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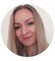

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Activity during Learning and the Nonlinear Differentiation of Experience

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Abstract: *Walter Freeman's work emphasises the role of individual activity and intentionality as opposed to the traditional stimulus-reaction view and the machine metaphor. The results of our computer modeling studies suggest the nonlinear dynamics of experience emerging from perception-action cycles. We consider the perception-action cycle as a behavioral continuum of anticipated outcomes of actions. Neuroscientific research shows that each behavioral act is based on the activity of behaviorally specialized neurons distributed across the brain. Active learning during individual development leads to an increasing differentiation of the structure of individual experience through the formation of such groups of behaviorally specialized neurons. We consider the differentiation of individual experience as a nonlinear process which is implemented at different levels, and argue that consciousness and emotion can be described as dynamic characteristics prominent at the most and least differentiated systemic levels, correspondingly.*

***Key Words*:** intentionality, brain, behavior, individual development

INTENTIONALITY VS. THE MACHINE METAPHOR

Great attention was paid in Walter Freeman's work to the philosophical foundations of neuroscience. Analyzing the metaphors underpinning a significant part of theoretical bases and research in contemporary neuroscience, Walter Freeman particularly criticized the input–output approaches to brain dynamics (Freeman, 1997, 2008). In the search for the neural mechanisms for intentionality Walter Freeman turned to the neo-Aristotelian philosophy of the later Middle Ages and the philosophy of Thomas Aquinas as well as advances in nonlinear dynamics and chaos theory. Criticising the machine metaphor that originated in Cartesian ‘‘reflections’’ and culminated in 19-20th century reflexology, he referred to "the Aquinian view of mind, which was focused on

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the emergence of intentionality within the body, with control of output by input through brain dynamics:" "The process of self-determination is inherent in the Aquinian concept of intentionality by which each soul (mind/brain) intends (''stretches forth'') outside itself and into the world. It acquires knowledge by shaping itself (learning) in accordance with the effects (sensory feedback) of its endogenous action. The soul creates itself and its virtue by its own actions" (Freeman, 1997, p.1175, p.1180). Walter Freeman stressed the importance of the impact of behavior onto the environment within a perception-action cycle. The concept of intentionality was central in his work and he considered applying it at the neuronal level: "Patterns of neural activity are endogenous. Their structure emerges from within" (Freeman, 1997, p.1180). Later in this work we describe our view on activity and the system-evolutionary theory that has been developed during the past decades (Aleksandrov & Aleksandrova, 2007; Alexandrov, 2008, 2015; Alexandrov & Grinchenko, 1980; Alexandrov & Korpusova, 1987; Alexandrov & Jarvilehto, 1993; Alexandrov & Sams, 2005; Alexandrov et al., 2000; Shvyrkov, 1986, 1990, 1995). In our opinion, it corresponds to some of the fundamental points in Walter Freeman's work, expanding them further, theoretically and empirically. Here we start with a formal description of the machine metaphor. We criticize it like Walter Freeman did, but from another angle, and demonstrate its faults within the formal description.

REACTIVITY VIEW: A FORMALIZATION

Building on physical analogies, Descartes considered a reflected action as a universal law for inanimate objects and living beings. According to this view, the external environment presents the primary cause of behavior, and an action is regarded as an objective reflection of components of the external environment that influence an organism. Descartes put forward a provision about the constancy of a reflected action in response to stimuli, which may be interpreted as a claim for the unambiguity of behavior determination by the external environment. Drawing upon the ideas expressed by Descartes, the reflex theory was developed (Alexandrov & Jarvilehto, 1993). We argue that the essence of the reflex theory may be expressed as follows: *an individual in his action and state objectively reflects precedent external signals* (Krylov, Alexandrov, 2009).This statement can be formalized:

$$\text{Action}(t + \tau) = \text{F}\,[\text{Signal}(t)],\ \tau > 0 \qquad (1)$$

where *Signal(t)* is an external signal perceived by an individual, *Action(t)* is an action of the individual at the moment t and F is a function. This equation indicates that there is a *functional dependency* between the perceived external signal and the subsequent behavior. Thus, a certain function F is applied to the input signal $S(t)$, and the action is the output after a delay τ. Descartes' reflex objectivity and its constancy are in line with the definition of functional dependency. Thus, the structure of the reflex arc and the dynamics of the reflex follow from the presence of the delay τ between the input signal S and the consequence A caused by S, provided that $\tau > 0$, which means that a cause precedes its consequence.

