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Age-related development trajectories of components of mental functions in children 4-17 years old

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ABSTRACT

The present paper is dedicated to the problem of age-related changes in features of neuropsychological development. The sample consisted of 922 conditionally healthy subjects ranging from 4 to 17 years of age, comprising 603 boys and 319 girls. The study participants underwent neuropsychological diagnostics using the psychometric battery "Multifactorial Investigation of Neuropsychological Development" (MIND). The assessment was conducted in two psychological centres in Moscow, Russia. Trajectories of growth for 22 components of mental functions and the general level of development were obtained. This article examines the peculiarities of curve fitting using polynomials, Gompertz, Verhulst, and Schmalhausen-Brody functions. The study reveals that components of mental functions develop at different rates. Some of them complete their growth during the adolescence, while others continue to increase after the age of 18.

Keywords: child neuropsychology; neuropsychological development; quantitative assessment; curve fitting; growth functions

1. INTRODUCTION

Russian neuropsychology is based on the theory of systemic and dynamic localisation of higher mental functions (HMFs) proposed by Luria (1980). The main method used by Russian neuropsychologists is a qualitative analysis of the defect that occurs with localised brain damage (Glozman, 2007). Most practitioners prefer a subjective interpretation of the examination results, following Luria's approach (Eling, 2019), rather than standardised testing. It is believed that a healthy person easily copes with functional tasks, while the presence of impairments leads to specific errors, which then serve as material for syndrome analysis. Scoring is organised as a system of penalties, where a higher score indicates poorer performance on the task. However, transferring this paradigm to differential and developmental neuropsychology poses challenges.

We believe that when studying HMFs, it is not feasible to consider the norm as a fixed ideal. Taking into account significant individual differences, it is advisable to rely on a statistical norm, which, in turn, requires a graded assessment of success in performing tasks. One drawback of qualitative diagnostics is that the ratings are initially presented on an ordinal scale. Standardisation is necessary, that is, translating raw scores into an interval scale. To achieve this, detailed norms are required, which can only be obtained through studying large samples.

In child neuropsychology, it is necessary to consider the nonlinear relationship between task performance and age. For foreign neuropsychology, this is not such a big problem due to the availability of quantitative diagnostic batteries. Quantitative methods are widely employed by practicing specialists, who place great emphasis on the standardisation of diagnostic procedures and formalisation of diagnostic decisions (Casaletto & Heaton, 2017; Goldman et al., 1983; Miller, 1992; Suhr & Angers, 2019; Winiarski & Whitaker, 2015).

In the works of Russian child psychologists, norms often have a descriptive character. Less frequently, the percentage of successful completion of tasks at a certain age is indicated, and only occasionally are descriptive statistics provided. Data from age groups are used, although it would be more informative to consider age as an independent variable (Wohlwill, 1970). Correlations between tasks can be explained by the relationship between the success of their performance and age. Therefore, when analysing data, it is necessary to operate not only with absolute values but also with relative values (adjusted for age). To achieve this, the trajectories of age development should be represented algebraically. It is known that the growth of the nervous system is described by a sigmoid curve, reaching a plateau with the onset of sexual maturation (Scammon, 1930). It can be expected that the development of HMFs as functional systems is completed somewhat later, but generally conforms to this regularity. There is literature dedicated to the development of cognitive functional systems during ontogenesis (Spreen et al., 1995), but it does not contain mathematical descriptions. Our investigations indicate that growth curves are a useful heuristic for predicting cognitive development based on single or incomplete measurements (Khokhlov, 2022). Unfortunately, neuropsychologists usually study preschool and early school-age children without tracking the developmental trajectory until growth completion.

At the same time, research is being conducted in the field of global neuroscience to identify trajectories of age-related development of mental functions and their brain organisation. It has been shown that dynamic changes occur in the brain with age, including a predominance of grey matter reduction associated with cellular pruning and an increase in white matter reflecting myelination and connectivity (Bigler, 2021; Matsui et al., 2016). Age-related changes in white matter indicate structural connectivity within the brain, which correlates with the development of cognitive functions (Dosenbach et al., 2010; Goddings et al., 2021). This relationship is not the same for different functions, and in some studies, its importance is called into question (Mürner-Lavanchy et al., 2020). It should be noted that different structures and regions of the brain have their own growth trajectories. They depend on both developmental environmental influences and genetic predisposition (Brouwer et al., 2022). From a psychological perspective, scientists observe different development trajectories for various mental functions (Chen et al., 2021; Hao et al., 2021; Mous et al., 2017). They can be described algebraically and shown in the form of curves. This information allows us to identify sensitive periods during which remedial and developmental learning is most effective. Research progress is complicated by the fact that the connections between functions also change with age (Treviño et al., 2021). Mental functions, as functional systems, constantly change their composition. Therefore, it seems promising to focus on the trajectories of development regarding the stable components of mental functions.

