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EXPERIMENTAL PAPERS

Age-Related Characteristics of the Formation of Neurophysiological Mechanisms of the Phonemic, Grammatical, and Semantic Linguistic Levels

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Abstract—The structure of regional interactions of brain bioelectric potentials has been studied during performance by adults ($n = 18$) and children aged five to six ($n = 15$) and eight to nine years ($n = 17$) of three analytical verbal tasks: recognition of a given phoneme in the context of auditory presented words and recognition of grammatical and semantic mistakes in auditory presented sentences. According to the data of cross-correlation and coherent EEG analyses, adults and, to a lesser extent, children of both age groups showed a noticeable intensification of interhemispheric interaction during the performance of all three tasks, especially between temporal areas, with relatively minor changes in ipsilateral EEG relations. Children were shown to have elements of immaturity of neurophysiological mechanisms underlying various aspects of the language function, such as the analysis of the grammatical formation of a verbal utterance and the semantic content of a phrase. The results also suggest that the level of maturation of neurophysiological mechanisms underlying phonemic analysis is somewhat higher at these age stages than the level of maturity of central mechanisms responsible for the analysis of the semantic content and grammatical construction of a phrase. Quantitative comparison of the patterns of spatial interaction of cortical bioelectric potentials recorded during the performance of the tasks related to different linguistic levels showed a high degree of their statistical similarity for each of the age groups. The findings confirm the assumption that the distributive central maintenance of different linguistic levels is based on topologically close constellations of interacting cortical areas and on similar organization of their regional interactions.

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INTRODUCTION

Language, a complex communicative sign system, includes phonetic, phonological, morphological, syntactic, semantic, and discursive components. Its development is influenced by both biological and social factors. To what degree is the rate of the ontogenetic formation of the cerebral mechanisms of this most important, specifically human function related with the development of linguistic levels at different age stages? The morphofunctional maturation of brain structures involved in the maintenance of cognitive functions is known to be accompanied by improvement of the systemic organization of intercentral relations, which is also reflected in the age-specific characteristics of verbal activity [1–3].

Cerebral mechanisms of different linguistic levels involve not only classical speech centers, but also other areas of the cortex, as well as some subcortical formations that are not related directly to the speech function [4–7]. The system of connections of these areas with language areas; their total quantity; the functional contributions of individual cortical areas of not only the left, but also the right hemisphere; and, above all, the algorithm of interaction of spatially distributed brain structures involved in constellations are determined by the specific nature of the task. At the same time, the degree of participation of different cerebral structures and the patterns of their interaction at particular linguistic levels have not been sufficiently investigated.

The evolutional approach seems promising for analysis of these problems. Formation of the capacity for analysis of phonetic, lexical, and grammatical components of verbal activity apparently starts as early as the prenatal period [8], intensely develops in the first years of life, and reaches a definitive level only by the age of 12–16 years. However, whereas considerable attention has been paid to the initial steps of speech function formation in small children (see reviews [9–11]), the central mechanisms of speech at older ages have been studied to a lesser extent. However, the intercentral interactions necessary for the maintenance of more complex forms of speech activity, associated with improvement of the grammatical structure and semantic content of a verbal utterance and with gradual enrichment of the vocabulary, continue to develop at the preschool and primary school ages.

In this work, we attempted to reveal the age-specific characteristics of the formation of the central mechanisms of different linguistic levels (phonemic, grammatical, and semantic) in children of preschool and primary school age performing tasks of recognition of phonemes in words and grammatical and semantic mistakes in sentences.

METHODS

Two groups of children, five to six ($n = 15$) and eight to nine ($n = 17$) years of age, were examined by methods of multivariate EEG analysis in two series of observations. All of the tested children were right-handed. The results were compared with the results of examination of 18 adults at an age of 22–28 years.

The EEG was recorded by a 24-channel computer-based electroencephalograph with a bandwidth of 0.5–30 Hz, at a sampling frequency of 185 Hz in each channel. Twenty monopolar derivations were used, 16 of which were located according to the international 10–20 scheme symmetrically in the prefrontal (Fp_1, Fp_2), postfrontal (F_3, F_4), inferior frontal (F_7, F_8), central (C_3, C_4), middle temporal (T_3, T_4), posttemporal (T_5, T_6), parietal (P_3, P_4), and occipital (O_1, O_2) areas. For more detailed analysis of the role of the temporal areas in the speech function, four more electrodes were used: two electrodes in the frontotemporal areas of each hemisphere (T_1, T_2) and two electrodes in the *TPO* areas, i.e., the areas of overlap of the temporal, parietal, and occipital areas (TP_1, TP_2). Linked earlobe electrodes were used as a reference. The EEG was recorded continuously, both in the background state (quiet wakefulness with the eyes closed) and during the performance of the test tasks. The average time of observation was 30 min; the subjects were in a horizontal position in a soundproof darkened chamber.

The tasks given to children and adults were selected so as to ensure, in each test, preferential analysis of aspects of verbal utterance mainly associated with a specific linguistic level: phonemic, grammatical, or semantic.

