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To the 100-Anniversary of N. N. Traugott

Peculiarities of Formation of the Cognitive Functions in Junior School Children with Different Maturity of Regulatory Brain Systems

R. I. Machinskaya and O. A. Semenova

Institute of Age Physiology, Russian Academy of Education, Moscow, Russia

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Abstract—To reveal the specific role of maturation of modulating, regulatory brain systems in formation of cognitive processes at the junior school age, was performed a complex electroencephalographic and neuropsychological examination of the 7–8-year-old children with different degrees of functional maturity of the regulatory systems. It has been shown that an essential factor determining formation of the higher psychic functions (HPF) at the junior school age is maturation of the fronto-thalamic system. Immaturity of this system in the 7–8-year-old children leads to a deficiency of functions of programming, regulation, and control of the activity. The most substantial changes were revealed for the components of the voluntary organization of the activity, which are connected with its selectivity both in realization of current tasks and in creation of the activity strategy. The deficiency of processes of voluntary regulation in the 7–8-year-old children with immaturity of the fronto-thalamic system is combined with a delay of development of the meaning-forming speech function. Comparison of data of the neuropsychological and electroencephalographic examination has permitted suggesting that the basis of the revealed changes in the HPF formation in the 7–8-year-old children is immaturity of the main neurophysiological mechanisms that provide a selective involvement of different cortical regions in providing their activity both in the course of its realization and during preparation to it as well as an under-development of differentiated intracortical connections in the left hemisphere.

INTRODUCTION

For many years, the problem of effect of social and biological factors on formation of cognitive activity has been drawing interest of psychologists and neurophysiologists. Vygotskii [1] has proposed theoretical solution of this problem by formulating the concept of "zone of the nearest development." According to this concept, the progressive development of cognitive activity is initiated by learning and an essential condition of the learning is a certain level of brain maturity. The current data confirm correctness of L.S. Vygotskii's ideas and indicate that formation of the higher psychic function (HPF) is determined by a gradual and heterochronous maturation of different cortical and subcortical brain structures [2]. As shown by the last decade studies, of the most important significance for development of the higher psychic functions in children is maturation of modulating brain systems including the higher regulatory centers—frontal cortical regions [2–5].

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Owing to advances in non-invasive methods of brain investigation, such as the quantitative evaluation of bioelectric activity and functional tomography, many facts have been accumulated in the world neuroscience, which shed light on providing by the cortex of individual psychic functions. Considerably less studied is the question on effect of deep regulatory structures of different levels both on realization and on formation of cognitive processes in children.

The goal of the present study was to reveal specific role of maturation of modulating, regulatory brain systems in formation of the cognitive processes in the 7–8-year-old children. Based on the concept of Luria about participation of three cerebral blocks in providing psychic activity [6], we have suggested that functional maturation of regulatory brain systems can produce a dual effect on the HPF development: the direct one (on regulatory HPF aspects, i.e., organization of psychic activity) and the indirect one, on operational HPF aspects. The latter can be realized by affecting formation of functional organization of the brain cortex in the state of rest as the initial background for the activity.

Study of the role of functional maturation of regulatory systems (RS) in formation of HPF in the 7–8-year-old children implied performance of complex neurophysiological and neuropsychological study. At the first stage, an electroencephalographic analysis of the cerebral RS state was performed; based on it, groups of children with different levels of functional maturity of RS were formed. In children of these groups, to study direct effect of the functional RS maturity on the psychic activity organization, a neuropsychic examination of the state of programming function and of control of activity control was carried out. The study of indirect action of the functional RS maturity of RS on the operational HPF aspects included a comparative neuropsychological analysis of the degree of formation of the verbal function and an electrophysiological analysis of functional organization of the large hemisphere cortex in the state of rest.

MATERIALS AND METHODS

Examined in this study were 63 children (30 girls and 33 boys) aged 7–8 years. All of them were right-handed and had no neurological pathology in anamnesis. The age diapason of the examined children was from 7 years to 8 years 11 months. All children studied in ordinary schools: by the program of the first grade (1–3-grade junior school), 18 persons (the mean age 7 years 11 months); of the first grade (1–4), 9 persons (the mean age 7 years 7 months), and of the second grade (1–4), 36 persons (the mean age 8 years 1 month). The investigation was carried out in general-education junior schools of Moscow.