The above approach considers behavior as a set of reactions to various stimuli presented in the environment. A reaction is based on the propagation of excitation along the reflex arc: from receptors through central structures to effector organs. From this point of view, a neuron is an element of the reflex arc and its function is the propagation of excitation. Impulses that the neuron receives from other cells are considered as stimuli causing it to discharge in response to the synaptic input (Fig. 1). In this model the neuron becomes a computational element (see Eq. 1), “encoding element.” “feature detector.” “conductor” or “summator” of electric pulses. This is a consequence of Descartes’ machine metaphor representing an organism as an input-output transforming device.

In the input-output approach (*the reactivity paradigm*) to the study of beha-vior and action-perception cycles experimenters analyze the pairs $<S(t), A(t+1)>$,

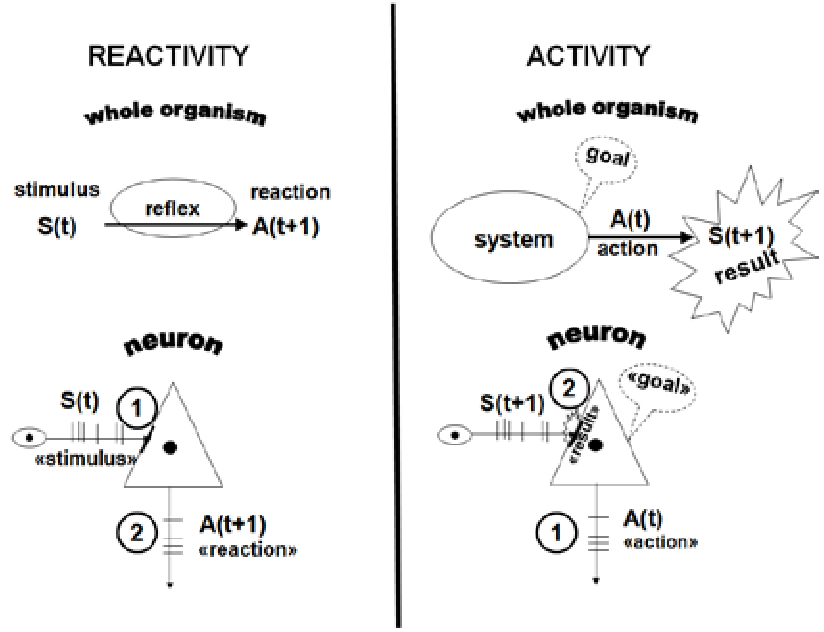

Fig. 1. The reactivity and activity paradigms at the levels of individual behavior and neuronal activity. The digits indicate the order of events on a timeline. According to the reactivity paradigm, a stimulus (1) is followed by a reaction (2), behavioral and neuronal. At the level of neurons, synaptic input is considered as a stimulus, and neuronal discharges are considered as reactions. According to the activity paradigm, an action (1) (behavior in individuals and discharges in neurons) leads to achieving an outcome (a result) (2).

where *S* is an external stimulus or an observed state of the environment and A is an action (labelled as "reaction"). This approach excludes any possibility of studying the impact of actions onto the environment, i.e. $<A(t), S(t+1)>$, which represents the main focus of study within *the activity paradigm.*

ACTIVITY VIEW: TELEOLOGY STARTING FROM A NEURON

The activity paradigm views behavior as consisting of goal-directed actions. Each action is internally determined by motivation and leads to achieving a result. The outcome of an action is evaluated and compared with the initial goal. An important role in the development of the activity paradigm belongs to Aristotle and his ideas about the causes of behavior, in particular the *causa finalis* – purposefulness (Lombrozo & Carey, 2006). The activity principle implies that an individual's actions are directed into the future, goal-directed and defined by goals. The cause of an action is characterised by an internal nature and is related to future events. The activity principle can be implemented not only at the level of an organism's behavior but also at the level of the cells comprising this organism (Aleksandrov, 2006; Shvyrkov, 1995).