1. Phonemic analysis consisted of recognition of a given sound in the context of auditory presented words. A series of words containing or not containing a certain sound was presented to a subject binaurally through earphones. The stimulus material was a set of singular nouns in the nominative case, balanced with respect to the sound–syllabic structure. The specified sound was located in different positions in the presented words. The subject was to press a button only if the specified sound was present in the word.

2. Recognition of grammatical mistakes in auditory presented sentences. Russian sentences containing or not containing a grammatical mistake (50 sentences in total, 30 of them containing a mistake) were presented binaurally through earphones in random order. The duration of each sentence varied within 4–6 s, with a 2-s interval between sentences; thus, the presentation of the whole series of sentences took 5–6 min. In the sentences containing a mistake, the following types of grammatical relations were distorted: (a) agreement errors: in personal endings of verbs (e.g., “Pod stolom sidel sobaka” (“A dog [masculine] sat [feminine] under the table”)) and in gender endings of adjectives (“Devochka nadela goluboe yubku” (“The girl put on a blue [neuter] skirt [feminine]”)); (b) mistakes of government: in declensional endings of nouns (“Ya prochital interesnuyu knizhkoy” (“I have read an interesting [accusative case] book [instrumental case])). On finding a mistake in an auditory presented sentence, the subject was to press the button with the right hand.

3. Recognition of semantic errors in auditory presented sentences. In this case, the presented sentences either contained or did not contain a semantic mistake (50 sentences in total, 30 of them containing a mistake). The duration of each sentence, as in the first case, varied within 4–6 s, with a 2-s interval between the sentences. Thus, the presentation of the whole series of sentences also took 5–6 min. The stimulus material contained the following types of semantic mistakes: (a) mistakes in constructions reflecting the time sequence of events (“Winter comes after spring”) and (b) constructions containing a semantic paradox (“A tortoise overtook a deer”). Semantically correct sentences alternated randomly with sentences containing a mistake. The subject was to press the button only if there was a mistake in the presented sentence.

The stimulus material was selected in accordance with the age of the subjects.

The results were processed by correlation and coherent analyses of a multichannel EEG.

Throughout the period of examination, matrices (20×20) of cross-correlation coefficients (CCs) between the EEG from all derivations by pairs (190 EEG CCs altogether) were calculated every 4 s (the analysis epoch).

The EEG coherence (Coh) matrices were also calculated for each analysis epoch in the main frequency bands: Δ, θ, α, and β. For this purpose, the following computing operations were performed successively for all pairs of the 20 EEG derivations: (a) autocovariance and cross-covariance EEG functions were calculated; (b) the corresponding values of autospectra and cross-spectrum were determined using the fast Fourier transformation after function smoothing, and the values of the Coh function were calculated in the frequency band 0.5–30.0 Hz at a step of 0.5 Hz; (c) the mean Coh values were determined within the main frequency bands of EEG oscillations (Hz): Δ, 0.5–3.5; θ, 4.0–7.5; α, 8.0–12.5; and β, 13.0–30.0; and (d) the obtained mean values of Coh for all pairs of EEG derivations were combined into Coh matrices (20×20). Thus, five matrices were calculated for each of the successive EEG analysis epochs: one cross-correlation matrix and four Coh matrices of the EEG. These algorithms were used for the processing of 30–60 EEG analysis epochs, containing no artifacts, in some of the subjects in the states under study (in the background state and during the performance of the test tasks). The duration of the analyzed EEG periods corresponding to a specific type of activity in each of the subjects varied from 2 to 4 min.

With special software using hierarchical agglomerative cluster analysis,[1], we excluded from further processing the CC matrices of the EEG that did not differ significantly from one another in the background state or during the tested activity. This method allowed us to avoid an effect of short-term changes in the uniformity of the functional state of a subject on the observation results.

Element-by-element values of the recorded correlation and coherent matrices of the multichannel EEG were averaged both within the studied functional states and over the group of subjects; the mean values and variances of EEG CC and Coh were calculated. Fisher's z transformation was used in all operations with the correlation and Coh coefficients.

The changes in distant EEG relations occurring during the performance of the test exercises were estimated by subtraction of element-by-element values in the CC and Coh matrices of the EEG, averaged for the background state of quiet wakefulness, from the values of each cell in the average CC and Coh matrices of the EEG corresponding to the test exercises. Thus, differential CC and Coh matrices of the EEG were formed, the elements of which reflected the changes in the spatial organization of the EEG during the performance of different tasks. The significance of CC and Coh changes in the EEG typical of the test tasks relative to the corresponding CC and Coh values of the EEG in the background state was assessed in each cell of the differential matrices using Student's t test ($p \leq 0.05$).

Statistically significant values of the differences between EEG CC and Coh in the background and tested states were used to construct schemes of changes in interregional relations using special software.[2]

The statistical similarity coefficients of the patterns of regional interactions of cortical bioelectric potentials recorded during the performance of different tasks were calculated for each age group. For this purpose, Pearson's correlation coefficient was used for gradual calculation of the statistical similarity coefficients between the averaged values of the CC matrices of the EEG in one of the tasks with the CC matrices of the EEG obtained in the study of the two other states.

RESULTS

To estimate the age-specific characteristics of the reorganization of the field of brain bioelectric potentials during the performance of verbal tasks by children, we compared the results obtained in children of both age groups with the data on adult subjects.

