methods selected all regions without errors.
3. "Noisy model":

   a. 5% noise: both methods selected regions without errors;
   b. 15% of noise: CSM method - without errors, FSM method - 0.5% of total number of voxels differs to ground truth data;
   c. 25% noise: CSM method - 0.2% voxel mismatch, FSM method - 18% voxel mismatch.

The results show that for the CSM method, the error is insignificant even at a noise level of 25%. For the FSM method, the error rate is quite high - 18%. The high percentage of mismatch values can be explained by the dependence of the method results on the parameter values. For the FSM method, the parameter is the minimum correlation level. If the correlation between the voxels is lower than this value, then they should not be included into the same FHR. We performed an estimate for LMC = 0.85, while adding 25% noise can decrease the correlation level between voxels to 0.7 or less. Therefore, such voxels should not be included into the same region. For comparison, reducing the LMC value to 0.75 leads to the percentage of voxels that do not match ground truth data is reduced to 2.8%. It is impossible to determine the only one correct value of the LMC, because at the moment there is no single opinion - what level of correlation between voxels of one region is considered high enough. Different studies use various levels: from 0.6 and higher [8–11].

3.2 Experimental Data

The experimental data were used to identify FHR using the CSM and FSM methods. As mentioned earlier, the result of the FSM method depends on the selected level of minimum correlation. Figure 1 shows the dependence of identified FHR characteristics on the selected LMC.

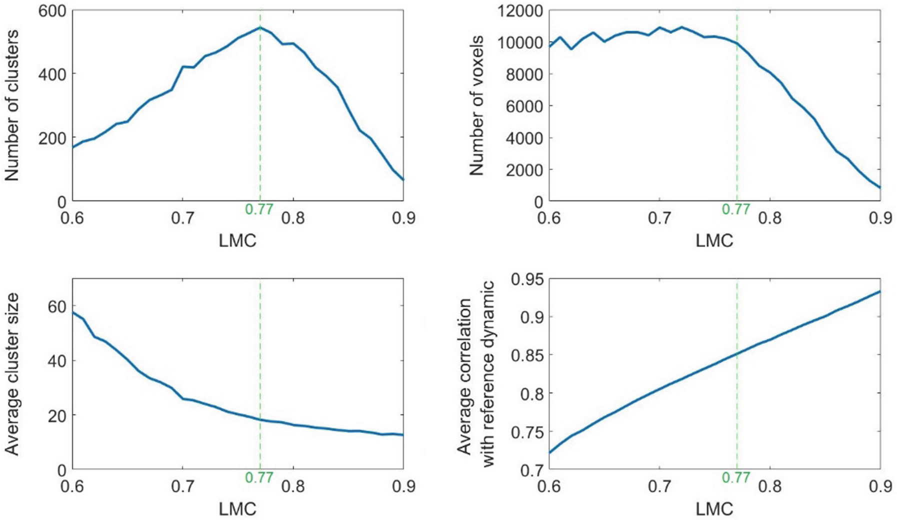

Fig. 1. Dependence of the characteristics of FHRs identified by FSM method on the LMC value.

What LMC value should be chosen? The answer to this question should be based on two factors (in descending priority): 1) the LMC value should not be lower than a good level of correlation (we choose values 0.7 and above as a good level of correlation); 2) as many voxels as possible should be distributed across the FHR. Based on this criterion, we chose LMC equal to 0.77 for the experimental data. This LMC does not give the absolute maximum number of distributed voxels, but the graph in Fig. 1 (top right) shows a flat section starting from the 0.77 level and below, where the number of distributed voxels does not differ much. But at the same time, a maximum number of regions is formed at the LMC = 0.77. It should be noted that for other data this level may be different.

We also estimated the dependence of the CSM method results on the length of time windows. For this, we obtained the FHR for time windows of different lengths (from 50 to 400 with a step of 50) and calculated the degree of overlap between the obtained FHR sets corresponding to different windows. The result is shown in Fig. 2. It can be seen that the larger the window size is, the more stable becomes the map of obtained FHR.

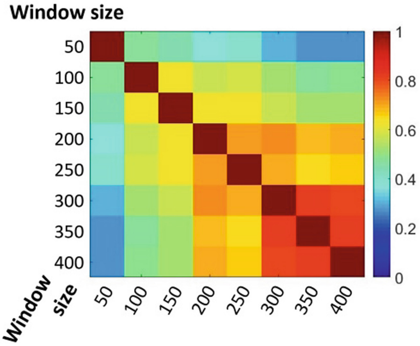

Fig. 2. The degree of overlap of the FHRs identified by the CSM method at different parameters of the time window: from 50 to 400 with a step of 50. The FHRs were compared in terms of the intersection level using the formula I/U, where I is the intersection, U is the union of the FHRs.

Based on these estimates, we fixed a window length of 300 and an overlap of 50%, thus obtaining 5 time windows.

Having fixed the parameters of the developed methods, we assessed the main characteristics of the obtained FHRs and compared the result with Glasser's anatomical atlas [12], which we have extended adding internal structures to it (see Table 1).

Table 1. The main characteristics of the FHRs obtained by the CSM and FSM methods on experimental data and the regions of the extended Glasser's atlas.

Characteristic	CSM	FSM	Extended Glasser's atlas
Number of regions	519	544	401
Average correlation between voxels of one region (averaged over all regions)	0.7	0.78	0.35
STD of correlation between voxels of one region (averaged over all regions)	0.15	0.1	0.22
Quantile of correlation between voxels of one region (averaged over all regions) (10% / 90%)	0.49/0.89	0.64/0.91	0.08/0.64
Minimum correlation between voxels of the same region (averaged over all regions)	0.44	0.53	0.11
Percentage of voxels, distributed by regions (according to extended Glasser's atlas)	32	33	100

The table shows that the average correlation within the regions obtained by the proposed methods is higher than in the regions in extended Glasser's atlas. Also, even the minimum correlation between voxels of one region, averaged over all regions, in the case of the proposed methods is higher than the average intraregional correlation for the extended Glasser's atlas.

Figure 3 shows a distribution of the correlation level between voxels of the same region. The extended Glasser's atlas gives a distribution with a peak in the region of 0.3, and the proposed methods give a distribution with a peak in the region of 0.8.

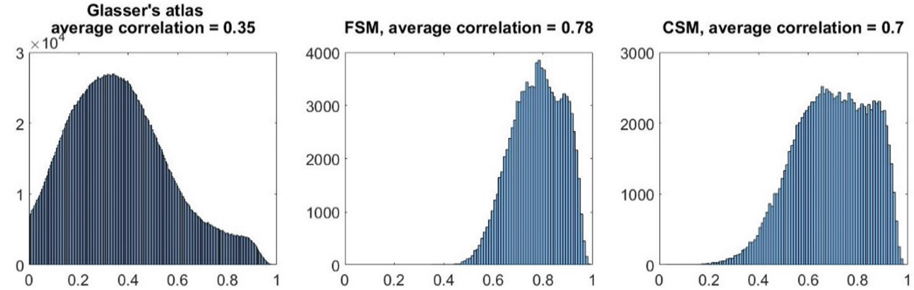

Fig. 3. The distribution of correlation values between voxels of one region (each histogram includes data from all corresponding regions).