The analysis of neuronal mechanisms of goal-directed behavior had previously led many authors to the idea that an organism performs goal-directed behavior, whereas its separate elements (neurons) respond to incoming excitation (stimuli). This interpretation of neuronal activity as a response to synaptic inflow has been abandoned within the system-evolutional theory which proposes to view neurons, like any other living cells, as realizing a genetic program requiring metabolites which can be received from the environment and other cells (Shvyrkov, 1995). Thus, the activity of neurons appears analogous to the goal-directed activity of an organism (Fig. 1). Like any behavior of an organism, neuronal activity is not a response but a way of changing the relation with the environment, an "action" that eliminates a discrepancy between "needs" and the microenvironment, causing modifications in blood flow, metabolic inflow from glial cells, and activity of other neurons. If these modifications are adequate to the current metabolic "needs" of a neuron, they enable the cell to achieve an anticipated "result" (i.e. receive a set of metabolic substances binding to its receptors) and cause the cessation of the unit's discharges. Thus, according to the activity paradigm, a neuron is not an "encoding element," "conductor," or "summator." but an organism within an organism, providing for its needs with metabolic substances received from the microenvironment, i.e. other neurons, glia, blood, lymph and cerebrospinal fluid.

A neuron may provide for its metabolic "needs" only by joining with other elements of an organism to form *a functional system*. Their joint cooperative activity leads to the adaptive *result*, i.e. a new relation between a whole individual and the environment. "From within" at the level of separate neurons, achieving an adaptive result appears as satisfying metabolic "needs." From this perspective, the activity of a neuron is seen as a means of changing its relations with the environment, as an "action" directed to the future in order to eliminate an imbalance between "requirements" of the cell and its microenvironment. Thus, a neuron acts as an organism in ensuring its “needs” at the expense of metabolites from the environment, including other neurons.

BEHAVIORAL CONTINUUM: NONLINEAR DYNAMICS OF RESULTS

We consider a behavioral act not as an isolated entity, but as a component of the behavioral continuum, the succession of behavioral acts performed by an individual during their lifetime (Shvyrkov, 1990; Alexandrov, 2015). Each behavioral act in the continuum is implemented after the result of the previous act has been achieved and evaluated. Such evaluation is a necessary part of the organizational processes of the next ensuing act. These processes may be considered as transitional, because they underlie the transition from the realization of one act to the realization of the subsequent act. There is no place for a stimulus in the continuum (Fig. 2). The environmental changes traditionally considered as stimuli are informationally linked with the preceding behavior in course of which these changes are anticipated and planned for in a model of the future behavioral result, the goal of behavior. Thus, behavior may be considered as the continuum of results (Anokhin, 1978) and a behavioral act as a part of the behavioral continuum between two subsequent results (Shvyrkov, 1990). It is important to take into account the subjects’ goals and not to rely on the observed behavior alone.

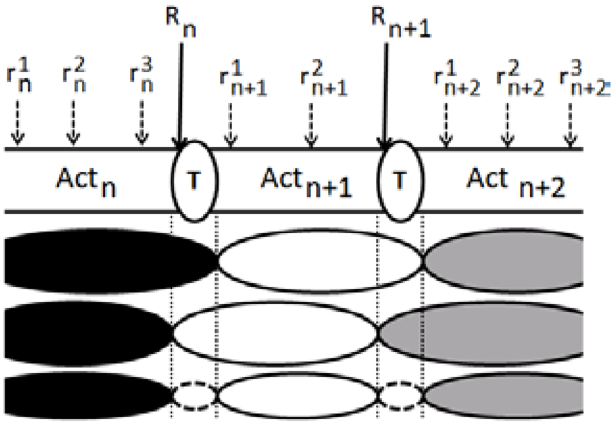

Fig. 2. The behavioral continuum of anticipated results. Above are intermediate results (r1,r2,r3) and final results of behavioral acts (Rn, Rn+1) corresponding to lower and higher levels of anticipation. “T” labels the transitional processes. Below are the sets of systems that subserve the realization of the successive acts within the continuum (each set is represented by its own shading). Open dashed ovals depict the systems of “additional” neurons that are inactive during realization of the studied behavioral acts. It was shown that the transitional processes were characterized by “overlapping” activations of neurons related to the preceding and following behavioral acts, and by activations of the “additional” neurons. See details in Shvyrkov (1990) and Alexandrov (1999).