The complex examination of the children included recording of the baseline EEG followed by a visual and spectral-correlation analysis and neuropsychological examination.

EEG recording was performed with the aid of computer-equipped electroencephalograph ("Biola," Russia) (the permeance frequency of amplifiers 0.1–35 Hz) from occipital (O_1, O_2), parietal (P_3, P_4), central (C_3, C_4), frontal (F_3, F_4) and posterior temporal (T_5, T_6) leads of the left and right hemispheres whose locations were determined by the system "10–20." For visual analysis of EEG, there were used the bipolar and monopolar assembled electronic schemes with ipsilateral aural indifferent electrodes, for spectral-correlation analysis, the monopolar assembled scheme with an averaged ($(A_1+A_2)/2$) aural indifferent electrode. Recording of EEG was performed at the state of wakefulness at rest with closed ears and during functional loads (1.5–2.5-min long hyperventilation and rhythmic photostimulation). The photostimulation by the flash with an intensity of 0.2 J was performed with a frequency of 4 to 12 Hz and an interval of 1 Hz. Duration of each series of stimulation was 7 s, the interval between them 10 s.

Assessment of functional maturity of deep cerebral regulatory systems of children's brain was carried out by the method specially designed in our previous studies—the structural analysis of native EEG [7], which implies unified description of EEG patterns by functional signs, i.e., by a functional state of brain cortex, diffuse (whole-brain) changes of electric activity, local changes of electric activity, state of deep regulatory structures. Earlier, in study with the aid of structural analysis of EEG of the brain state of the 5–6-, 6–7-, and 7–8-year-old children with different level of learning progress [8, 9], we determined electroencephalographic criteria of functional maturity of RS in the 7–8-year-