Phonemic analysis, i.e., recognition of a given sound in the context of auditory presented word, by adult subjects ($n = 18$) showed the involvement of many cortical areas of the left and right hemispheres (Fig. 1). As can be seen in Fig. 1 (Adults, CCs of the EEG), the CCs of the EEG as compared with the background state changed nearly everywhere towards an increase in interhemispheric interaction of bioelectric potentials of different cortical areas, particularly between temporal and frontal cortical areas and the *TPO* zones of the left and right hemispheres. At the same time, intensification of EEG relations of bilaterally symmetric areas, i.e., the inferior frontal (F_7–F_8), frontotemporal (T_1–T_2), middle temporal (T_3–T_4), and posttemporal (T_5–T_6) areas, was the most pronounced, along with an increase in the number of "diagonal" interactions of the activities of these and the prefrontal (Fp_1, Fp_2) areas, as well as the postfrontal (F_3, F_4) areas and *TPO* zones (TP_1, TP_2). A decrease was observed only for interhemispheric "diagonal" relations of the EEG of the inferior frontal areas of both hemispheres (F_7, F_8) with the EEG of the posttemporal areas (T_5, T_6), as well as between the bioelectric activity of the right *TPO* zone (TP_2) and the activity of the left inferior frontal area (F_7). It is important that the changes in intrahemispheric relations of the EEG in adult subjects during the performance of this task were insignificant.

The results of coherent EEG analysis showed that interhemispheric interactions during the performance of phonemic analysis by adult subjects intensify mainly in the slow-wave bands of EEG oscillation frequencies: Δ and θ (Fig. 1, Adults, Δ, θ). In the β- and α frequency bands, significant changes ($p = 0.05$) in interregional EEG relations were less expressed. It is noteworthy that coherent EEG interactions tended to decrease in the β band, particularly ipsilateral relations of the middle temporal area of the left hemisphere (T_3), while the relations of bioelectric potentials of the symmetric area of the right hemisphere (T_4), on the contrary, showed intensification of interactions with cortical areas of the left hemisphere (Fp_1, F_3, F_7, C_3, P_3). The strengthening of such a spatial structure of EEG relations of this area (T_4) with cortical areas of the left hemisphere may also be traced on the diagrams of changes in interregional relations in the α-, θ-, and Δ frequency bands (Fig. 1). Note that Wernicke's area (T_5) in adult subjects is characterized by intensification of contralateral rather than ipsilateral correlation and coherent relations of the EEG, particularly in the θ- and Δ bands.

During the performance of phonemic analysis (i.e., the task of recognition of a specified phoneme in auditory presented words) by children aged five to six and eight to nine years, the results of correlation analysis of the EEG (Fig. 1, CCs of the EEG) showed both similarity and some differences between the changes in the

[1] The procedure and software were developed by A.A. Pogosyan, Cand. Sci. (Biol.), a senior researcher at the Sechenov Institute of Evolutionary Physiology and Biochemistry of the Russian Academy of Sciences.

[2] The software was developed by V.P. Rozhkov, a senior researcher at the Sechenov Institute of Evolutionary Physiology and Biochemistry of the Russian Academy of Sciences.

spatial structure of interregional interaction of bioelectric potentials as compared with the results obtained in adults.

The similarity was intensification of mainly interhemispheric interactions with little change in the ipsilateral relations of the EEG; in addition, intensification of distant EEG relations between temporal areas of the cortex of both hemispheres (T_1, T_2, T_3, T_4, T_5, T_6), particularly bilaterally symmetric areas, was shown in the children, and intensification of interhemispheric EEG relations of the *TPO* zones (TP_1, TP_2) was shown in the five- to six-year-old children.

The differences were as follows: The children of both age groups showed a much less explicit participation of anterior areas of the cortex, especially the five- to six-year-olds (as estimated by both cross-correlation and coherent EEG analysis). In addition, the five- to six-year-olds were characterized by a greater involvement of the posterior areas of the cortex.

The coherent EEG analysis showed that children of both groups during the recognition of phonemes in words showed a significant decrease (as compared with the background state) of ipsilateral interactions of the inferior frontal and temporal areas and the *TPO* zones in both hemispheres (Fig. 1). The lower level of intrahemispheric relations of the EEG of these areas was particularly pronounced in the α band and to a slightly lesser degree in the β band. In the Δ- and θ bands, the decrease in ipsilateral EEG relations was typical mostly of the five- to six-year-old children, particularly for EEG relations of the frontal and temporal areas of the left hemisphere. In the children of this age group, intensification of the coherent interactions of bioelectric potential fluctuations in all frequency bands was observed mainly for interhemispheric EEG relations of the posterior areas of the cortex. In the anterior areas of both hemispheres, there was almost no intensification of the coherent EEG relations. Still greater intensification of the coherent relations of bioelectric potential fluctuations in the anterior areas of the cortex was observed in all frequency bands in the eight- to nine-year-old children during the performance of phonemic analysis. This fact indicates that the spatial structure of the changes in coherent EEG relations is more similar in the children of primary school age and in adults in this task as compared with the children of preschool age.