As noted above, the FSM method is focused on identifying the FHR with a high level of internal connectivity, but the configuration of the selected regions changes over time. The CSM method weakens the requirement for the strength of voxel connectivity within the region, but highlights the time-stable FHR. Nevertheless, it can be seen from the figure that the level of connectivity within the regions identified by the CSM method is high.

We also analyzed the stability over time of the regions obtained by the FSM method. To do this, we split the entire experimental data set into overlapping time windows of length 300 with a step of 50 time samples. And in each time window, we determined the FHR by the FSM method. Next, we compared the FHRs allocated in different time windows with each other by calculating their overlap. The result is shown in Fig. 4. Adjacent time windows give a better match of the allocated FHR, but even in non-adjacent windows, overlap of FHRs id more than 50%.

FMRI data is known to have autocorrelation in voxel dynamics. Obviously, methods for studying functional connectivity based on correlation depend on the presence of autocorrelation. The developed methods use correlation as the central metric of voxel connectivity, so we analyzed the effect of autocorrelation on the results of identifying the FHR based on the developed methods.

We removed autocorrelation from the experimental data, performed the extraction of FHR on the cleaned experimental data, and compared the characteristics and maps of the extracted FHRs. Figure 5 shows a comparison of the number of allocated voxels for cleaned and uncleaned data. The figure shows that autocorrelation significantly affects the results of the FSM method. The presence of autocorrelation changes the dependence of the number of regions and the total number of voxels distributed across regions on the LMC parameter. At the same time, in the CSM method, removal of autocorrelation did not greatly change the dependence of these characteristics on the window size parameter.

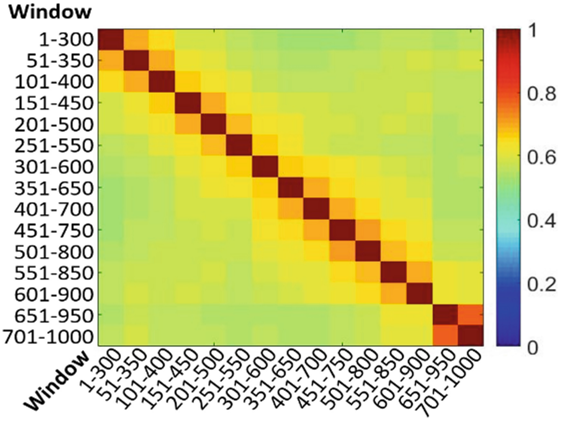

Fig. 4. Stability in time of FHRs, allocated by the FSM method on experimental data. The entire dataset is divided into sections of length 300 time samples with a step of 50 time samples. In each time window, the FHRs were identified by the FSM method. The FHRs between the windows were compared in terms of the intersection level using the formula I/U, where I is the intersection, U is the union of the FHRs.

We can see that autocorrelation strongly affects the results of the methods, therefore we recommend removing autocorrelation from the data, but since at the moment there is no consensus in the scientific community on this issue, this remains at the discretion of the researchers.

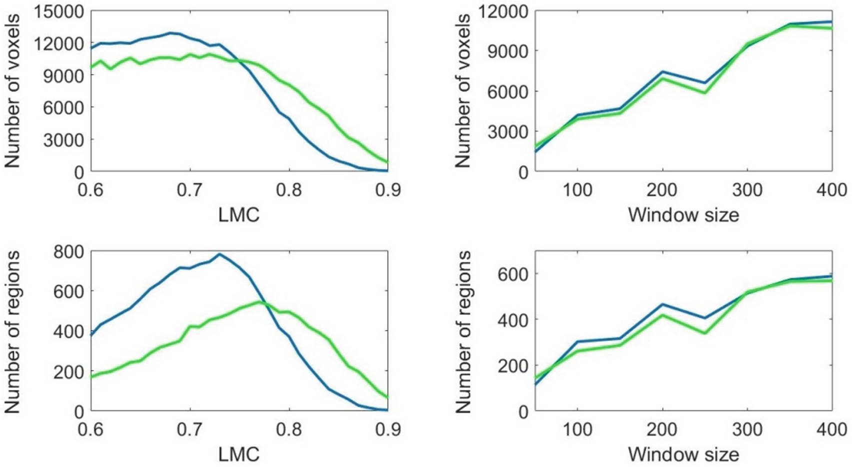

Fig. 5. Dependence of the number of voxels (top) and the number of regions (bottom), distributed over the FHR using the FSM (left) and CSM (right) methods, depending on the LMC and the length of the time window on the data before removing autocorrelation (green) and after removing autocorrelation (blue).

4 Conclusion

In this paper we have shown that the brain regions taken from established anatomical atlases are not functionally homogeneous. Therefore, we have developed two new methods: one method is focused on identifying regions with a high level of connectivity between voxel dynamics, the second method is aimed at selecting regions that are stable in time. An essential feature of the proposed approaches is the possibility of the presence of voxels that do not belong to any brain macroscopic region. For example, based on our experimental fMRI data, extended Glasser's atlas includes 29 757 voxels, and the regions created based on proposed methods include the order of ten thousand voxels. Next, we showed that the obtained partitions give a high level of homogeneity of functional connections (the average correlation within the region is 0.8).

Nevertheless, the partitioning results obtained by the developed methods must be checked and updated from the physiological point of view. To assess the stability of the spatial distribution of obtained brain regions, it will be important to study the effect of autocorrelation in fMRI data on the developed methods. The proposed approaches are important for identifying functionally homogeneous brain regions, which can subsequently be used to calculate causal and correlational connectivity in brain neural networks responsible for cognitive processes.

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References

1. Smitha, K.A.: Resting state fMRI: a review on methods in resting state connectivity analysis and resting state networks. Neuroradiol. J. **2017**, 305–317 (2017)
2. Orlov, V.A., Ushakov, V.L., Kozlov, S.O., Enyagina, I.M., Poyda, A.A.: A review of method and approaches for resting state fMRI analyses. In: Samsonovich, A. (ed.) Biologically Inspired Cognitive Architectures 2019. BICA 2019. Advances in Intelligent Systems and Computing, vol. 948, pp. 400–404. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-25719-4_52
3. Betzel, R.F., Bassett, D.S.: Multi-scale brain networks. Neuroimage **160**, 73–83 (2017). https://doi.org/10.1016/j.neuroimage.2016.11.006
4. Wang, C., Ng, B., Garbi, R.: Multimodal brain parcellation based on functional and anatomical connectivity. Brain Connectivity **8**, 604–617 (2018). https://doi.org/10.1089/brain.2017.0576
5. Wang, L., Xu, J., Wang, C., Wang, J.: Whole brain functional connectivity pattern homogeneity mapping. Front Hum Neurosci. **12**, 164 (2018). https://doi.org/10.3389/fnhum.2018.00164
6. Kozlov, S., Poyda, A., Orlov, V., Malakhov, D., Ushakov, V., Sharaev, M.: Selection of functionally homogeneous brain regions based on correlation-clustering analysis. Procedia Comput. Sci. **169**, 519–526 (2020). https://doi.org/10.1016/j.procs.2020.02.215
7. SPM12 Software home page. https://www.fil.ion.ucl.ac.uk/spm/software/spm12/, Accessed 25 Oct 2020