Typically, during neuropsychological assessment, the state of HMFs such as perception, memory, thinking, voluntary movements and actions, energy support, voluntary regulation, etc., is evaluated. However, these functions are rather linguistic constructs, the substantive content of which depends on the chosen theory. The essence of these functions also changes with age. Khokhlov (2024) conducted work on factorising the results of individual methods without prior conceptualisation. This allowed for an approach closer to the empirical level of cognition, minimising dependence on theoretical views. Therefore, we speak about components of mental functions, rather than the functions themselves.

The goal of the present study is to identify the trajectories of age-related development of components of mental functions in children aged 4–17 using materials from neuropsychological diagnostics. An additional research task is to develop an optimal method for mathematically describing the growth of neuropsychological indicators and indices. Solving this problem is necessary to improve the accuracy of neuropsychological diagnostics and reduce the dependence of its results on the psychologist's subjectivity. Furthermore, it will be possible to determine at what age the formation of various neuropsychological functions is completed. This evidence will provide additional backing for the advisability of neuropsychological correction in teenage years.

2. Method

2.1 Sample

The sample consists of 922 participants, including 603 boys and 319 girls aged 52–215 months, with a mean of 121 and a standard deviation (SD) of 44. From 2014 to 2023, they underwent neuropsychological diagnostics at the Centre for Testing and Development "Humanitarian Technologies" and the Psychological Centre "Galton" (Moscow, Russia) upon the parents' request. The purpose of consulting a psychologist was to assess the state of HMFs and obtain developmental recommendations. All schoolchildren (n = 656) were educated according to standard (not remedial or adapted) curricula. The assessed children, even those who had partial dysfunctions, demonstrated social adaptation. The exclusion criteria were significant speech disorders, states of disorientation and confusion, and affective conditions that made meaningful interaction with the psychologist impossible. The inclusion of diagnostic results from all remaining children into the study renders the sample statistically representative.

2.2 Assessment

For the purpose of neuropsychological diagnostics, the psychometric battery "Multifactorial Investigation of Neuropsychological Development" (MIND) was used (Khokhlov, 2024). It was designed in 2023 as a result of a study of 860 individuals aged 4–17 years (M = 10, SD = 3.7). The battery consists of 40 techniques (functional tasks) that measure 171 variables. Some variables are measured quantitatively, while others are assessed using multiple qualitative rating systems. All variables are unified using the percentile standardisation (forced normalisation) method. As a result, they are represented in z-scores (0 ± 1). Based on 106 variables, 21 factors can be extracted:

- F1. Visual-spatial information processing
- F2. Attention

- F3. Auditory-verbal memory capacity
- F4. Memory for word order
- F5. Resistance to confabulations in auditory-verbal memory
- F6. Voluntary movements and actions in space
- F7. Small size of drawings
- F8. Activities of daily living skills
- F9. Visual memory
- F10. Drawing straight lines
- F11. Keeping lines straight across the page and absence of macrography
- F12. Combination of analysis and synthesis in visual object perception
- F13. Serial organisation of movements
- F14. Tendency to draw with strokes
- F15. Resistance of auditory-verbal memory to the recency effect
- F16. Resistance of working memory to interference
- F17. Resistance of auditory-verbal memory to the primacy effect
- F18. Projective (three-dimensional) representations
- F19. Tendency to draw thin lines
- F20. Predominance of conceptual generalisations
- F21. Tactile perception.

Four variables, derived from the remaining variables after factor analysis, are used to assess verbal-logical thinking (VLT). In addition to the scales mentioned, the general level of development (GLD) is calculated using 50 variables. Other variables are used for qualitative analysis, which is not discussed in this article.

The assessment is conducted individually. The procedure takes about 1 hour, ranging from 42 to 102 minutes.

2.3 Data analysis

RStudio 2021.09.0 Build 351 (with packages Deriv, ggplot2, minpack.lm, stringr) was used for data analysis.

The imputation of missing values (6.6%) was carried out based on multiple linear regression models that included predictors such as age, grade, and other neuropsychological variables.