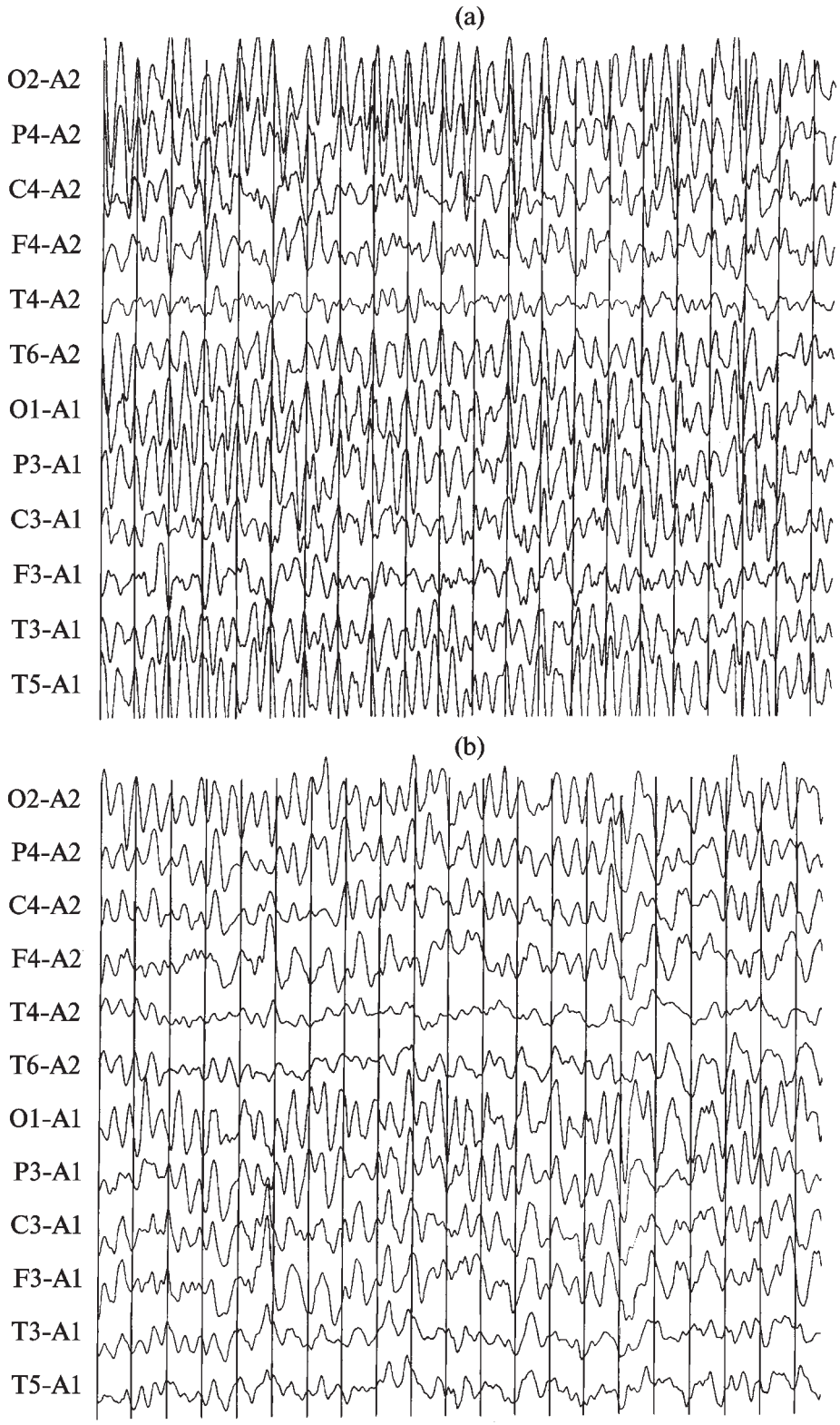

Fig. 1. Examples of native EEG of the 7–8-year-old children, in whom electroencephalographic patterns are demonstrated, which are signs of functional immaturity of regulatory brain systems. (a) System of unspecific activation, (b) fronto-thalamic regulatory system.

old children. To the signs of functional immaturity of fronto-thalamic regulatory system (FTS) in children of this age there were attributed the groups of regulatory bilateral-synchronous oscillations with a frequency of 4–6 Hz in the anterior (frontal and central) brain regions (Fig.1b), to the signs of functional immaturity of the system of unspecific activation—hypersynchronous alpha-rhythm and/or groups of bilateral-synchronous oscillations of theta-diapason in caudal (occipital and parietal) brain regions (Fig. 1a).

Based on these criteria, three groups of children examined in the present study were formed:

–children, in whose EEG no signs of functional immaturity of cerebral RS and other alterations of functional state of the brain were revealed (norm) (20 persons);

–children, in whose EEG some signs of functional immaturity of the system of unspecific activation were revealed (deficiency of unspecific activation, DUA, 10 persons);

–children, in whose EEG some signs of functional immaturity of the fronto-thalamic regulatory system were revealed (IFTS, 19 persons).

The children, in whose EEG some other disturbances of the functional brain state (local and whole-brain ones, immaturity of rhythmogenic cortical systems) were not included in the experimental groups.

Assessment of the functional organization of cortical regions in the rest state was carried out by the spectral-correlation analysis of EEG [10], that permitted studying the degree of synchronism of different rhythmic oscillations of biopotentials in two cortical regions on the basis of determination of coherence (COH) function. The spatial synchronization of rhythmic EEG components is in electroencephalography a commonly accepted parameter of functional combination of cerebral structures [11–13] and is used for study of morphological and functional cortex organization both in the rest state [3, 14, 15] and in the process of cognitive activity [13]. The maximum of assessments of the COH function of rhythmic components in alpha-diapason was used in the present study as the main analyzed variable of the spectral-correlation analysis. For this analysis, a rapid Fourier transformation in the frequency diapason of 2 to 30 Hz was used. Initial materials were the EEG fragments without artifacts of 1-min duration recorded in the state of quiet wakefulness with closed eyes. The frequency interval for calculation of maxima of assessments of alpha-coherence was selected based on analysis of individual curves of assessments of COH functions. The individual approach to choose alpha-interval is connected with age peculiarities of the alpha-rhythm in the 7–8-year-old children, as well as with greater individual dispersion of these parameters in the analyzed age diapason. As a result, after analysis of COH function curves, the range was selected from 6.5 to 9 Hz, into which there were "included" predominant peaks of alpha-COH in all examined children. In each child, the mean values of maxima of alpha-COH function assessments were calculated in all intrahemispheric pairs of leads. Statistical comparison of these parameters in the children's groups was performed using the one-factor dispersion ANOVA analysis.