8. Biswal, B., Yetkin, F.Z., Haughton, V.M., Hyde, J.S.: Functional connectivity in the motor cortex of resting human brain using echo-planar MRI. Magn. Reson. Med. **34**, 537–541 (1995). https://doi.org/10.1002/mrm.1910340409
9. Raichle, M.E., MacLeod, A.M., Snyder, A.Z., Powers, W.J., Gusnard, D.A., Shulman, G.L.: A default mode of brain function. Proc. Natl. Acad. Sci. **98**, 676–682 (2001). https://doi.org/10.1073/pnas.98.2.676
10. Fox, M.D., Corbetta, M., Snyder, A.Z., Vincent, J.L., Raichle, M.E.: Spontaneous neuronal activity distinguishes human dorsal and ventral attention systems. Proc. Natl. Acad. Sci. **103**, 10046–10051 (2006). https://doi.org/10.1073/pnas.0604187103
11. Vincent, J.L., Kahn, I., Snyder, A.Z., Raichle, M.E., Buckner, R.L.: Evidence for a frontoparietal control system revealed by intrinsic functional connectivity. J Neurophysiol **100**, 3328–3342 (2008). https://doi.org/10.1152/jn.90355.2008
12. Glasser, M.F., Coalson, T.S., Robinson, E.C., Hacker, C.D., Harwell, J., Yacoub, E., Ugurbil, K., Andersson, J., Beckmann, C.F., Jenkinson, M., Smith, S.M., Van Essen, D.C.: A multimodal parcellation of human cerebral cortex. Nature **536**, 171–178 (2016). https://doi.org/10.1038/nature18933

Designing Sense of Agency Experiments to Study Joint Human-Machine Grasping Actions

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Abstract. In this paper, we present a novel experimental design for studying sense of agency (SoA) in joint human-machine actions than involved grasping movements. The joint actions were implemented by using an electromechanical grasping device propelled by a servo drive. The device completed a grasping action initiated by a participant. These actions were contrasted with other levels of the participant's involvement, including active movements, passive movement and observation of a dummy's movement. Our experimental setup allows us for studying the possible correlation between the level of involvement into action and quantitative distance estimates. The proposed experimental design was tested in a pilot study involving 9 heathy volunteers. In particular, the survey results showed a significant correspondence between the score of reported SoA and participant's role in action. We suppose that our new design for studying joint actions will contribute to the development of exoskeletons, rehabilitation technologies and advanced human-machine systems.

Keywords: Joint actions · Active-passive actions · Sense of agency · Intentional binding · Spatial binding

1 Introduction

1.1 Sense of Agency

The sense of agency (SoA) is an essential part of human self-consciousness [1]. It refers to the subjective experience of discovering oneself as the author of an action. This sense may dramatically fail in some situations as for instance in cooperative problem solving and in swift joint attention [2]. One of the most important issues in SoA studies is quantifying it in various conditions. The early discovered problem is that a direct interview with the subject can force them to reevaluate their experience, and will only grant access to the high-level judgements of agency, leaving aside the low-level feeling of agency [3]. This obstacle urges the experimenters to search for behavioral and physiological correlates of SoA. The correlates would make the implicit evaluations of SoA possible, which in turn would help to discover the necessary conditions for the emergence and dissipation of SoA.

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1.2 Intentional Binding and Spatial Binding

A probable behavioral correlate of SoA known as intentional binding has been widely discussed in literature. Intentional binding refers to an effect in quantitative subjective estimates of time reported by Haggard et al. [4]. The participants estimated a time interval between an action and its outcome as significantly shorter than it actually was, but this effect was observed only when the action was voluntary, and not induced by transcranial magnetic stimulation. A similar effect called spatial binding was reported for the subjective estimates of distance [5]. A distance travelled by the mark from the moment of action to a certain event was perceived as shorter by the participants when the action and the event were causally connected. Since causal binding has been observed in time intervals as well [6], it could be fruitful to study the relation between the subject's involvement into action and their subjective estimates of distance.

1.3 SoA in Joint Actions

It is common for the experimental studies of SoA to contrast voluntary actions with the involuntary ones. However, new advancements in exoskeletons and rehabilitative technologies raise the issue of SoA in joint human-machine actions. Accordingly, the array of situations where an intermediate level of involvement of the human subject takes place has to be considered. Would the subject experience sense of agency as in regular voluntary actions, if the action they intended were completed by a machine? The case we view as even more interesting is the possibility of enhancement of the human actions using mechanical devices. Few studies were dedicated to SoA in joint human-human [7] and human-machine [8] actions, but we were unable to find any published studies of SoA in actions enhanced by the machine, or committed with the machine acting as an instrument, rather than an independent co-agent. However, in our recent study of SoA [9] we had already considered interaction between human agent and assisting device, though the assisting device in that experiment did not boost one's performance.

In the current paper we present an experimental design for studying the possible connection between the subjective estimates of distance and the level of subject's involvement into action. The action implemented in our design is a grasping movement, that is made with a thumb and an index finger. By creating an exoskeletal claw-like device, we were able to include joint actions into the design. Also, we made a silicone dummy of a human hand to organize a condition where the subject is only an observer. In total the design we propose features four levels of human involvement. The method was tested in a preliminary study, which yielded promising results, that yet have to be verified in a full-scale experiment.

2 Methods

2.1 Apparatus

We designed an experimental setup (see Fig. 1) in order to probe the supposed correlation between the subjective estimates of distance and subject's degree of involvement into action. The setup included two devices: a wire lifting device and a grasping device (the "claw") that aided a participant in grasping the wire.

Participant's wrist was fastened on a wooden platform at the base of the device. A metallic stand containing the controller board, servo drive and a capacitive sensor was also fixed on the platform. A wire was attached to the lever, which could be lifted by a servo drive at the top of the stand. The servo drive was covered with an opaque case so a participant would not be distracted when it was operating. The wire went through the base of the device into the wooden box that supported the whole setup. At the bottom of the box the wire was hooked to a weak spring, so the wire always would be straightened. The fragment of the wire within the experimental purview stretched from an opening in the stand to the base of the device, and was visible to a participant. The wire was marked with a solid drop of tin painted black. Three lasers were on the sides of the stand, emitting beams at the sensors on the base parallel to the wire. A holder with two LED lamps illuminating the working area was also placed on the base, as well as a monitor and a numeric keypad used for data input.

The claw consisted of two aluminum plates forming a gear train. A servo drive bolted to the claw could make it clench and unclench automatically safe for a participant. With the claw a participant was able to move only their metacarpophalangeal joints, therefore the grasping motion had a single degree of freedom. The claw was tightly fixed on the participant's thumb and index finger by hook-and-loop fasteners. During the experiment, when the claw was clenching it would cross the laser barrier imposed by three laser beams. This event in turn would trigger the servo drive at the top of the stand, and the wire would start to lift. When participant's fingertips touched the wire, it would immediately stop, the tin drop reaching a certain position. A participant then estimated the distance between the drop and the opening in the stand. After 500 ms would pass, the LED lamps would turn off, leaving no source of light and no means to reevaluate the distance. A participant used a numeric keypad to enter their subjective estimate of distance which appeared on the monitor screen. The screen was adjusted to low brightness and framed by a cardboard shutter so only a small window with a number was left.