Thus, the maturity of systemic interaction of cortical structures responsible for cerebral mechanisms of the phonemic linguistic level seems already to approach the definitive level in children.

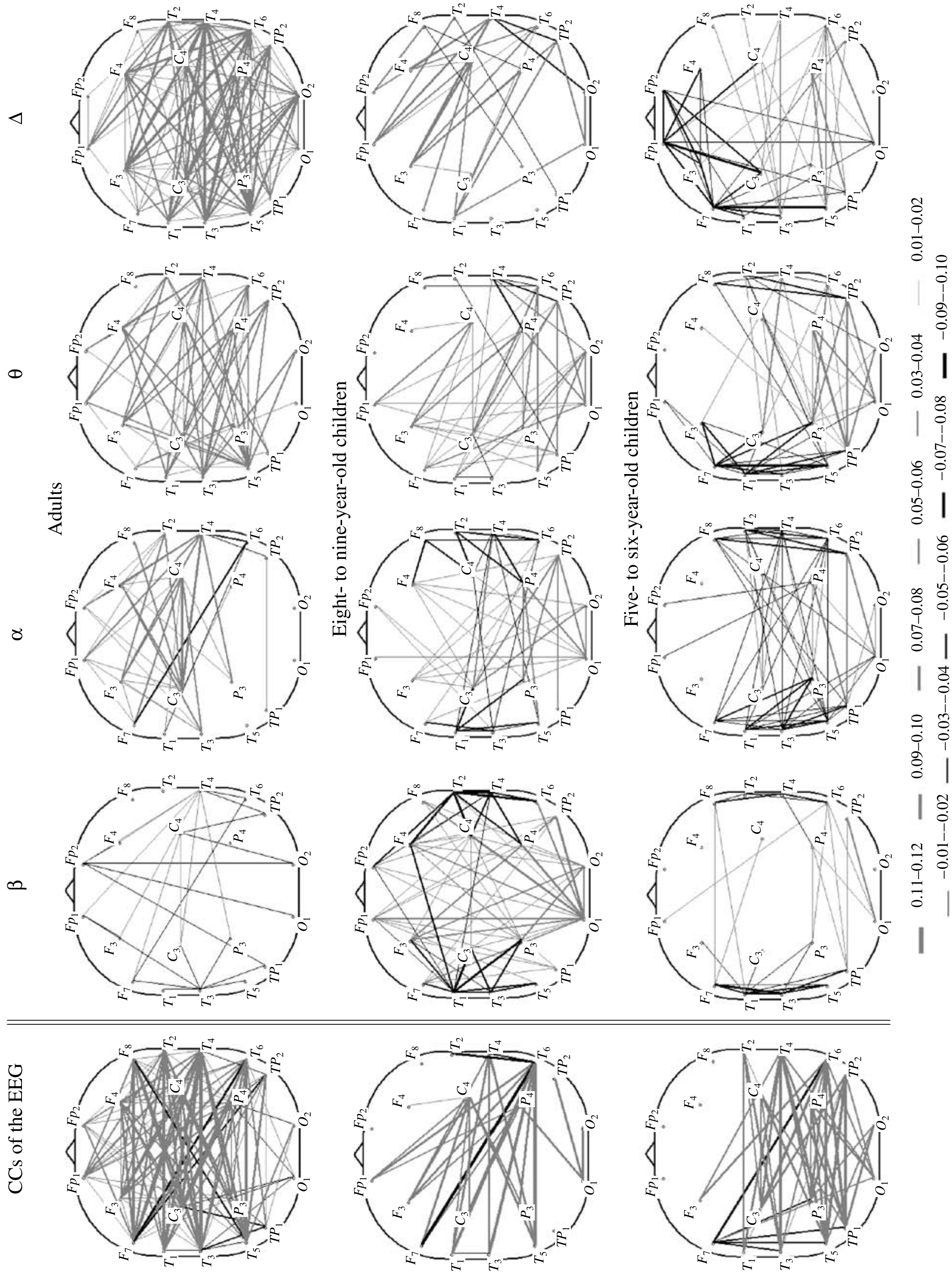
The test for recognition of grammatical mistakes in auditory presented sentences performed by adult subjects showed predominant intensification of interhemispheric interaction of neocortex bioelectric potentials (Fig. 2, Adults, CCs of the EEG), as was the case with phonemic analysis. However, a somewhat higher intensification of interregional relations of bioelectric potentials during the performance of this task was typical of the posttemporal area of the cortex (T_5, Wernicke's area). Intensification of EEG relations was also observed in other temporal areas of the left and right hemispheres, area F_7 (Broca's center), and the *TPO* zones; the enhancement of the relations of the activity of these zones with cortical areas of the contralateral hemisphere was the greatest. Intensification of interhemispheric bilaterally symmetric and "diagonal" relations of the EEG during recognition of grammatical mistakes in sentences by adult subjects was demonstrated previously [12].

Coherent analysis of the EEG showed a high similarity of the changes in the spatial organization of brain bioelectric potentials during these two tasks, but certain differences were found as well. During the recognition of grammatical mistakes, a more pronounced intensification of interhemispheric relations of the EEG of the *TPO* zones and the occipital areas of both hemispheres was observed in the θ frequency band, intensification of the EEG relations of the temporal areas of the left hemisphere was more marked in the α band, and the β band was characterized by less intense ipsilateral relations of the EEG of temporal areas of the right but not the left hemisphere.