Growth curves were constructed using the locally estimated scatterplot smoothing (LOESS) method. Alternative methods were used for algebraic description: polynomial fitting, Gompertz, Verhulst, and Schmalhausen-Brody functions.

The following algorithm was used for polynomial fitting. First, the

LOESS method was applied, and the sum of the absolute values of the residuals was computed. Then, a polynomial of degree from two to six was fitted to obtain the growth function that had the sum of the absolute values of the residuals closest to the value obtained by the LOESS method. The sign of the first derivative characterises the increasing and decreasing of the function. The second derivative reflects the change of acceleration over time.

Gompertz presented his function in 1825 (Gompertz, 1825). Originally, the function was developed to describe human mortality, but later it was modified for use in biology, particularly for describing population growth. We use the formula (1), where *t* is the argument (age), e – the Euler's number (constant), *a* – maximum value (asymptote), *b* – displacement along the *x*-axis, *c* – growth rate.

$$f(t)=a\mathrm{e}^{-b\mathrm{e}^{-ct}} \quad (1)$$

Verhulst developed the logistic function in a series of three papers (Verhulst, 1838; 1845; 1847). Subsequently, this function has been repeatedly rediscovered by other researchers, among whom the best known are Pearl and Reed (Lloyd, 1967). We use the formula (2), where *t* is the argument (age), e – the Euler's number (constant), *r* – growth rate, *P* – starting value, *K* – maximum value (asymptote).

$$f(t)=\frac{KP\mathrm{e}^{rt}}{K+P(\mathrm{e}^{rt}-1)} \quad (2)$$

The last formula was independently proposed by Schmalhausen and Brody in the 1920s–1930s. We refer to it as the Schmalhausen-Brody function, acknowledging that other authors were also describing it during the same years (Shock, 1951). We use the formula (3), where *t* is the argument (age), e – the Euler’s number (constant), α – maximum value (asymptote), *k* – growth rate.

$$f(t)=\alpha\left(1-\mathrm{e}^{-kt}\right) \quad (3)$$

Using these functions, we follow the trend of using mathematical apparatus borrowed from population biology to analyse growth trajectories (Bacaër, 2011; Tsoularis, 2001; Tsoularis & Wallace, 2002; van Geert, 1991). For many of such functions, parameter fitting can be performed in the SigmaPlot programme using the built-in Regression Equation Library (Hilbe, 2005).

3. Results

The age development trajectories of the measured scales constructed using the LOESS method are shown in Figure 1.

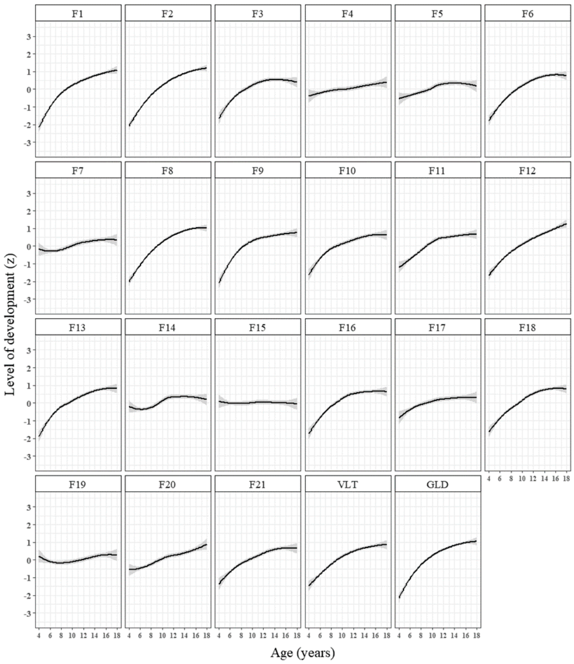

Figure 1. Age-related changes in features of neuropsychological development

An algebraic description of these trajectories using polynomials is given in Table 1. In Tables 1–4, the “Range” column shows the difference between the function values at 215 and 52 months.