Data processing and control of the servo drives and lamps was carried out via a program developed in Delphi 2010.

2.2 Experimental Design

The experiment was conducted in four distinct stages. Each stage consisted of multiple identical trials. In every stage the grasping movement was executed in one of four different ways, presumably with varying involvement of a participant:

- active movements (Act) – a participant grasped the wire on their own;
- active-passive movements (Actpas) – a participant initiated the action with a slight move, whereas the servo completed it.
- passive movement (Pas) – the servo grasped the wire while the participant was idle;
- hand dummy movement (Dum) – the participant's hand was unfastened and replaced with a silicon dummy of a human hand. The servo grasped the wire on its own,

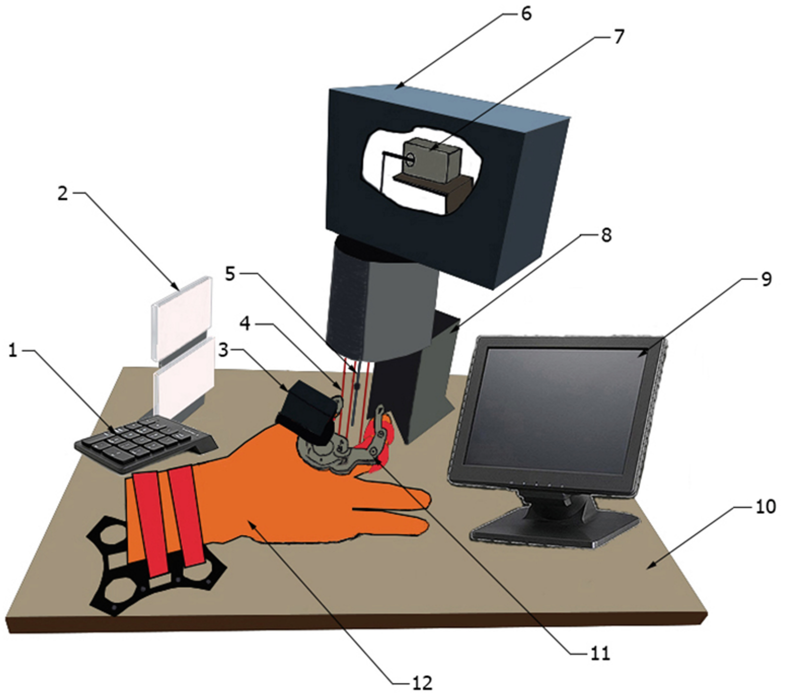

Fig. 1. Sketch of the experimental setup. 1 – Numeric keypad; 2 – LED lamps; 3 – Claw servo drive; 4 – Laser barrier; 5 – The wire; 6 – Opaque case; 7 – Wire lifting servo drive; 8 – Controller board; 9 – LCD monitor; 10 – Wooden platform; 11 – the "claw"; 12 – Participant's hand or a hand dummy.

while a participant observed the movements and made distance estimates as in other conditions.

All these activities were perfectly safe for the participants. The experimenter presented the Actpas condition to a participant as a part of the experiment where the claw served as "the assistant", helping them to grasp the wire faster and with minimal effort. We expected these joint actions to be quicker than active movements, the data on action durations is provided in the "Results" section. It has to be noted that active and active-passive movements were voluntary, while passive and dummy movements were committed by the device. During the Pas and Dum stages, the experimenter made sure that the participant did not move by tracing the EMG.

After the experimental session the experimenter asked the participant to evaluate their experiences of sense of agency in every block of trials using a Likert-type scale that ranged from 0 to 9. The exact formulation of the question was the following: "Evaluate your sense of authorship over each kind of actions; 9 – you are the author of the action, 0 – the action was perceived as externally caused.

2.3 Participants

The group of 9 naïve right-handed healthy volunteers (5 males and 4 females, average 20.7 years) participated in the pilot experiment. Due to the well-known epidemic situation of the year 2020, we were unable to involve a larger sample size of subjects for testing this novel method in a full scale. All subjects were introduced to the procedure and signed an informed consent. The experiment procedures were in agreement with the institutional and national guidelines for experiments with human subjects as well as with the Declaration of Helsinki.

2.4 Data Processing and Analysis

Statistical analysis was carried out using *Statistica* 10 (*StatSoft*, USA). To analyze the effects in distance differences, repeated measures ANOVA was used. Further comparisons were made using the Fisher LSD post-hoc criterion. For survey results the Friedman test was used and post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied.

3 Preliminary Results

3.1 Enhanced Action Speed in the Actpas Condition

In this study we intended to create an instance of the joint human-machine actions with enhanced performance. The reasoning behind this idea was simple: we reckoned that acceleration provided by the device would make the interaction seem more useful and ergonomic for the participants. We compared the characteristic durations of grasping actions in the Act and the Actpas blocks, thus juxtaposing the unaided movements with those performed together with the device. The action time durations of respective actions were calculated as differences between two events: the participant's exceeding of the EMG threshold and activation of the capacitive sensor when the wire was caught. In two participants the durations could not be calculated due to invalid registration of EMG threshold exceeding in the Act block. In Pas and Dum conditions the durations were impossible to determine, because the EMG threshold exceeding was simulated in these conditions. We conducted tests of significance for the mean durations using 1-way repeated measures ANOVA. The analysis showed a significant effect: Wilks' $\lambda = 0.03$, $F(2, 5) = 25.08$, $p < 0.0002$. As we intended, on average, grasping actions in the Actpas block were completed faster than in the Act block. The group means of action time durations can be seen in Fig. 2.

3.2 Subjective Estimates of Distance

In the present study we investigated the non-verbal subjective estimates of distance in condition with varying degree of involvement into action. According to our hypothesis, the shortened subjective estimates of distance may be an implicit correlate of SoA, not unlike intentional binding that refers to shortened estimates of time intervals between the action and its effect. The distance we considered in this experiment was the displacement of the tin drop that happened before the capacity sensor activated. The drop began to