Neuropsychological examination was carried out by the procedure of Akhutina and co-authors [16], based on the principles proposed by A.R. Luria. Studied were functions of programming, regulation, and control of activity, motor functions, speech, aural gnosis, auditory-verbal memory, visual gnosis, visual memory, and space images. Due to the fact that one of the tasks of the present study was analysis of the regulatory component state of HPF in children with different levels of brain maturity, the main technique of neuropsychological examination was added by a specially developed method of assessment of functions of programming, regulation, and control of activity (hereafter, the term "executive functions" will be used to characterize these functions).

Analysis of the literature data has shown that in foreign studies there exists a considerable dispersion of opinions about the competent content of executive functions, which is due, to a greater extent, to the absence of the common theoretical position of researchers. In this connection, we have found it necessary to take the Luria's work [17] as the theoretical basis for detachment of the components of executive functions. These components and possible manifestations of their deficiency are presented in Table 1.

To analyze the state of executive functions by the chosen parameters, the following tests of neu-

Table 1. Components of functions of programming, regulation, and control of the activity, which are analyzed in the course of neuropsychological examination

Components	Manifestations of deficiency
I—selective response to stimuli essential for to realization of activity tasks and inhibition of direct reactions	impulsivity as disturbance of selective character of the activity (echo-responses and forestalling behavior)
II—switching-over from one element of the program to another	inertness of the program element (perseveration)
III—switching-over from one program to another	difficulties of switching-over to another program—an enhanced inert influence of stereotypes
IV—stable following of the learned program	instability of the program—subject to external or internal side influences
V—selection and consideration of several basic program predesigned by instruction	difficulties of performance of complex program
VI—creation of the own strategy of activity	difficulties of creation of strategy of activity
VII—control of performance of the own activity	difficulties of self-control

ropsychological examination were used: choice reaction, study of dynamic praxis, graphical test (fence), assessment of rhythms and performance of rhythmic structures according to a sample and verbal instruction, copying of complex figure (Taylor's figures), remembering of 2 word groups by 3 words in each, tactile recognition of geometrical figures, story telling according to a series of plot pictures ("The frog and the heron"), retelling of the story "The jackdaw and the pigeons".

For quantitative assessment of deviations in the state of executive functions in every test, such parameters were used, as the number of certain-type errors made by the examinee and the presence or absence of some peculiarity if it cannot be evaluated in another form. These "absolute" indices were compared with normative data. As the latter there were used the means and standard deviations (SD) for indices of identified components of executive functions in different tests for 27 children from the examined group with good study progress without alteration in behavior. Ranging of absolute values (from −1 to 3) with respect to normative parameters was performed as follows: (−1)—performance differing from the mean to the better direction more than by two SD; 0—performance characteristic of norm (mean ± 1 SD, 27 children); 2—performance differing from the mean to the worse direction by one–two SD; 3—performance differing from the mean to the worse direction by more than two SD. Then, for each examinee and for each components of executive functions, there was calculated the deficiency coefficient of the component (for example, coefficient of program instability). For this purpose, the ranged error values related to manifestation of deficiency of this component were averaged for different tests. The common coefficient of deficiency of functions of programming (CDFP) in each examinee was the mean of all 7 components of executive functions. Statistical comparison of CDFP in the children's groups was performed using the non-parametric Mann–Whitney criterion.

In his communication, results of examination of operational HPF are presented only by data of the state of verbal function, which was assessed in three tests: memorizing of two groups of words, each group composed of three words (the material not connected semantically), writing of dictated sentences, and retelling of a story.