Table 1. Description of age-related development trajectories using polynomials

Scales	Polynomial coefficients							Range
	Degrees of argument (*t*)							
	6	5	4	3	2	1	Intercept	
F1			-1.49 x 10^-8	9.25 x 10^-6	-2.16 x 10^-3	2.36 x 10^-1	-9.81	3.20
F2				7.99 x 10^-7	-4.46 x 10^-4	9.15 x 10^-2	-5.67	3.31
F3			-8.64 x 10^-9	5.50 x 10^-6	-1.37 x 10^-3	1.60 x 10^-1	-6.94	2.04
F4			-1.02 x 10^-8	5.58 x 10^-6	-1.10 x 10^-3	9.53 x 10^-2	-3.18	.79
F5	-5.28 x 10^-12	4.32 x 10^-9	-1.42 x 10^-6	2.39 x 10^-4	-2.16 x 10^-2	1.01	-19.49	.92
F6			-5.28 x 10^-9	3.18 x 10^-6	-8.11 x 10^-4	1.09 x 10^-1	-5.61	2.46
F7			1.44 x 10^-8	-8.34 x 10^-6	1.71 x 10^-3	-1.40 x 10^-1	3.63	.58
F8				5.40 x 10^-7	-3.56 x 10^-4	8.12 x 10^-2	-5.28	3.02
F9			-1.55 x 10^-8	9.89 x 10^-6	-2.37 x 10^-3	2.59 x 10^-1	-10.48	2.86
F10			-2.82 x 10^-8	1.58 x 10^-5	-3.26 x 10^-3	3.05 x 10^-1	-10.81	2.12
F11		-1.40 x 10^-10	1.08 x 10^-7	-3.16 x 10^-5	4.25 x 10^-3	-2.41 x 10^-1	3.79	1.70

F12			-6.65 x 10^-9	4.38 x 10^-6	-1.08 x 10^-3	1.30 x 10^-1	-6.13	2.97
F13			-2.72 x 10^-8	1.54 x 10^-5	-3.21 x 10^-3	3.06 x 10^-1	-11.20	2.63
F14	-1.27 x 10^-11	1.02 x 10^-8	-3.25 x 10^-6	5.27 x 10^-4	-4.55 x 10^-2	1.98	-34.20	.46
F15	-3.81 x 10^-12	3.11 x 10^-9	-1.03 x 10^-6	1.74 x 10^-4	-1.60 x 10^-2	7.55 x 10^-1	-14.28	.10
F16		1.19 x 10^-10	-8.28 x 10^-8	2.30 x 10^-5	-3.34 x 10^-3	2.68 x 10^-1	-9.40	2.56
F17	-3.44 x 10^-12	2.72 x 10^-9	-8.66 x 10^-7	1.42 x 10^-4	-1.26 x 10^-2	5.94 x 10^-1	-12.11	1.09
F18		5.24 x 10^-10	-3.55 x 10^-7	9.29 x 10^-5	-1.18 x 10^-2	7.45 x 10^-1	-19.55	3.02
F19				-1.26 x 10^-6	5.40 x 10^-4	-6.90 x 10^-2	2.55	-.06
F20			2.15 x 10^-8	-1.13 x 10^-5	2.09 x 10^-3	-1.53 x 10^-1	3.29	1.56
F21	4.80 x 10^-12	-3.64 x 10^-9	1.10 x 10^-6	-1.67 x 10^-4	1.33 x 10^-2	-4.99 x 10^-1	5.42	2.10
VLT			5.52 x 10^-9	-2.61 x 10^-6	3.26 x 10^-4	1.17 x 10^-2	-2.52	2.29
GLD			-1.11 x 10^-8	7.01 x 10^-6	-1.70 x 10^-3	1.97 x 10^-1	-8.76	3.20

The use of derivatives allows us to obtain trajectories of growth (Figure 2) and acceleration (Figure 3). Comparing the three figures provides comprehensive information about age-related changes.

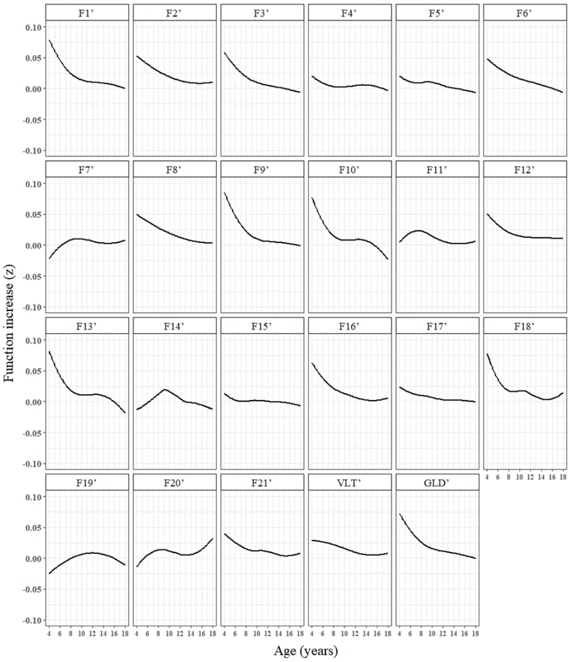

Figure 2. First derivative of functions of age-related changes in features of neuropsychological development