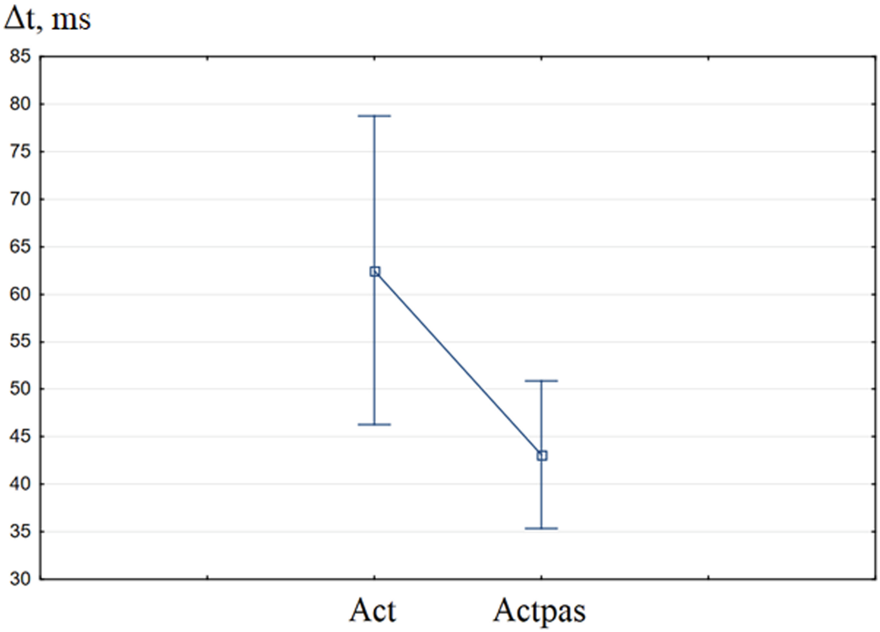

Fig. 2. Group means of action time durations. Vertical lines denote 95% confidence intervals.

ascend swiftly when the laser barrier was crossed, i.e. when the action commenced, and it stopped in result of the action having been performed. We calculated differences between the actual and subjectively estimated distances and averaged them in every participant.

We analyzed the mean differences between distances using 1-way repeated measures ANOVA. All four kinds of conditions were considered. The analysis showed a significant effect: Wilks' $\lambda = 0.02$, $F(5, 4) = 25.08$, $p < 0.04$. Post-hoc analysis revealed differences between the Act and Dum conditions ($p < 0.03$), and also between the Act and Pas conditions ($p < 0.02$). No significant differences in other pairs of conditions were found. The group means of differences between the subjective estimates and real distances can be seen in Fig. 3.

3.3 Survey Results

After the experimental session the participant was asked to evaluate the experienced sense of agency in every block of trials. For that purpose, a Likert-type scale ranging from 0 to 9 points was used. To analyze the scores, we used the Friedman test, and the post-hoc analysis was conducted by means of Wilcoxon signed-rank test with Bonferroni correction. The Friedman test demonstrated a significant effect ($\chi^2(3) = 21.6375$, $p < 0.001$). The interquartile range equaled 0 (from 9 to 9), 1.75 (from 6.75 to 8), 4 (from 0 to 4) and 0 (from 0 to 0) in the Act, Actpas, Pas and Dum conditions respectively. Post-hoc analysis showed a significant difference between the Act and Actpas conditions

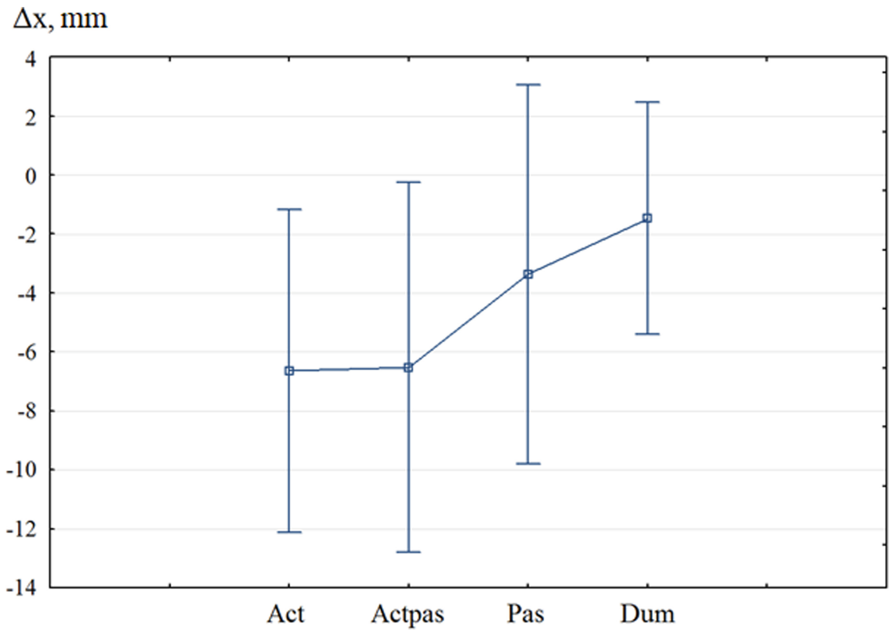

Fig. 3. Group means of differences between the actual distances and subjective estimates. Vertical lines denote 95% confidence intervals.

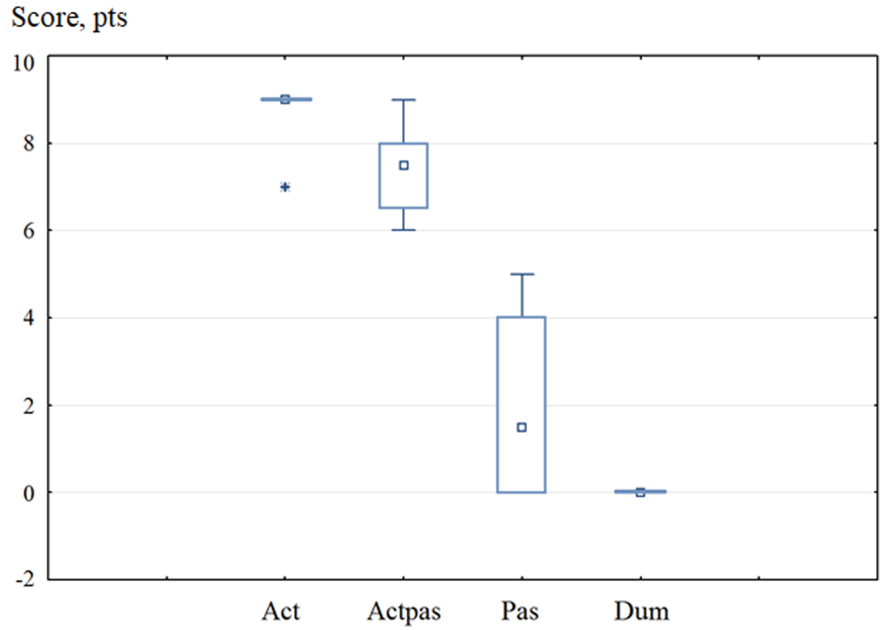

Fig. 4. The box-and-whisker diagrams for mean SoA scores.

($Z = -2.3664$, $p < 0.05$), the Actpas and Pas conditions ($Z = -2.5205$, $p < 0.05$). The box-and-whiskers diagrams for mean SoA scores in all conditions can be seen in Fig. 4.

4 Discussion

In the present study, we successfully tested a novel experimental design for exploring the possible correlation between the subjective estimates of distance and sense of agency (SoA). The main advantage of our design is that it features a wide range of levels of subject's involvement into action. Partial involvement of the subject is a necessary condition for studying SoA in joint human-machine movements, e.g. in interactions with an exoskeleton. A variety of joint actions examined in the present study is referred to as the active-passive (Actpas) action. In our setup, an active-passive action was initiated by the human agent and completed by the "claw" – an exoskeleton fragment created for assistance in grasping movements. We contrasted the active-passive movements with the active ones (Act), the passive ones (Pas) and with the movements of a silicone hand dummy (Dum). In the Act condition, the participants performed an action on their own, while the "claw" was deactivated. In the Pas and Dum conditions the action was involuntary: the "claw" moved in a preprogrammed way, having been attached to the participant's hand (Pas) or a hand dummy (Dum).