This approach leads an experimenter to analyze the pairs $<A(t), S(t+1)>$ (action-result) or the organism-environment interactions <S(t), A(t), S(t+1)> (Krylov & Alexandrov, 2009) showing how an action $A(t)$ transforms the situation in the environment from S(t) into S(t+1):

A(t): S(t) à S(t+1) (2)

Unlike the reactivity paradigm, this approach does not involve a functional dependence. The nonlinear dynamics of the variables is observed during learning to perform an action A (Krylov & Alexandrov, 2009). An example of $<A(t), S(t+1)>$ (action-result) statistics from a modeling experiment is shown in Fig. 3 (the dotted line). This model was used to study the behavior of a two-wheeled animat in a foraging task. The agent had several receptive visual fields and was able to capture “food” appearing as objects within the receptive fields. The agent could move left or right and was trained using the algorithm Actor/Critic from reinforcement learning (Krylov, 2004). An S-shaped learning curve was observed (Fig. 3, the solid line). Statistics of the distributions of objects within the receptive fields was analyzed in this computer experiment. As an example, the probability of achieving the result “object within the top left receptive field” while performing the action “turn right” changed during learning (Fig. 3, the dotted line). Although the characteristics of the environment remained unchanged, the probability of achieving the result by performing this action doubled during the learning period. This example shows that the probability of achieving a result described by the pair $<A(t), S(t+1)>$ (action-result) is not defined by the environment or the experimenter but determined by the interactions between the agent and its environment which change during learning. However, such variables are not considered within the reactivity paradigm.

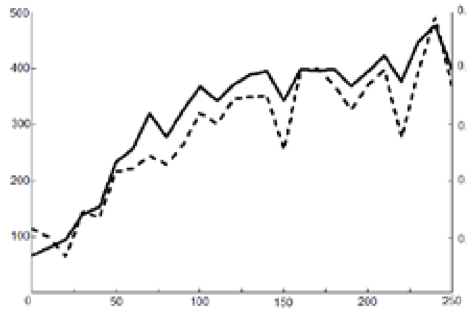

Fig. 3. The dynamics of learning within the modeling experiment. The X-axis represents time (in thousands of time steps). The solid line is an S-shaped learning curve showing the number of captured items of “food” (left Y-axis). The dotted line is a probability of the situation “object in the top left visual field” after performing the action “turn right” (right Y-axis). The probability doubles during learning (from 0.06 to 0.12).

Active interaction with the environment leads to changes in situations for the agent. Figure 4 shows distributions of objects within the receptive fields in the beginning of learning (first 5000 time steps) and at the end (last 5000 time steps). Behavioral dynamics during learning changes, therefore the objects appear within the visual field irregularly. During learning in the environment the agent developed a strategy of searching new objects and approaching them effectively which resulted in objects appearing in the receptive fields more frequently. Learned behavior is reflected in <*S*(*t*)> statistics although the environment remains unchanged. For example, the probability of an object appearing in the top left receptive field increases during learning from 0.06 to 0.12. From the perspective of the reactivity paradigm, this phenomenon would be described in terms of the probability of stimuli appearing in the receptive field which *surprisingly* increases during learning. In another modeling study this phenomenon was regarded as self-selecting of input stimuli" (Nolfi & Parisi, 1993). Thus, this phenomenon is not considered within the consistent reactivity paradigm.

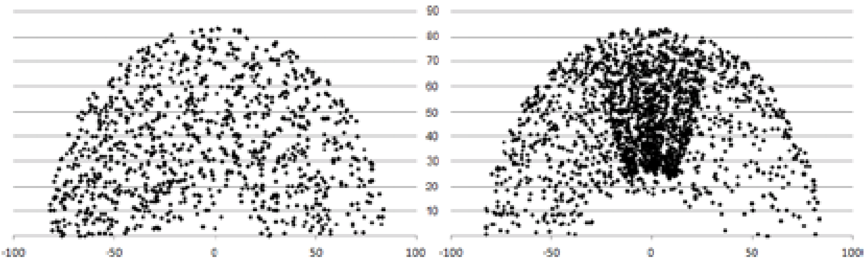

Fig. 4. The results of the modeling experiment. The distribution of objects in the receptive fields is shown in the beginning (left) and in the end (right) of learning. Statistics for 5000 time steps is displayed in both cases. In the beginning of learning objects randomly appear in the receptive fields. In the end of learning in most cases objects appear within the front receptive fields, although the environment is the same. This demonstrates the impact of the agent's behavior onto the distribution of situations it faces.