RESULTS AND DISCUSSION

Analysis of functions of programming, regulation, and control of activity. For comparative assessment of the state of functions of programming, regulation, and control of the activity, on the whole, in

the children in norm and with functional immaturity of the brain RS, the index integrated by all 7 components of executive functions (summarized CDFP, see "Materials and Methods") was used. Distribution of ranged values of this index in the examined groups of children (Fig. 2) indicates that the state of functions of programming in the children without signs of functional RS immaturity on EEG corresponded in most cases (75%) to the mean normative values, whereas in children with functional immaturity of the fronto-thalamic regulatory system (IFTS), much more often than in other groups there were observed deviations from the mean normative values in the state of executive functions (values of the summarized CDFP range were 2 and 3). Distribution of the analyzed index in children with immature system of nonspecific activation (DUA) is close to the norm than to that in the IFTS group: in this group, like in norm, there were no cases with pronounced (CDFP > 3) deviations of the programming function. Statistical analysis of the values of summarized CDFP in the groups by Mann–Whitney criterion has shown that in children with IFTS, this index is significantly higher as compared both with the group of norm ($p = 0.001$) and with the group DUA (deficiency of unspecific activation) ($p = 0.001$).

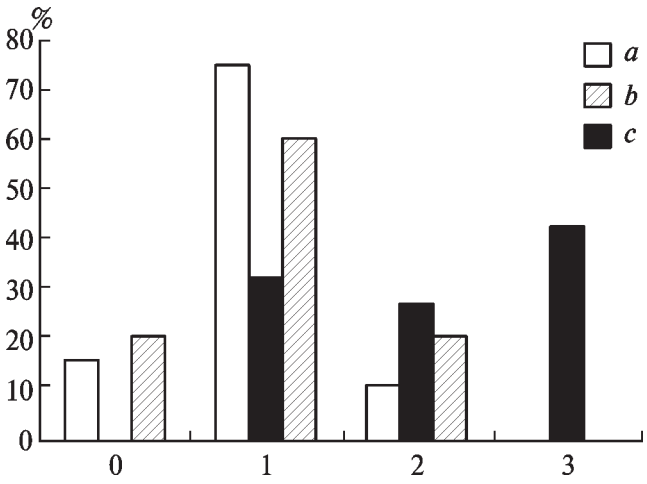

Fig. 2. Frequency of representation (%) of various values of the summarized coefficient of deficiency of functions of programming (CDFP) in three groups of the 7–8-year-old children. (*a*) Group of norm, (*b*) group with DUA, (*c*) group with IFTS. Values of CDFP: 0—values of CDFP were in the range from $m - 2$ SD to $m - 1$ SD; 1—in the range of $m \pm 1$ SD; 2—values of CDFP were in the range from $m + 1$ SD to $m + 2$ SD; 3—values of CDFP were higher than $m + 2$ SD, where m is the mean value for children without learning difficulties and deviations on EEG accepted as normative indices.

The obtained results indicate that the characteristic HPF peculiarity in children with immature FTS is the absence of formed programming functions, regulation, and control of the activity. It can be suggested that it is the insufficiently formed voluntary control responsible for functional FTS immaturity, which is one of the main causes of difficulties of learning in children of the junior school age. This suggestion is confirmed by data of our previous studies [8, 9]: in the 6–7- and 7–8-year-old children with difficulties of learning, in most cases (from 60 to 80% in different samples), signs of functional FTS immaturity are revealed in EEG, whereas in children with high leaning progress, such changes of the electric brain activity are absent. According to Batuev [18], the fronto-thalamic regulatory system or thalamo-frontal associative system, as shown by neuromorphological [19] and experimental electrophysiological data [18, 20], is a morpho-functional assembly of prefrontal regions of the frontal cortex and the mediodorsal thalamic nucleus that, in turn, receives afferentation from the cingulate cortex (cortical center of the limbic system) and has efferent connections with unspecific thalamic nuclei that have selective modulating effects on various projective and associative cortical zones. Due to its morpho-functional connections, FTS realizes selective ascendant control effects from higher frontal regulatory centers to the cortical structures performing information processing [21]. These data permit suggesting predominant influence of the FTS immaturity on the aspects of the functions of programming, regulation, and control of the activity, which are connected with its voluntary selective organization.

To study the specific influence of FTS immaturity on development of various components of the functions of programming, regulation, and control of the activity, CDFP from 7 components (see "Materials and Methods") were compared in children with IFTS, DUA and in norm, using the non-parametric Mann–Whitney criterion. The results of intergroup comparisons are presented in Table 2.