We were interested in portraying the device's assistance as beneficial in the Actpas condition, and so we attempted to make the joint movements faster than the active movements. We pursued this endeavor because in real life situations one would rather prefer joint actions if they enhanced one's capabilities, given the agent is able to perform an action on their own. Our preliminary results show that in our setup the active-passive movements were performed significantly faster than in the case of active movements.

A possible correlate of SoA considered in our design was the difference between the estimated and actual displacement of a tin drop. The drop's relocation started when the action was initiated, and ceased, when the action (grasping the wire) was completed. An effect we expected to find may have been similar to intentional binding – the subjective shortening of time intervals between the action and its result. The preliminary results support our hypothesis: the mean differences between the distance estimates and actual distances were significantly higher in the Act condition than in Pas and Dum conditions. In order to make further speculations, a research with a larger sample is required. However the experimental design we presented here seems to be adequate and sufficient for conducting such a full scale study.

While testing the new design, we also conducted a survey where the participants were asked to give explicit SoA scores to all the four movement types. The preliminary results show a significant difference between the Act and Actpas conditions, the Actpas and Pas conditions and the Act and Pas conditions. No differences between the Pas and Dum conditions were detected, reminding some of the out-of-body effects [10, 11]. However, it has to be noted that both types of movement presuppose little agency. The gradation that manifested itself in the results corresponds with varying degrees of involvement implemented in the experimental design. It suggests that the active-passive actions are experienced as actions with intermediate intensity of SoA. Again, as with the subjective estimates of distance, a more substantial research is needed to test this particular hypothesis.

5 Conclusion

We developed a novel experimental design for studying SoA in joint human-machine grasping actions. We successfully tested the proposed design, and the first data was collected. According to these preliminary results, the joint actions were performed faster by the participants than similar unaided actions. There also was a correlation between subject's degree of involvement into action and the subjective estimates of distance travelled by the mark between the moments of action initiation and completion. In addition, survey results showed a significant statistical correspondence between the score of reported SoA and subject's role in action.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Gallagher, S.: Philosophical conceptions of the self: implications for cognitive science. Trends Cogn. Sci. **4**, 14–21 (2000). https://doi.org/10.1016/S1364-6613(99)01417-5
2. Velichkovsky, B.M.: Communicating attention. Pragmat. Cogn. Cogn. **3**, 199–223 (1995). https://doi.org/10.1075/pc.3.2.02vel
3. Georgieff, N., Jeannerod, M.: Beyond consciousness of external reality: a "Who" system for consciousness of action and self-consciousness. Conscious. Cogn. **7**, 465–477 (1998). https://doi.org/10.1006/ccog.1998.0367
4. Haggard, P., Clark, S., Kalogeras, J.: Voluntary action and conscious awareness. Nat. Neurosci. **5**, 382–385 (2002). https://doi.org/10.1038/nn827
5. Kirsch, W., Pfister, R., Kunde, W.: Spatial action-effect binding. Attention Percept. Psychophys. **78**, 133–142 (2016). https://doi.org/10.3758/s13414-015-0997-z
6. Suzuki, K., Lush, P., Seth, A.K., Roseboom, W.: Intentional binding without intentional action. Psychol. Sci. **30**, 842–853 (2019). https://doi.org/10.1177/0956797619842191
7. Obhi, S.S., Hall, P.: Sense of agency in joint action: influence of human and computer co-actors. Exp. Brain Res. **211**, 663–670 (2011). https://doi.org/10.1007/s00221-011-2662-7
8. Sahaï, A., Desantis, A., Grynszpan, O., Pacherie, E., Berberian, B.: Action co-representation and the sense of agency during a joint Simon task: comparing human and machine co-agents. Conscious. Cogn. **67**, 44–55 (2019). https://doi.org/10.1016/j.concog.2018.11.008
9. Dubynin, I.A.., Yashin, A.S., Velichkovsky, B.M., Shishkin, S.L.: Intentional binding in joint human-machine motor actions (2021 under review)
10. Ehrsson, H.H.: The experimental induction of out-of-body experiences. Science **317**(5841), 1048 (2007). https://doi.org/10.1126/science.1142175
11. Bekrater-Bodmann, R., Azevedo, R.T., Ainley, V., Tsakiris, M.: Interoceptive awareness is negatively related to the exteroceptive manipulation of bodily self-location. Front. Psychol. **11**, 562016 (2020). https://doi.org/10.3389/fpsyg.2020.562016

Machine Learning in the Diagnosis of Disorders of Consciousness: Opportunities and Challenges

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Abstract. The detection of conscious awareness in patients with disorders of consciousness using behavioral signs is challenging in the presence of sensory, motor, or executive function deficits. Brain signal measurements provide additional information for patient stratification, and the large amounts and multidimentional nature of the obtained data motivate the application of machine learning (ML) methods. We review some of the recent studies applying this approach to data from electroencephalography, diffusion magnetic resonance imaging (MRI), and resting-state functional MRI. Each of these modalities provided features correlating with the behaviorally determined levels of consciousness. At the same time, considering the accuracy of the obtained classification algorithms, we highlight the problem of simultaneous model selection and accuracy estimation using the same sample, which requires special techniques of statistical analysis, otherwise the obtained accuracy estimates can be biased and prone to misinterpretation. Additionally, there is a need for greater generalization ability of the classifiers over the whole spectrum from the UWS to the conscious state. The use of ML within brain-computer interfaces for the detection of command following is discussed as a promising complementary method able to detect patients with cognitive motor dissociation, and its results may prove useful as labels in the training of algorithms for the direct stratification of DOC patients.

Keywords: Disorders of consciousness · Diagnosis · Unresponsive wakefulness syndrome · Minimally conscious state · Machine learning · Cross-validation · Brain-computer interface

1 Introduction

Disorders of consciousness (DOC) are some of the most devastating neurological conditions resulting from severe brain damage. In addition to the extremely difficult task of improving the state of the patients, there are significant diagnostic problems. A distinction is made between the unresponsive wakefulness syndrome (UWS, also called the vegetative state, VS), in which wakefulness occurs without any behavioral signs of awareness, and the minimally conscious state (MCS), in which there are minimal but

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reproducible signs of awareness of oneself and the environment. The behavioral tests used to identify these conditions can underestimate the level of consciousness due to impairments in the sensory, motor, and executive functions.

This motivates the present active research interest in finding objective methods to assess the level of consciousness based on instrumental techniques, such as structural, diffusion-based and functional magnetic resonance imaging (MRI) of the brain [1], electroencephalography (EEG), as well as recording evoked potentials, including EEG responses to transcranial magnetic stimulation [2]. The multiplicity of the modalities used and the multidimensionality of the data obtained in each of them make it highly desirable to automate the search for patterns and combined features useful for diagnostics, which can be done using machine learning methods. At the current, initial stage of development of such approaches, the clinical assessment is used as the true classification for training and testing the algorithms. Assessing their ability to go beyond the limitations of behavioral tests and surpass the clinical scales in assessing the state of consciousness in the presence of sensorimotor dysfunctions is a challenge for the future. In some studies, the correctness of the results of instrumental studies disagreeing with the clinical diagnosis is indirectly assessed on average based on the subsequent disease dynamics in such cases.