Figure 4 demonstrates two perceptions of the environment based on different subjective experience and different visions of the regularities underlying objects appearing in the environment. Although the "physical" environment is the same, if the agents could speak they would have spoken about it differently. If they could converse, they would have concluded that they lived in two different environments. This example demonstrates that the activity of behavior leads to a subjective vision of the environment which is not a simple reflection of its parameters as was seen by Descartes. An individual in his subjective world does not reflect the environment; he reflects his interactions with the environment based on his goals, intentions, past experience, previous successes and losses etc.

These examples from modeling show what characteristics of the behavioral continuum are omitted within the reactivity paradigm which is focused on studying the relations between the pair <S(t), A(t+1)>. Analysing complex interactions with the environment represented by variables < S(t), A(t), S(t+1)> and the impact of actions onto the environment (Eq. 2), the activity paradigm enables researchers to study a broader class of phenomena. The examples above also show why the interaction with the environment cannot be described as a functional dependency (Eq. 1) but requires the nonlinear approach which takes into account the direct and reverse influences between actions and their consequences (results), comprising the integrity of the behavioral continuum (see Fig. 2).

NEURONAL DYNAMICS AND NONLINEAR DIFFERENTIATION

The properties of the brain are not a sum of the properties of single neurons but emerge as a result of dynamic interactions among the neurons within a system (Milner, 1998; Mountcastle, 1995). The elements of subjective experience form during learning of new behavioral acts and then their activation underlies the realization of these behavioral acts. An element of subjective experience represents a group of neurons and other cells of the body composing a system. A well-developed systemic approach to the neuronal bases of behavior is based on P. Anokhin's *theory of functional systems;* for a review, see Anokhin (1973). Of importance in this theory is the definition of a system-creating factor as a *result* of a system. The result of a system is a desired relation between an organism and the environment achieved through the realization of that system. The principal determinant of a system is not a stimulus, an event in the past, but the *future result* of the behavior. Thus, a system is understood as a dynamic organization of activity of components in different anatomical localizations, *both in the brain and in the rest of the body*. The interaction of the components provides an adaptive result for an organism.

The interaction of neurons underlying goal-directed behavior is accomplished by synchronizing the activity of the neurons in different brain structures (Aleksandrov & Shvirkov, 1974). We established that the response latency of a single neuron in a behavioral act is determined by the whole range of influences to which the neuron is subjected to when included into the general integration of the behavioral act, and not just by the number of synaptic relays or the length of the conducting fibers from receptors to the recorded neurons. This implies that, although neurons in different brain areas are located at different "anatomical distances" from the receptor, they may discharge synchronously because the latency of neuronal activation depends on numerous influences that coordinate activity of different neurons into the united system. A very similar conclusion about the synchronous activity of neurons within different brain structures, but related to the "binding" problem, was developed later and has gained considerable experimental support (Roelfsema et al., 1997; see also Thatcher, 1997). The synchronization of neurons located in different brain areas has been argued to be important for understanding behavior and consciousness (Engel, 1999; Thompson, 2001), and was particularly emphasised by Walter Freeman (2003).

The neural basis of learning is the specialization of ‘‘reserve’’ (silent) neurons in relation to a newly forming system, but not a change in the specialization of already specialized units. Neurophysiological studies have demonstrated that the specialization of recently specialized neurons does not change during single-unit recordings lasting for weeks and even months, and that there are many silent neurons in different brain areas (Alexandrov, 2008). This directionality and irreversibility of neuronal changes during the specialization represents a nonlinear property of learning.

As an individual interacts with the environment the models of such interactions accumulate in the structure of individual experience so that during development the structure of experience becomes more complex and differentiated. The formation of new functional systems during development results in growing complexity and differentiation of organism-environment relations. Individual development can be considered as the process of increasing differentiation along with the number of learned behaviors (Kolbeneva & Alexandrov, 2016). A new, more differentiated system is added to the existing ones (Alexandrov et al., 2000). It does not replace the previously formed systems, but instead is ‘‘superimposed’’ on them. The structure of experience grows like a tree in modeling terms (Fig. 5, left). This structure is nonlinear because the functioning of each of its elements depends on its position and upon which lower level (less differentiated) elements it is connected to.