According to the data presented in Table 2, chil-

Table 2. Results of statistical comparison of indices of neuropsychological testing of functions of programming, regulation, and control of activity in three groups of the 7–8-year-old children

Analyzed deviations of functions	Level of statistical significance of differences (p) by Mann–Whitney nonparametric criterion		
	IFTS and norm	IFTS and DUA	norm and DUA
I—impulsivity (echo-responses and forestalling behavior), separately echo-response	0.232 0.001	0.206 0.039	0.574 0.334
II—inertness of the program element (perseveration)	0.004	0.192	0.221
III—difficulties of switching-over to another program	0.016	0.098	0.884
IV—instability of the program	0.001	0.022	0.766
V—difficulty of performance of complex programs	0.032	0.137	0.891
VI—difficulties of creation of strategy of activity	0.002	0.018	0.940
VII—difficulties of self-control	0.001	0.144	0.200

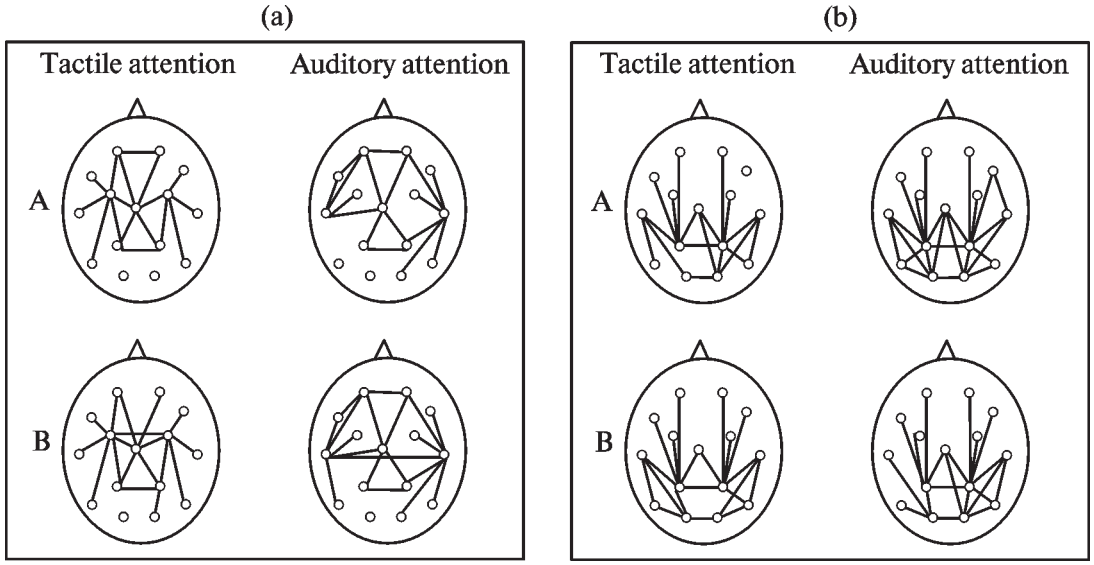

Fig. 3. Dynamics of functional interaction of cortical zones in the situation of selective preadjustment to discrimination of tactile and auditory signals in the 7–8-year-old children in norm (a) and IFTS (b). (A) Test-signals are addressed to the left hemisphere; (B) connected with lines are the lead pairs, for which a statistically significant increase ($p < 0.05$) of the maximum of assessment of the COH function in the range of alpha-rhythm was observed in situations of effective attention as compared with the non-effective one.

dren with IFTS had statistically significant differences from norm in all components of executive functions, while children with DUA did not differ from norm by any of studied components. The intergroup differences were not revealed only for impulsiveness. However, a more detailed analysis of this deviation of voluntary organization of the activity has shown that by the presence of echo-responses (direct responses conflicting with the instruction requirements), children with IFTS differed statistically significantly not only from the norm, but also from children with DUA. The in-

stability of the learned program and the difficulties of creation of strategy of the activity also are specific of children with IFTS. By these both components, the group with IFTS differed statistically significantly both from norm and from the group with DUA.

Thus, the results of the neuropsychological analysis have shown that especially sensitive to the functional FTS maturation are components of functions of programming, regulation, and control of the activity connected with a selective adjustment to perception of important information, selective response, and suppression of direct or side effects.