In this perspective paper, we summarize some of the recent results of applying machine learning techniques for the extraction of features correlating with the level of consciousness from brain signals of different modalities. We highlight the problem of feature selection with limited amounts of data, as well as the challenge of finding classifiers applicable across a range of states of consciousness, which will maximize their chance of capturing brain properties genuinely related to conscious awareness.

2 Recent Applications of Machine Learning to the Differentiation Between Disorders of Consciousness

In this section, we review three studies employing machine learning for stratifying DOC patients based on different types of brain measurements: EEG, diffusion MRI, and resting-state functional MRI (rs-fMRI).

The study [3] analyzed 181 EEG recordings with 256 channels from 167 patients (75 UWS, 68 MCS, 24 brain-damaged, but conscious), as well as 14 healthy volunteers. A recording session lasted 30 min and included auditory stimulation with regularities at two different hierarchical levels (the 'Local-Global' protocol). The characteristics of evoked potentials (including late P300 peaks and the mismatch negativity) and background EEG activity (in particular, power in frequency bands, entropy and algorithmic complexity, as well as spectral and informational measures of connectivity) were calculated. The parameters were averaged over *a priori* regions of interest, and the resulting 92 characteristics were compared between the UWS and MCS. The effect size was described by the area under the ROC-curve (AUC) with values above 50% corresponding to parameters that are higher in the MCS than in the UWS. The most informative parameters were the weighted symbolic mutual information in the theta range ($\text{AUC} = 74\%$), and the normalized power of the delta rhythm ($\text{AUC} = 31\%$) and alpha rhythm ($\text{AUC} = 72\%$). To investigate the possible complementarity of information from different features and to refine the classification by combining the data, the support vector machine (SVM) classification algorithm was used, with an assessment of accuracy using cross-validation. A classifier set to use the best cross-validated single EEG measure gave AUC = 71%, and the classifier based on all the parameters reached AUC = 78%. Thus, a certain complementarity of the EEG measures was found, and the use of the SVM method made it possible to find their combination allowing a more accurate classification of patients in the UWS and MCS than that obtained using single EEG characteristics.

An important general issue illustrated by the study [3] is that using the same sample for selecting the best-performing feature and estimating its accuracy can make the resulting estimate biased in the optimistic direction. Moreover, the magnitude of this bias depends on the details of the distributions involved and cannot be easily determined, so the cited best AUC values for specific EEG characteristics should be interpreted with caution. An approximately unbiased accuracy estimate can be obtained for a classification algorithm involving selection of features (as well as models, hyperparameters, etc.) using cross-validation (CV), provided that all the selection steps are performed separately for each fold (e.g., using nested CV), based only on that fold's training set rather than on the whole sample. In the context of significance testing, the issue of selection and inference on the same data is called the multiple comparisons problem, and several methods of accounting for it are available. One of them (the false discovery rate correction) was used in [3] and helped reliably identify the EEG features significantly different in the UWS and MCS.

Another important aspect is the ability of the classifiers to generalize across several states of consciousness. It is natural to expect that a binary criterion separating the UWS and MCS by capturing features genuinely related to consciousness should classify subjects in a conscious state (CS) as belonging to the higher-consciousness class (MCS rather than UWS). Misclassification of CS subjects is arguably more problematic than that of DOC patients both because CS subjects presumably have higher awareness than MCS patients (and should thus be easier to classify correctly) and because such a discrepancy cannot be explained by the limitations of behavioral detection of consciousness (which is possible in a fraction of DOC patients). Importantly, while most EEG features in [3] showed similar effects in the MCS-UWS and CS-UWS contrasts, some measures produced diverging results, e.g., the mean non-normalized theta power (AUC = 65% and 49% respectively). Perhaps partly due to such features, the SVM classifier trained to distinguish the UWS from MCS classified the majority but not all the brain-damaged CS patients and healthy subjects correctly (34 of 38, or 89%). A conceptually similar situation was observed in the study [4], where a UWS-MCS classifier based on functional connectivity (derived from rs-fMRI) classified 37 out of 39 healthy controls correctly. Studying the causes of the remaining discrepancies is important for increasing the accuracy of the algorithms and, crucially, for making them more likely to capture the neural correlates of consciousness rather than being influenced by confounding factors that may be specific to each patient subpopulation, as well as random features (sampling error) in the particular patient samples.

The study [5] involved 25 patients: 10 in the UWS and 15 in the MCS, who were further subdivided into 7 MCS– and 8 MCS + patients. The aim was to investigate the differences between these groups in the structural thalamo-cortical connectivity using diffusion MRI data. A searchlight mapping technique was used, in which a 5-voxel sphere is built around each brain voxel, and the thalamic connectivity values from the voxels within each sphere are used as features in a classifier. Three separate SVM models were constructed to distinguish three pairs of states: MCS + vs. UWS, MCS– vs. UWS, and MCS + vs. MCS–. The accuracy was assessed by cross-validation, and the significance was determined at the level of 0.05 with a Bonferroni correction for the number of spherical regions, which corresponded to the classification accuracy thresholds of 81–84%. Only clusters with at least 50 contiguous voxels were reported. For each pair of consciousness states, regions were found (predominantly in the frontal, parietal and sensorimotor areas) whose patterns of thalamic connectivity gave a 100% classification accuracy. However, the accuracy estimates for the best-performing regions are subject to the bias mentioned above and must be interpreted very cautiously. Unbiased estimates can be obtained either by placing the region selection step into a cross-validation loop or by collecting additional data and validating the effects in the regions selected in the study [5]. At the same time, in the tests of statistical significance (i.e., of better than random separation of the patients), the region selection problem was accounted for by using a correction for multiple comparisons.

The ability of the pairwise classifiers to generalize to the third state of consciousness (e.g., the performance of the UWS vs. MCS– separation criterion in the UWS vs. MCS + classification problem) was not directly investigated in [5]. In this regard, the authors note that although the most significant regions for all the three contrasts traversed parts of the frontal, parietal, and sensorimotor zones, their precise locations were different. Similarly to the previous discussion, this motivates further work aimed at investigating whether there exist structural connectivity patterns showing a robust monotonic change with the consciousness level from the UWS to the conscious condition.