In accordance with the results of correlation analysis of the EEG, intensification of interhemispheric interactions of the bioelectric potentials of the temporal areas of both hemispheres was found in the children aged five to six and eight to nine years (Fig. 2) during the performance of the task of recognition of grammatical mistakes, but it was less pronounced than in adults. However, the changes in EEG interconnections within each hemisphere in adults were insignificant, whereas the changes in intrahemispheric EEG connections in children on recognition of grammatical mistakes were clearly marked, both towards an increase and towards a decrease. A decrease, as compared with the background state, of intrahemispheric EEG relations was most typical of the five- to six-year-old children, particularly in the left hemisphere (Fig. 2, Five- to six-year old children, CCs of the EEG).

The eight- to nine-year-old children, as compared with the children of preschool age, during performance of this test showed greater intensification of both intra- and interhemispheric regional interactions of the activities of frontal areas, whereas the maximum intensification of interhemispheric interaction in the five- to six-year-old children was typical of the posterior areas of both hemispheres.

Analysis of coherent EEG relations in the five- to six-year-old children (Fig. 2) showed the highest similarity with the results of correlation analysis in the θ band. This was evidenced by intensification of regional interactions of bioelectric potentials of the posterior areas of the cortex, particularly interhemispheric relations of the EEG of the posttemporal, occipital, and parietal areas, as well as the *TPO* zones. At the


CCs of the EEG
β
α
θ
Δ
Adults
Eight- to nine-year-old children
Five- to six-year-old children
0.11–0.12
0.09–0.10
0.07–0.08
0.05–0.06
0.03–0.04
0.01–0.02
–0.01–-0.02
–0.03–-0.04
–0.05–-0.06
–0.07–-0.08
–0.09–-0.10

same time, a decrease in the level of coherent EEG relations was also observed in the θ band, particularly of the EEG for the relations of the inferior frontal and the anterior and middle temporal areas of the left hemisphere. These changes were similar to the changes in EEG Coh observed in the θ band during the performance of phonemic analysis by the five- to six-year-old children. Similar changes in coherent EEG relations were also observed in the Δ band. In turn, a decrease in intrahemispheric coherent EEG relations in the β band was typical of ipsilateral EEG relations of the inferior frontal and temporal areas of both hemispheres. The θ- and Δ bands of the children of this age group, like those of adults, were characterized by intensification of the interaction of the activity of Wernicke's area with many areas of the contralateral hemisphere. In contrast to adults, intensification of systemic interaction between the fluctuations of bioelectric potentials of bilaterally symmetric areas of the cortex of both hemispheres was observed only for posttemporal and central areas in the Δ band and for central areas and the *TPO* zones in the θ band.

According to the results of coherent EEG analysis (mainly in the θ- and Δ bands), the eight- to nine-year-old children, as compared with the five- to six-year-olds, showed a higher similarity with the results obtained for the group of adult subjects (Fig. 2). This suggests that the systemic organization of interregional interaction of bioelectric potentials observed in children of this group during recognition of grammatical mistakes reflects a higher level of maturity than in the five- to six-year-old children. In contrast to the five- to six-year-old children, the eight- to nine-year-olds showed greater participation of the anterior areas of the cortex. However, both preschool children and young schoolchildren were characterized by less intense, relative to the background, intrahemispheric coherent relations of bioelectric potentials of the temporal areas of both hemispheres (the right one to a greater extent in eight- to nine-year-old children), especially in the β band (Fig. 2).

Recognition of semantic mistakes in sentences. Performance of this test by adult subjects, like the performance of the two previous analytical verbal tasks, was accompanied by intensification of interhemispheric EEG relations of the temporal and frontal areas (Fig. 3). In turn, intensification of intrahemispheric interactions during this test was also insignificant. It should be noted, however, that the spatial structure of the changes in interhemispheric EEG relations of the frontal areas (particularly Fp_1, F_3, Fp_2, and F_4) during this test showed a much higher similarity to the structure of CC and Coh changes in the EEG during recognition of phonemes in words than during recognition of grammatical mistakes in sentences. In addition, the changes in relations between fluctuations of bioelectric potentials of the F_7 area (Broca's center) with many other areas of the cortex, mainly of the contralateral hemisphere, were more pronounced during recognition of semantic mistakes and phonemes in words. Along with the similarity, certain differences were found. During recognition of semantic mistakes, the activation of interhemispheric relations of the *TPO* zones was lower as compared with the two other tasks (particularly as shown by the data of EEG correlation analysis, Fig. 3). Intensification of relations of the activities of bilaterally symmetric areas of both hemispheres was also somewhat less marked. The intensification of correlation relations of the EEG was less marked in the T_5 area (Wernicke's area) as well.