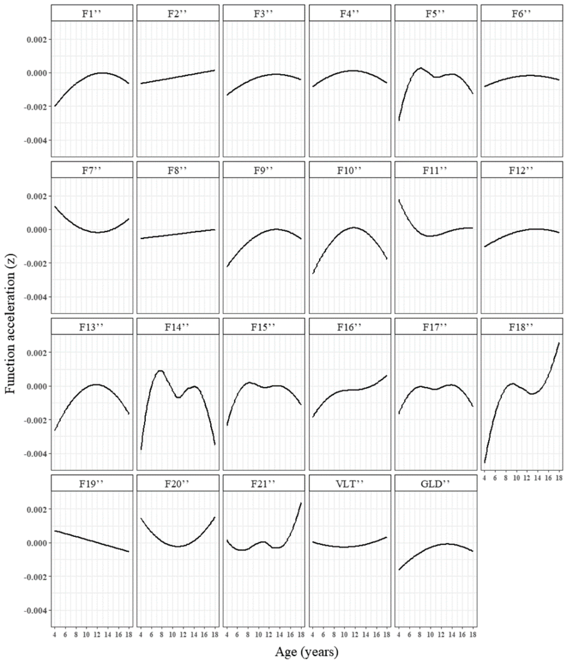

Figure 3. Second derivative of functions of age-related changes in features of neuropsychological development

Functions designed for analysing population growth do not work correctly with negative values. Therefore, for further calculations, the initial data was increased by 3.27, which is the absolute value of the z-score for the minimum percentile given the sample size. The results of applying the Gompertz function are shown in Table 2, the Verhulst function in Table 3, and the Schmalhausen-Brody function in Table 4.

Table 2. Description of age-related development trajectories using the Gompertz function

Scales	Equation parameters			Range
	a	*b*	*c*	
F1	4.27	4.17	2.62 x 10^-2	2.74
F2	4.56	3.73	2.23 x 10^-2	3.00
F3	3.81	4.82	3.46 x 10^-2	2.09
F4	7.14	9.56 x 10^-1	1.67 x 10^-3	.69
F5	3.70	9.61 x 10^-1	1.92 x 10^-2	1.05
F6	4.23	3.29	2.40 x 10^-2	2.50
F7	4.64	6.51 x 10^-1	5.24 x 10^-3	.93
F8	4.44	3.97	2.40 x 10^-2	2.92
F9	3.93	7.07	3.67 x 10^-2	2.55
F10	3.92	3.08	2.75 x 10^-2	2.01
F11	4.04	2.47	2.32 x 10^-2	2.04
F12	4.71	2.13	1.57 x 10^-2	2.55
F13	4.17	3.05	2.38 x 10^-2	2.37
F14	3.82	8.02 x 10^-1	1.50 x 10^-2	1.05
F15	3.29	3.24 x 10^-1	4.47 x 10^-2	.10
F16	3.97	4.56	3.10 x 10^-2	2.35
F17	3.65	1.10	2.20 x 10^-2	1.04
F18	4.27	2.75	2.17 x 10^-2	2.41
F19	70.23	3.23	3.37 x 10^-4	.56
F20	5.49	1.01	5.60 x 10^-3	1.47
F21	4.15	1.82	1.87 x 10^-2	1.93
VLT	4.26	2.42	2.06 x 10^-2	2.28
GLD	4.33	4.36	2.60 x 10^-2	2.86

Note. *a* – maximum value (asymptote); *b* – displacement along the *x*-axis; *c* – growth rate.