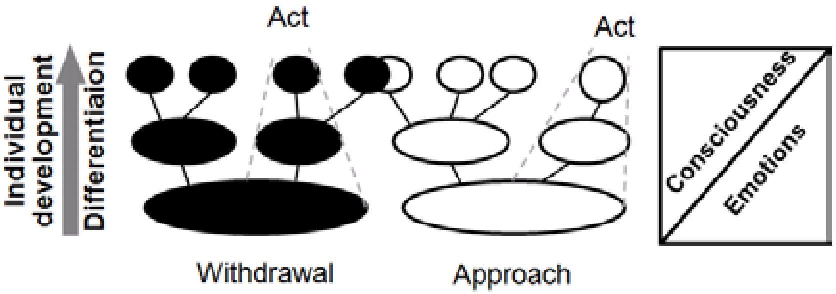

Fig. 5. Consciousness and emotion at successive stages of differentiation. The two big ovals at the bottom symbolize the earliest low-differentiated systems subserving the first forms of behavior: approach (white) and withdrawal (black). Differentiation increases upwards. Dashed lines delineate the sets of systems of different ages. The simultaneous realization of these systems subserves achieving results of different behavioral acts. Triangles illustrate the view that emotion and consciousness are characteristics of an integrated multilevel systemic organization of behavior; they also illustrate that the levels of differentiation vary in relative amount of these characteristics.

It has been shown (Alexandrov et al., 2000, 2008; Shvyrkov, 1986) that complex instrumental behavior is realized by a new system formed during learning of the acts composing this behavior, and by simultaneous activation of older systems that had been formed at previous stages of individual development (Fig.5, left). The older systems become involved in many behavioral patterns when they belong to the elements of subjective experience that are common for various acts (see Fig.5, ovals on the bottom). Therefore, behavior is based on the realization of the history of behavioral development (Fig.5, see vertical lines representing simultaneously activated low and higher differentiated systems). Multiple systems are involved in behavior, and each of them fixing a certain stage of development of the given behavior. The brain organization of behavior reflects the history of its formation. The activation characteristics and sets of active neurons are different in outwardly similar types of behavior that have different histories of formation. Environments with similar physical parameters are differently reflected in the activity of central and peripheral neurons depending on the goal of behavior.

EMOTIONS AND CONSCIOUSNESS AS OPPOSITE CHARACTERISTICS OF NONLINEARITY OF DIFFERENTIATION

We argue (Alexandrov & Sams, 2005) that emotion and consciousness should not be regarded as separate psychological processes with distinct neurophysiological mechanisms. Both characterize similar functions in goal-directed behavior, but with different aspects and at different levels. As stated earlier, the performance of a behavioral act is subserved by the simultaneous realization of systems corresponding to both minimal and maximal levels of differentiation. Consciousness and emotion can be described as systemic characteristics prominent at the most and least differentia-ted systemic levels, correspondingly. Therefore, behavior is simultaneously *emotional and conscious*. What differs is the relative amount of these two characteristics, connected to developmentally older and newer systems composing the behavioral act (Fig. 5).

The content and significance of consciousness are the evaluation by an organ-ism of its relation to the environment during the realization of a behavioral act (external or internal) and during transitional processes between acts (Fig. 2, see “T” labels). In addition to its role in the control of an individual’s behavior, conscious-ness is also crucial in communication, because it provides for high-level interactions with other conscious beings (Frith, 1995). In humans, the use of language in social interaction is an important ‘‘carrier’’ of consciousness. It is essential in the collective achievement of results (Vanderwolf, 1998). ‘‘Conscious facts’’ can be shared through communication with others (Hilgard, 1980). Using language, individuals can evaluate their own behavior (give a self-report) and also share this evaluation with others (social report).