During the performance of the task of recognition of semantic mistakes in sentences by children aged five to six and eight to nine years, according to the results of both the correlation and coherent EEG analyses, the interhemispheric interactions of cortex bioelectric potentials intensified to a lesser extent as compared with adults (Fig. 3). Five- to six-year-old children, in addition, showed a marked decrease (as compared with the background state) in ipsilateral EEG interconnections of the temporal areas of the cortex and inferior frontal area of the left hemisphere, particularly in the Δ frequency band. The group of eight- to nine-year-old children, in contrast to the younger group, was characterized during this test by a somewhat more intense distant interaction of the activity of the frontal areas. This was mainly demonstrated by intensification of coherent EEG relations in the α- and β frequency bands. At the same time, in the θ- and Δ bands of the children of this age group, the intensity of coherent relations of the EEG in the anterior areas of the cortex was much lower than in adults.

As a whole, the results show that there were three most characteristic differences of five- to six-year-old children from eight- to nine-year-olds in all of the studied types of speech tests. First, according to the results of both the correlation and coherent EEG analyses, they showed a greater decrease (relative to the state of quiet wakefulness) in intrahemispheric interactions of the temporal areas, particularly in the left hemisphere. Second, a greater involvement of the posterior areas of the

Fig. 1. Changes in the spatial structure of regional interactions of cortex bioelectric potentials during performance of the task of recognition of phonemes in auditory presented words by adults and children aged five to six and eight to nine years. On the left, a diagram of changes in the spatial structure of cross-correlations (CCs) of the EEG. On the right, diagrams of changes in coherent relations of bioelectric potential fluctuations in the main frequency bands (β, α, θ, and Δ). The diagrams show significant changes in cross-correlation and coherent relations of the EEG as compared with the data on the background state, $p = 0.05$. Gray lines correspond to enhancement of these relations and black lines, to their attenuation, in accordance with the scale at the bottom of the figure.

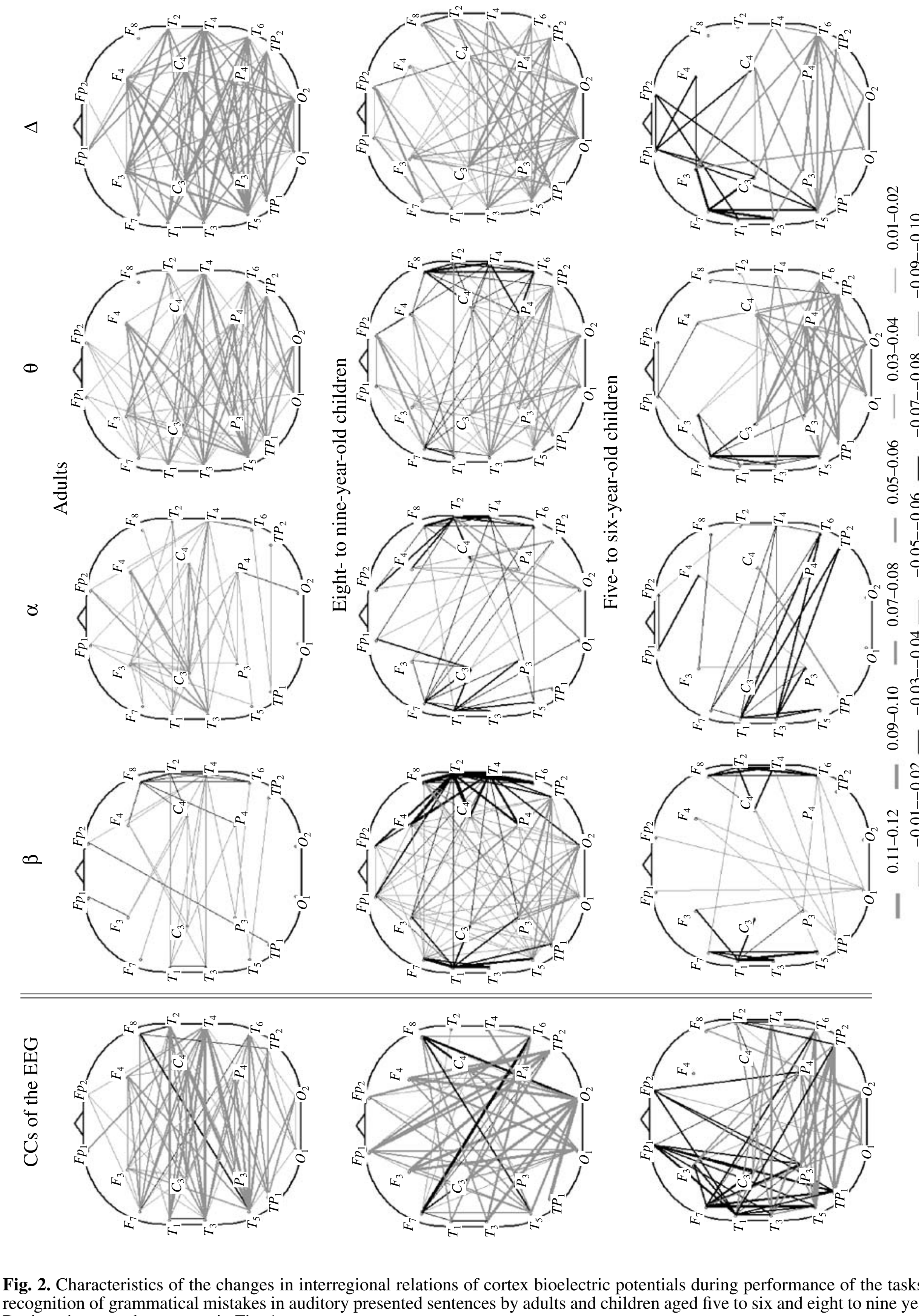


Fig. 2. Characteristics of the changes in interregional relations of cortex bioelectric potentials during performance of the tasks of recognition of grammatical mistakes in auditory presented sentences by adults and children aged five to six and eight to nine years. Designations are the same as in Fig. 1.

cortex of both hemispheres was observed in children of preschool age. Third, preschool children exhibited lesser participation of the frontal areas of the cortex during the performance of verbal tasks.