Table 3. Description of age-related development trajectories using the Verhulst function

Scales	Equation parameters			Range
	K	*P*	*r*	
F1	4.21	4.21×10^{-1}	3.26×10^{-2}	2.59
F2	4.45	4.56×10^{-1}	2.94×10^{-2}	2.85
F3	3.80	3.90×10^{-1}	4.00×10^{-2}	1.98
F4	5.97	2.75	2.88×10^{-3}	.69
F5	3.68	1.62	2.16×10^{-2}	1.03
F6	4.16	5.44×10^{-1}	3.00×10^{-2}	2.39
F7	4.40	2.43	7.22×10^{-3}	.93
F8	4.35	4.25×10^{-1}	3.10×10^{-2}	2.77
F9	3.91	2.37×10^{-1}	4.40×10^{-2}	2.38
F10	3.89	6.24×10^{-1}	3.20×10^{-2}	1.92
F11	3.99	7.30×10^{-1}	2.85×10^{-2}	1.97
F12	4.56	8.90×10^{-1}	2.09×10^{-2}	2.45
F13	4.13	6.24×10^{-1}	2.87×10^{-2}	2.26
F14	3.78	1.82	1.76×10^{-2}	1.05
F15	3.29	2.47	4.48×10^{-2}	.10
F16	3.94	3.90×10^{-1}	3.72×10^{-2}	2.22
F17	3.63	1.48	2.44×10^{-2}	1.03
F18	4.20	6.68×10^{-1}	2.71×10^{-2}	2.30
F19	4.40×10^{4}	2.88	1.04×10^{-3}	.56
F20	5.01	2.05	8.41×10^{-3}	1.46
F21	4.09	1.02	2.28×10^{-2}	1.87
VLT	4.19	7.54×10^{-1}	2.59×10^{-2}	2.20
GLD	4.26	3.91×10^{-1}	3.29×10^{-2}	2.70

Note. *K* – maximum value (asymptote); *P* – starting value; *r* – growth rate.

Table 4. Description of age-related development trajectories using the Schmalhausen-Brody function

Scales	Equation parameters		Range
	α	*k*	
F1	5.45	8.08 x 10^-3	2.62
F2	6.42	6.19 x 10^-3	2.96
F3	4.18	1.40 x 10^-2	1.81
F4	3.47	2.84 x 10^-2	.79
F5	3.64	2.20 x 10^-2	1.13
F6	5.01	9.40 x 10^-3	2.41
F7	3.60	2.32 x 10^-2	1.06
F8	5.99	6.90 x 10^-3	2.83
F9	4.64	1.10 x 10^-2	2.18
F10	4.28	1.32 x 10^-2	1.90
F11	4.37	1.25 x 10^-2	1.98
F12	5.43	8.11 x 10^-3	2.61
F13	4.83	1.01 x 10^-2	2.31
F14	3.67	2.13 x 10^-2	1.17
F15	3.28	6.25 x 10^-2	.13
F16	4.54	1.15 x 10^-2	2.11
F17	3.63	2.24 x 10^-2	1.10
F18	4.93	9.69 x 10^-3	2.37
F19	3.37	3.68 x 10^-2	.50
F20	3.96	1.62 x 10^-2	1.59
F21	4.35	1.27 x 10^-2	1.97
VLT	4.78	1.04 x 10^-2	2.27
GLD	5.73	7.41 x 10^-3	2.74

Note. α – maximum value (asymptote); *k* – growth rate.

The correlations of the initial data and the values predicted by the different methods with age are given in Table 5.

Table 5. Correlation of initial data and predicted values with age

Scales	Initial data	Curve fitting methods			
		Polynomial	Gompertz	Verhulst	Schmalhausen-Brody
F1	.72	.95	.95	.95	.99
F2	.82	.97	.96	.96	.99
F3	.47	.89	.90	.90	.97
F4	.19	.99	~1	~1	.90
F5	.26	.93	.96	.96	.93
F6	.65	.95	.95	.95	.99
F7	.25	.97	~1	~1	.93
F8	.78	.96	.96	.96	.99
F9	.59	.90	.89	.89	.98
F10	.50	.93	.93	.93	.97
F11	.52	.94	.95	.95	.98
F12	.71	.98	.98	.98	.99
F13	.62	.95	.95	.95	.98
F14	.27	.87	.97	.97	.94
F15	.01	.41	.81	.81	.72
F16	.56	.92	.92	.92	.98
F17	.26	.94	.94	.94	.93
F18	.64	.95	.96	.96	.98
F19	.15	.81	~1	~1	.85
F20	.40	.99	~1	~1	.96
F21	.51	.96	.97	.97	.97
VLT	.63	.96	.96	.96	.98
GLD	.76	.95	.95	.95	.99

The correspondence of the predicted values to the initial data is shown in Table 6.