It has been suggested that emotion has its origin in pleasant and unpleasant sensations that an infant and even a fetus experiences (van der Veer, 1996). Some facial expressions of emotions are innate (Darwin, 1965; Ganchrow, 1983), observed even in prematurely born infants (Anokhin, 1973).We were born with ‘‘the mechanism of primary emotions’’ (Damasio, 1994). Thus, realization of the earliest forms of behavior is a sufficient condition for behavior to be emotional. Emotional characteristics of behavior are related to the actualized domains of individual experience, such as approach (positive emotions) or withdrawal (negative emotions) (from the third-person perspective). For the subject of behavior (the first-person perspective), it means a basic classification of things and events as good or bad (Damasio, 1994). This is a coarse nonlinguistic description and is used for self-reports about the results of actions already at the earliest stages of ontogeny. This is why we often cannot verbalize the reasons for our attraction or repulsion to things and events (Zajonc, 1980). Thus, even though emotion is related to the individual’s self-evaluation of behavior and its results just as is consciousness, it is its relation to the results of those systems that ensures the individual’s relation to the environment at a low level of differentiation. In the course of the differentiation of behavior, the number of behavioral acts shared by different emotions might increase. Outwardly similar actions may be used for both, approach and withdrawal. Such ‘‘common acts’’ are marked in Fig. 5 as the overlapping of emotionally positive and negative systems. We related the appearance of emotional characteristics to the formation of the oldest systems in ontogeny that are directed to the achievement of basic metabolic results. There is considerable evidence of specialized brain structures for negative and positive emotions (Cacioppo, 1999; Davidson, 1990; O’Doherty, 2001). We suggest that the existence of structures strongly related to positive or negative emotions implies that many neurons of this structure belong to relatively low-differentiated systems aimed at approach or withdrawal. In other words, positive and negative emotions reflect different sets of actualized systems (see Fig. 5).We argue that emotional characteristics are related to the global division of behavior while the characteristics of consciousness are related to the selection from a huge repertoire of situationally and individually specific systems of behavioral acts.

As stated earlier, the performance of a behavioral act is based on the simultaneous activation of systems corresponding to both minimal and maximal levels of differentiation. Later evolving forms of mental life do not eliminate or replace early ‘‘primitive’’ ones; see also Ribot (1901) and Werner (1948). Rather, consciousness and emotion may be considered as characteristics of different levels of systemic organization of the given behavioral act that correspond to different levels of the environment’s differentiation. Each of these levels is a transformed stage of individual development fixed in memory as systems that were formed during learning. It is impossible to define when consciousness appears. At each successive stage, as the differentiation of systems proceeds, the characteristics of consciousness increase. Consciousness and emotion are linked characteristics of the same whole systemic organization. Both of them necessarily characterize each developmental and differentiation level. Consequently, any change to this organization would cause some changes in both consciousness and emotion. However, consciousness and emotional characteristics are not equal for all systems; they are maximally prominent at the most and least differentiated systemic levels, respectively. The con-scioussness characteristics of behavior are related to which new systems are actualized out of the many different possibilities existing in an individual’s memory. The content of consciousness is related not to the analysis of stimuli or ‘‘sensori-motor coupling’’ as usually thought – see, however, Jordan (1998) and Vandervert (1995) – but through constructing models of results of both overt and covert behavior which are then compared to these models with actually achieved results. An important aspect of our concept is that the dynamics of behavior is described as successive achievement of intermediate and final results composing a behavioral continuum. This succession makes it easier to understand the continuous nature of consciousness.

Emotion does not influence or activate consciousness. Nor do emotion and consciousness interact, because two different characteristics of the same entity cannot influence each other. There is no behavior lacking some emotional basis, since any actualized set of systems is based on low-differentiated systems. It is not appropriate to speak about specific systems or mechanisms producing consciousness and emotion, because all systems are aimed at achieving less or more differentiated results. Consciousness and emotion are characteristics that are inherent to various systems composing the set to differing extents.

CONCLUSION

The concept of intentionality leads to considering behavior as a continuum of results and requires studying the nonlinear regularities of interactions between an organism and the environment, <situation – action - changed situation>, which form during learning and are reflected in behavior. It is important that environmental situations depend on actions (<action-situation>). New experience forms as a system aimed at achieving an adaptive result of a certain degree of differentiation. During learning neurons specialize in relation to the new system for life, and these neuronal changes are irreversible. New systems form on the basis of earlier formed systems, creating the nonlinear structure of individual experience. This structure can be described as a tree (acyclic connected graph) formed by the elements of experience of different degree of differentiation (as the graph’s nodes) and connections between them. The nonlinear processes during learning and behavior taken together with the nonlinear structure of individual experience create complexity during the realization of experience, the activity underlying behavior. This complexity can be described by a set of characteristics. The prevalence of low differentiated systems during certain periods of time is characterised as emotion, and the prevalence of highly differentiated systems is characterised as consciousness. Thus, the nonlinear dynamics of behavioral activity and the irreversibility of neuronal specializations during learning underlie the nonlinear differentiation of experience.

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