Thus, children of preschool and primary school ages display features of immaturity of neurophysiological mechanisms of the speech function, including grammatical formation of a verbal utterance and the semantic content of a phrase. At the same time, the results of the test for recognition of phonemes in words evidence the relatively earlier formation of neurophysiological mechanisms responsible for the maintenance of the phonemic linguistic level in the course of ontogeny.

DISCUSSION

Our studies have shown that the speech activity of adults and children, which requires selective attention to the characteristics of a verbal utterance largely associated with a specific linguistic level (phonemic, syntactic, or semantic), is accompanied by coordinated interaction of the cortical areas of both cerebral hemispheres. In accordance with the results of research on the central organization of speech obtained by modern methods of neurovisualization, this specifically human function involves many areas of the cerebral cortex [3, 13–17]. However, there are many fewer published data on simultaneous, joint participation of both hemispheres in speech perception and speech production [4, 5, 13, 18–20].

Studies performed in our laboratory showed that, in all cases of the performance of various verbal tasks (listening to and mentally reproducing a poem, mental calculation, tasks of verbal fluency, searching for homonyms, synthesizing words from phonemes and sentences from words), activation of distant relations of bioelectric potentials of the cortex of the left and right hemispheres, both intra- and interhemispheric, was observed [12, 21–26].

In this study, the contribution of both hemispheres to the performance of analytical speech tasks related to recognition of phonemes in words and mistakes in sentences was demonstrated by significant intensification of interhemispheric interactions of bioelectric potentials (especially distant relations of the EEG of the inferior frontal and temporal areas of the cortex of both hemispheres) with a relatively slight intensification of intrahemispheric relations. The changes in the level of intrahemispheric EEG relations were demonstrated to a slightly greater extent by coherent EEG analysis than by cross-correlation analysis (Figs. 1–3).

The results show relative immaturity of neurophysiological mechanisms of maintenance of various linguistic levels in children. This was evidenced, in children of both age groups, by lesser involvement of the frontal areas of both hemispheres as compared to adults. In addition, children aged five to six and eight to nine years, during the performance of the tasks of recognition of phonemes in words and grammatical and semantic mistakes in sentences, exhibited a significant decrease in coherent EEG relations of the temporal areas of the cortex and a somewhat lesser decrease in those of the inferior frontal areas, in both the left and the right hemispheres. In children of both groups, this decrease in the level of coherent EEG relations was mainly observed in the β band. Five- to six-year-old children showed a decrease in the Δ frequency band of distant EEG relations of the frontal areas of both hemispheres, particularly the left, in all three tests.

In the course of a child's brain development, the involvement of each hemisphere in verbal and closely related mental activities significantly changes. The internal structure of the central organization of higher mental functions is rearranged with age because these functions are formed on the background of intense but irregular development of cortical areas, deep cerebral structures, and connections between them. This results in changes in the cerebral organization of intercentral relations and, consequently, changes in the system of dominant functional relations both within each hemisphere and between hemispheres because any behavioral function (in our case, solution of a verbal task) is ensured by a constellation of many spatially remote structures.

The results of our studies allow us to believe that the neurophysiological mechanisms underlying phonemic analysis in children of preschool and primary school ages are characterized by a relatively higher level of maturation as compared to the central mechanisms of different aspects of the speech function, including syntactic and semantic processing of a verbal utterance. The data of linguistic [27, 28] and speech therapy [29] studies of children's speech are also evidence for earlier development of the phonetic system of language. At an age of five to six years, a child correctly articulates all phonemes of the mother tongue and can differentiate them from each other, whereas the formation of the syntactic and semantic levels still continues at older ages [28].

Our research has revealed the characteristics typical of children of preschool age, as compared with children of primary school age, during the performance of all three verbal tasks. Greater participation of the frontal cortical areas was shown in eight- to nine-year-old children as compared to five- to six-year-olds during the performance of the verbal tasks under study.