Table 6. Correlation of predicted values with initial data

Scales	Curve fitting methods			
	Polynomial	Gompertz	Verhulst	Schmalhausen-Brody
F1	.76	.76	.76	.75
F2	.85	.85	.85	.84
F3	.52	.52	.52	.51
F4	.19	.19	.19	.17
F5	.28	.28	.28	.28
F6	.69	.69	.69	.68
F7	.26	.26	.26	.24
F8	.82	.82	.82	.81
F9	.65	.65	.65	.63
F10	.53	.53	.53	.52
F11	.55	.55	.55	.54
F12	.72	.72	.72	.72
F13	.66	.65	.65	.65
F14	.32	.29	.29	.28
F15	.03	.02	.02	.02
F16	.61	.61	.61	.60
F17	.27	.27	.27	.27
F18	.67	.66	.66	.66
F19	.19	.15	.15	.07
F20	.41	.40	.40	.39
F21	.53	.53	.53	.53
VLT	.65	.65	.65	.65
GLD	.80	.80	.80	.78

4. Discussion

We have tried to describe the trajectories of age-related changes using different algebraic methods. It is shown that polynomials achieve the most accurate approximation (r = .520). However, the accuracy of growth functions is only slightly lower. Specifically, for the Gompertz function r = .515, for the Verhulst function r = .514, and for the Schmalhausen-Brody function r = .504. For most variables, the difference between the functions is negligible. Overall, the Schmalhausen-Brody function provides the worst approximation. The dependence of GLD on age is given as an example (Figure 4). Points indicate the initial data.

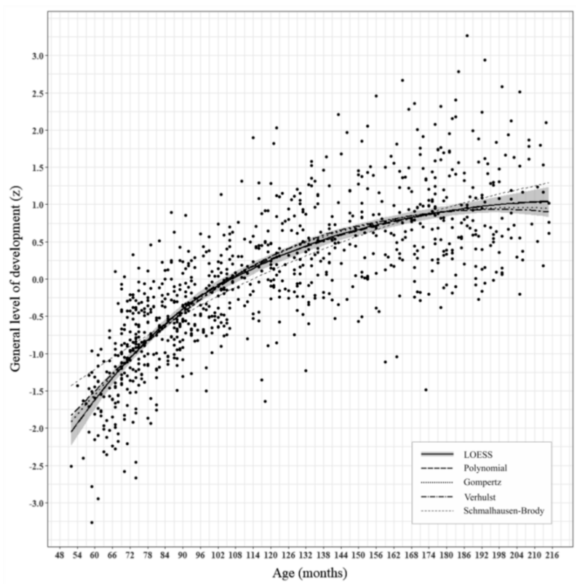

Figure 4. Age-related changes in general level of development

It should be noted that growth functions perform the worst on variables that are insufficiently related to age (e.g. F4, F15, F19). The algorithm of approximation tries to increase this linkage, which leads to a discrepancy with the initial data. Distortions can occur due to the existence of periods of temporary decline followed by subsequent growth. It is easier to describe the trajectories of variables whose growth is monotonic (F2, F8, F12, F16, VLT). In addition, variables with a high range (e.g. F1, F2, F8, F18, GLD) are better approximated than variables with a small range (e.g. F4, F7, F14, F15, F19).

An example of a poor approximation is F19 (Figure 5). As can be seen, the curves constructed using the Gompertz and Verhulst functions almost coincide. The curve constructed using the Schmalhausen-Brody function clearly differs from other curves. Moreover, all growth functions do not match well with the initial data.

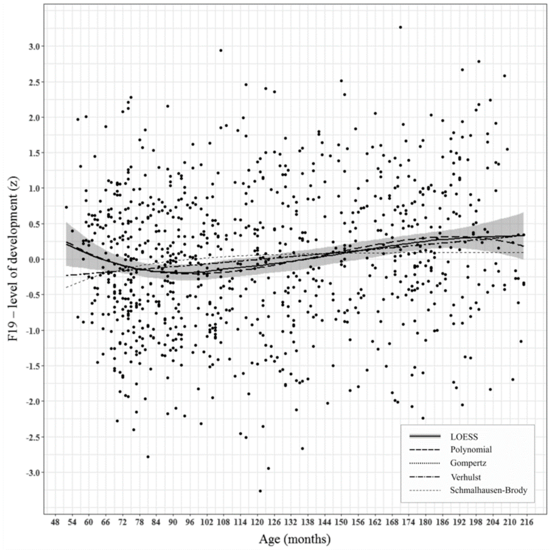

Figure 5. Age-related changes in tendency to draw thin lines

It is convenient to compare development trajectories with each other using similar curves that differ only in parameter values. The unevenness (heterochrony) of development can be clearly visualised using growth functions. As an example, we give the growth trajectories of all variables plotted using the Gompertz function (Figure 6). The bold grey line shows the GLD variable. At the age of 4, the highest values among all variables are F4, F15, F19, while the lowest values are F2, F8, F9. By 18 years, variables F2, F8, F12 have the highest values, whereas the lowest values are found in F15, F17, F19.