In the study [6], resting-state fMRI data from 44 conscious subjects was used to construct classifiers that distinguish the state of wakefulness from two unresponsive states: deep sedation and general anesthesia. Subsequently, the authors tested whether the obtained models were able to detect and differentiate between disorders of consciousness (21 patients: 13 UWS, 8 MCS, and 28 healthy volunteers). The calculated parameters included the fractional amplitude of low-frequency fluctuations (fALFF) and regional homogeneity (ReHo) of the rs-fMRI signal averaged by each of 10 resting-state networks represented by a total of 226 spherical nodes of a 10 mm diameter. Additionally, the functional connectivity within and between these networks was calculated. Three models were applied to the obtained 75 features: SVM, decision trees (Extra Trees variant of the Random Forest method, ET) and an artificial neural network (ANN). The ANN had 2 hidden layers of 25 and 5 ReLU units, with dropout, and a single-node (sigmoid) output layer, while the hyperparameters of the SVM and ET models were optimized using nested cross-validation. All three models successfully distinguished wakefulness from general anesthesia or deep sedation (AUC = 0.95, 0.92, and 0.94 for the SVM, ET, and ANN models, respectively). Additionally, the models separated healthy volunteers from UWS patients (AUC = 0.99, 0.94, 0.98, respectively). However, only the ANN model showed a significant difference between the UWS and MCS. The SVM and ET models classified the majority of UWS patients as unconscious, whereas the corresponding result was nonsignificant for the ANN model. All the three models gave mixed results when applied for the classification of MCS patients. Thus, the features that differ between wakefulness and sedation also distinguish healthy subjects from UWS patients, while the same features are much less effective in differentiating between the MCS and UWS. Once again, this situation illustrates the high dimensionality of neural correlates of consciousness and the corresponding difficulty of selecting generalizable features.

3 Classification of Mental States Using Machine Learning for Detection of Command Following in DOC Patients

The studies reviewed above used machine learning algorithms to directly predict the consciousness states of individuals from brain measurements. However, these methods can be used in the context of DOC diagnosis in a different way, namely to classify a patient's brain signals evoked by a verbal command, so that a meaningful correspondence between the instruction and brain activity is interpreted as mental command following. Two seminal papers [7] and [8] demonstrated this approach using fMRI, with several patients demonstrating command-related modulation of brain activity similar to that observed in healthy subjects, and one patient additionally being able to answer yes-no questions using brain signals. The data analysis was based on voxelwise statistics, which is standard for this type of data, and custom-designed procedures for synthesizing information from relevant voxels. At the same time, EEG-based brain-computer interfaces have considerable advantages over fMRI for this purpose, which include the wider availability of EEG equipment, potential for portability, and greater suitability for online data analysis with real-time feedback, which allows the patients with preserved awareness to engage more directly with the tasks.

This opportunity was explored in the study [9] involving 78 DOC patients (45 UWS and 33 MCS), none of whom showed behavioral command-following abilities. An EEG-based brain-computer interface (BCI) experiment was performed to detect command following, and the results were correlated with the rates of subsequent recovery. In the experiment, each patient was instructed to focus on one of two simultaneously presented visual stimuli (e.g., photographs). Flashing frames appearing around each stimulus marked the time points for the analysis of event-related potentials, while the two images flickered at different frequencies to assess the existence of time-locked EEG signals. In a calibration session, an SVM classifier was trained to distinguish the P300 components corresponding to the target vs non-target stimuli. In a subsequent evaluation session, each of the two stimuli was scored by the sum of two components: the output of the SVM classifier applied to the time points of frame flashes around this stimulus and a measure of EEG activity time-locked to the image flickering. The stimulus with the higher score was selected and compared to the true target, and a statistically significant number of successes (32 out of 50) obtained for a patient was interpreted as command following. Such patients were characterized as having cognitive motor dissociation (CMD) and constituted 44% of all the studied DOC patients. Within the UWS group, a transition to MCS happened in 15 of 18 patients with CMD (83.33%), but only in 5 of the remaining 27 UWS patients (18.52%). In the MCS group, improvements in the Coma Recovery Scale-Revised scores were observed in 14 of 16 patients with CMD

(87.5%), but only in 4 of the other 17 MCS patients (23.53%). Thus, CMD was shown to be associated with better outcomes.

The application of machine learning within BCIs differs from its use for directly classifying patients in several respects. An advantage of the former setting is that, within the training samples, the true labels (e.g., target stimuli) are known exactly, whereas the behaviorally determined patient classes used as labels in the latter case are affected by impairments in the sensory, motor, and executive functions. Additionally, the size of the training sample for a BCI is determined by the number of trials and can in principle be increased, although there are limitations due to patient fatigue. Conversely, recruiting additional DOC patients requires substantial efforts and may be limited by external factors. At the same time, the studies discussed in the previous section extracted features of brain signals related to a broad array of behaviors indicating the MCS, whereas the BCI-based methods typically are focused on command following only and rely on certain sensory functions. Additionally, as noted in [9], in some patients, a non-significant result of EEG classification may be due to the limitations of the BCI rather than the absence of command following, so that the resulting characterization of such patients is less exact ('potential non-CMD') than for the group with detected CMD.

4 Conclusions

Machine learning methods make it possible to efficiently synthesize information about states of consciousness obtained from multidimensional data of various modalities. Adequate assessment of the classification accuracy requires correct statistical analysis accounting for model selection, otherwise the results are prone to misinterpretation. Additionally, the optimal classifiers and the most relevant features obtained to date are typically specific to a particular pair of compared conditions and show only a limited ability to generalize to the entire spectrum of states of consciousness. Achieving this generality is important for increasing the reliability of the diagnostic performance and elucidating genuine physiological mechanisms of consciousness. The application of machine learning for the detection of command following and yes-no communication is a complementary approach providing important information about the patients in which the technique is successful. Using its results in training algorithms for patient stratification can help increase their accuracy in diagnosing disorders of consciousness.

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References

1. Sinitsyn, D.O., et al.: Degrees of functional connectome abnormality in disorders of consciousness. Hum. Brain Mapp. **39**(7), 2929–2940 (2018). https://doi.org/10.1002/hbm.24050
2. Sinitsyn, D.O., et al.: Detecting the potential for consciousness in unresponsive patients using the perturbational complexity index. Brain Sci. **10**(12), 917 (2020). https://doi.org/10.3390/brainsci10120917

3. Sitt, J.D., et al.: Large scale screening of neural signatures of consciousness in patients in a vegetative or minimally conscious state. Brain **137**, 2258–2270 (2014). https://doi.org/10.1093/brain/awu141
4. Demertzi, A., et al.: Intrinsic functional connectivity differentiates minimally conscious from unresponsive patients. Brain **138**(Pt 9), 2619–2631 (2015). https://doi.org/10.1093/brain/awv169
5. Zheng, Z.S., et al.: Disentangling disorders of consciousness - insights from diffusion tensor imaging and machine learning. Hum. Brain Mapp. **38**, 431–443 (2017). https://doi.org/10.1002/hbm.23370
6. Campbell, J.M., et al.: Pharmacologically informed machine learning approach for identifying pathological states of unconsciousness via resting-state fMRI. Neuroimage **206**, 116316 (2020). https://doi.org/10.1016/j.neuroimage.2019.116316
7. Owen, A., et al.: Detecting awareness in the vegetative state. Science **313**, 1402 (2006). https://doi.org/10.1126/science.1130197
8. Monti, M.M., et al.: Willful modulation of brain activity in disorders of consciousness. N. Engl. J. Med. **362**(7), 579–589 (2010). https://doi.org/10.1056/NEJMoa0905370
9. Pan, J., et al.: Prognosis for patients with cognitive motor dissociation identified by brain-computer interface. Brain **143**, 1177–1189 (2020). https://doi.org/10.1093/brain/awaa026

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