It can be suggested that responsible for the revealed specific deficiencies is the absence of formed basic neurophysiological mechanisms providing a selective modulation of activity of cortical regions in the process of activity, especially during preparation to it. This suggestion agrees with our earlier data [22] on cerebral organization of voluntary prestimulus attention in children with IFTS and in norm. Figure 3 shows formation of functional combinations of cortical regions on the basis of synchronization of their electrical activity in the alpha-rhythm diapason in the situation of preadjustment to different tactile and auditory signals in children in norm (a) and with IFTS (b).

It is seen that in children in norm in both hemispheres, topography of intercentral assemblies important for correct solution of a perceptive task depends on modality of the anticipated relevant signal, i.e., in the pre-stimulus period of voluntary attention, there occurs a selective "adjustment" of functional systems of cortical regions necessary for realization of the future activity. In children with IFTS, the selective pre-adjustment of the cortical functional systems to analysis of informational signal is absent. The presence of the "focus of interrelated activity" in temporal and occipital zones regardless of the relevant signal modality indicates predominance in these children, at the period of preadjustment, of non-voluntary attention to warning signals that were visual in this experimental situation.

Analysis of operational aspect of HPF. Apart from analysis of functions of the programming, regulation, and control of the activity, the performed neuropsychological study also included assessment of the state of operational processes, such as speech, memory, and motor functions. In the present communication, a small fragment of this study connected with the assessment of the verbal function is presented. Analysis of the results of performance of tests for the auditory-verbal memory, writing of dictated sentences and retelling has shown that a sufficiently frequent error in children is semantic substitution in the absence of phonematic substitutions. For example, in the auditory-verbal memory test, the words that were to be memorized were substituted by semantically closed ones (cold–frost) or in the writing of dictated sentences, such as the sentence "At the edge of forest, the hunter shut a wolf," the word "wolf" was substituted by "hare." The frequency of cases (%) when the semantic substitutions were observed in three groups of children during performance of various tests is presented in Fig. 4.

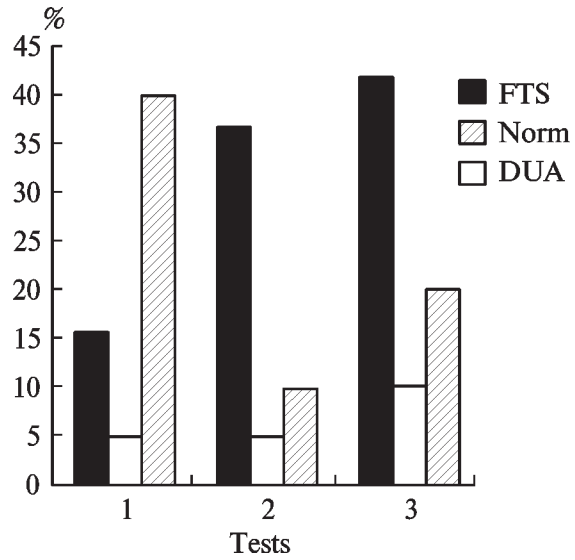

Fig. 4. Frequency (%) of representation of semantic substitutions in three group of children during performance of test for memorizing two group of words by three words in each group (1), writing of sentences (2), and retelling of a story (3). Designations of groups are as in Fig. 2.

Statistical analysis of the presented distributions has shown that in the tasks requiring "mechanical" memorizing of the material not semantically connected, the percent of semantic substitutions in the group with DUA is higher statistically significantly as compared both with the norm ($p < 0.003$) and with the group with IFTS ($p < 0.047$), which can indicate a decreased memory volume.