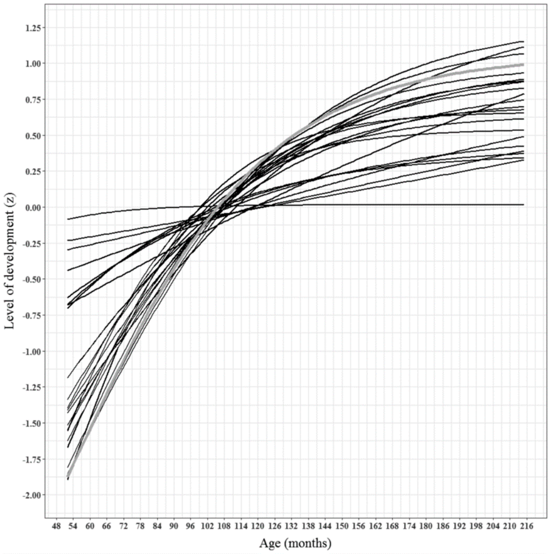

Figure 6. Age-related changes in mental function components

Growth functions, asymptotically approaching the maximum value, overestimate the age at which development ends. For the investigation of sensitive periods, it is better to focus on polynomials and their derivatives. Some variables (F2, F7, F8, F11, F12, F16, F18, F20, F21, VLT) appear to continue their increase after the age of 18. The others complete their growth between the ages of 11 and 18. In particular, the variable F15 is maximised at age 11; F14 at age 12; F3, F10, F19 at age 15; F4, F5, F6, F9, F13 at age 16; F1, F17, GLD at age 17.

5. Conclusion

As a result of the conducted research, the trajectories of age-related changes in 22 components of mental functions and overall level of neurocognitive development were identified. It is shown that they can be algebraically described using polynomials or growth functions commonly applied in population biology. Polynomials are suitable for the most accurate approximation, especially when monotonic growth is absent. Growth functions possess comprehensible parameters that facilitate the comparison of trajectories.

The obtained equations can be used to measure the development level based on age norms. Unlike tabular data, the calculation using the formula allows for accuracy up to one month. A measure of variance is also needed to assess the relative level of development. It can be calculated using the sliding window technique. After introducing such an adjustment, it becomes possible to work with samples of different ages, disregarding the relationship between the variable under study and age.

Almost half of the components of mental functions continue to grow beyond the age of 18. This result refutes the common belief that neurocognitive development is completed by the time of puberty. At the same time, there are high individual differences in the speed of mental development. Therefore, when assessing a specific child, it is advisable to construct personalised growth curves and track development over time. The success of developmental interventions can be monitored by analysing changes in growth rate.

This study has a number of limitations. We investigated only the most important components of mental functions, without considering taste, smell, temperature and pain sensitivity, vestibular functions, and much more. A cross-sectional method was used instead of a longitudinal approach, which limits the ability to observe individual age-related changes. In future studies, we plan to examine the possible influence of sex, interhemispheric asymmetry, and early development characteristics.

Data Availability

The psychometric battery MIND is described in the article (Khokhlov, 2024), which is available on the Lomonosov Psychology Journal (formerly known as Moscow University Psychology Bulletin) website at https://msupsyj.ru/en/articles/article/9948/. The initial data can be downloaded from http://nkhokhlov.ru/mind/curves_data.csv.

Ethic Statement

Parents (legal representatives) consented to the study of their children. All data were processed anonymously and aggregated, so the paper does not contain any personal information about the participants. The study complies with the ethical guidelines outlined in the 7th revision of the Declaration of Helsinki (2013). The psychology centres where the study was conducted have no conflicts of interest in relation to this research.

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Authors' contribution

Nikita Khokhlov conducted the neuropsychological diagnostics, performed the mathematical and statistical data analysis, and wrote the main text. Elizaveta Vasyura participated in the digitisation of the diagnostic protocols, proofread and edited the manuscript. Both authors contributed to the development of the research concept and conducted the literature review.

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