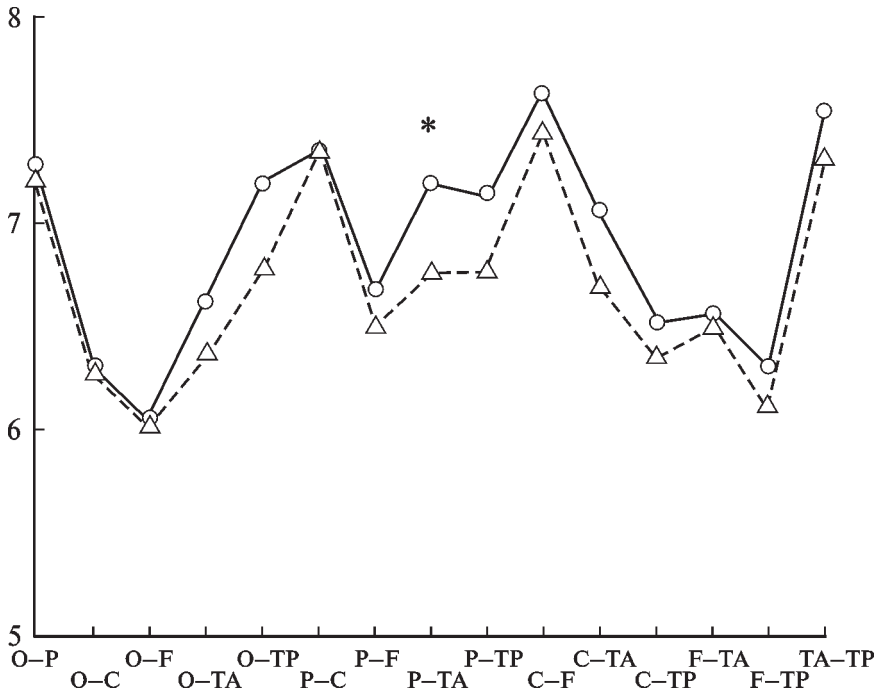

Fig. 5. Distribution of mean values of coherence of the rest EEG alpha-rhythm in leads of the left hemisphere in the 7–8-year-old children in norm (broken line) and with IFTS (solid line). *—Intergroup differences are statistically significant ($p < 0.05$).

Interestingly, the decreased memorizing volume in children of this group was also observed in tests for visual memory. Children with IFTS had difficulties in memorizing and reproduction of a semantically combined material. In this group the percentage of cases of semantic substitutions was significantly higher than in norm in tests 2 ($p < 0.014$) and 3 ($p < 0.020$). Similar results, such as the presence of semantic substitutions in memorizing the semantically connected material in the 7–8-year-old children with IFTS, were revealed in our previous study on formation of skill of writing [23]. The semantic substitutions in children with IFTS can be suggested to be connected with the absence of formed operations of selective identification of essential categorical signs of an object (in this case, of the word), i.e., the processes that are shown by studies of interhemispheric peculiarities of visual information processing to be realized by the left hemispheric structures [24]. To a certain extent, this suggestion is confirmed by the results obtained in the present study when comparing functional organization of the large hemisphere cortex at rest in children with IFTS and in norm. Figure 5 presents distribution in the groups of the mean COH values of alpha-rhythm in EEG at rest in the lead pairs from the left hemisphere.

As shown by the data presented in this figure, in children with IFTS, there is a decrease of the COH level of alpha-oscillations in the lead pairs from the left hemisphere, including temporal and posterior associative cortical regions. The monofactor dispersion analysis has revealed differences ($p < 0.05$) in the COH level of alpha-rhythm for EEG of occipital and anterior temporal regions. No statistically significant differences in the level of alpha-COH were revealed for leads from the right hemisphere as well as for the left hemisphere leads between the groups of children with DUA and in norm. Study of the verbal function and its cerebral mechanisms in the 7–8-year-old children with IFTS requires an additional both neuropsychological and neurophysiological analysis. At the same time, the already obtained results permit claiming peculiarities of

speech development at the functional FTS immaturity, which is likely to be due to the absence of formed local differentiated intercentral connections in the left hemisphere cortex.

In conclusion, it can be stated that the comprehensive neurophysiological and neuropsychological examination of the 7–8-year-old children with various degrees of maturity of cerebral regulatory systems has shown the functional maturation of the fronto-thalamic system to be an essential factor of formation of HPF.

A specific peculiarity of the 7–8-year-old children with immaturity of the fronto-thalamic system is deficiency of programming, regulation, and control of the activity. The most pronounced changes have been revealed for the components of voluntary organization of the activity, which are connected with its selectivity both in solution of the current tasks and in creation of the activity strategy.

Comparison of the data of neuropsychological and electrophysiological studies has allowed suggesting that the essence of the revealed deviations in the HPF formation in the 7–8-year-old children is immaturity of neuropsychological mechanisms of selective involvement of various cortex regions in the activity both in the course of its realization and during preparation to it, as well as the lack of formation of differentiated intracortical connections in the left hemisphere.

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