The above is in agreement with numerous literature data on an increase in the functional specialization of the frontal areas of the cortex at this age and their more important role in cognition [30]. The priorities of the forms of activation during purpose-oriented activity also change in this age period (corticalization of attention and an increase in the role of frontal areas in the control of activation processes [31]), and the role of thalamocortical modulating effects increases [32]. According to Semenova et al. [33], the cytoarchitecture

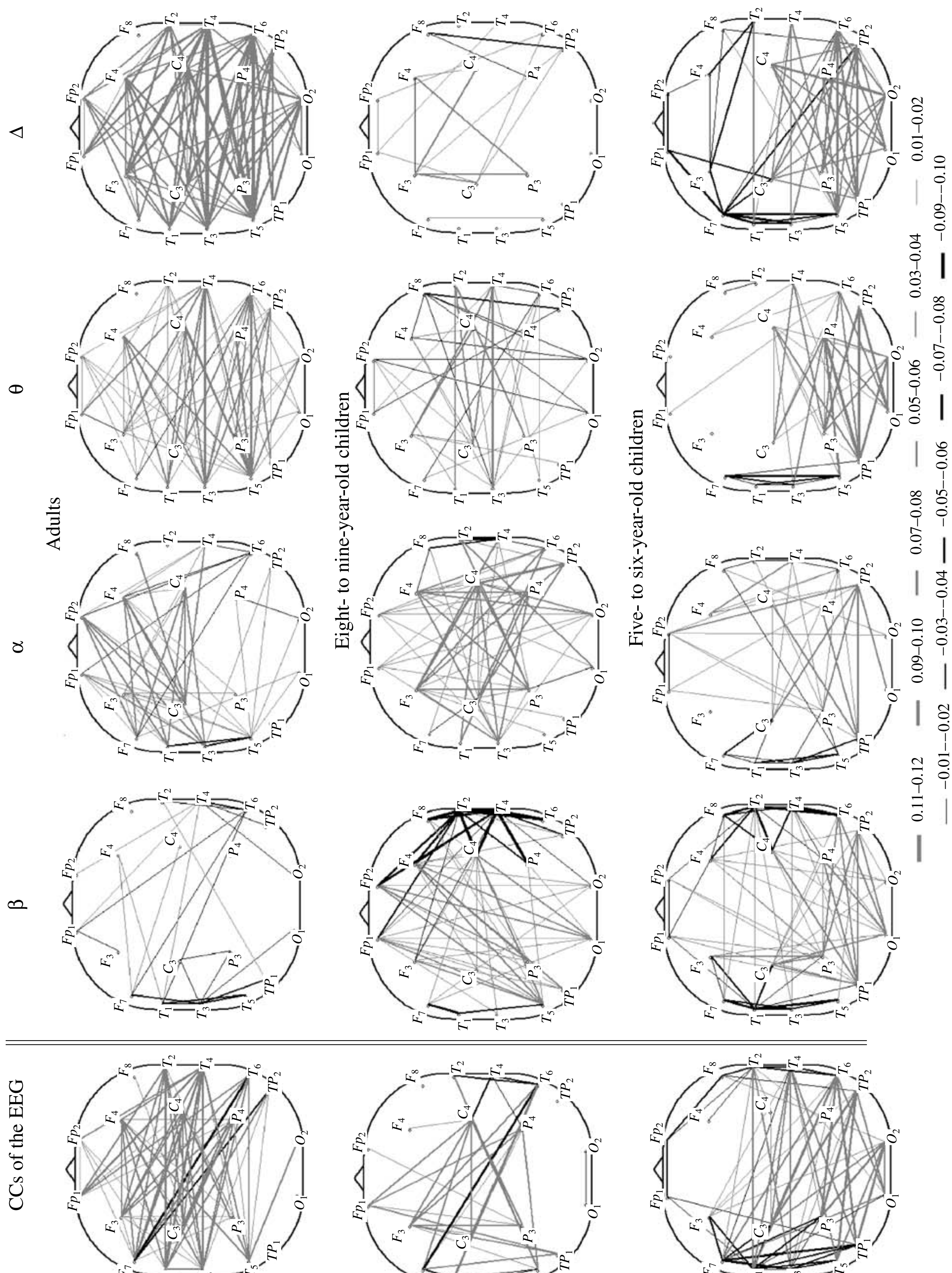


Fig. 3. Changes in the spatial structure of interregional relations of the EEG during performance of the tasks of recognition of semantic mistakes in auditory presented sentences by adults and children aged five to six and eight to nine years. Designations are the same as in Fig. 1.

of cortical fields in the frontal areas becomes significantly more complicated and the network of axon collaterals of cortical interneurons expands by the age of nine to ten years.

Some distant EEG relations were shown to decrease relative to the background state in the children aged five to six and eight to nine years during the performance of all three verbal tasks, in contrast to the adult subjects. This was particularly typical of intrahemispheric relations of bioelectric potentials of the temporal areas of both hemispheres. However, there were also some age-related differences in these cases. A decrease in intrahemispheric EEG relations of the temporal areas in the five- to six-year-old children was evidenced by both the results of EEG cross-correlation analysis and coherence analysis in all frequency bands. In eight- to nine-year-old children, on the contrary, this decrease was smaller, particularly in the case of correlation analysis, and mainly concerned the β- and α bands in the case of coherent EEG analysis.

The analysis of previous studies on age-related differences in the central organization of speech functions performed in our laboratory showed that the performance of verbal–mnestic tasks (mental calculation, listening to a poem, its memorization, and its subsequent mental reproduction) in children of different age groups (five to six, seven to eight, and nine to ten years of age) is characterized by selective intensification of distant statistical interactions of the EEGs of the posttemporal and parietal areas of the left hemisphere with the frontal and frontotemporal areas of both hemispheres [21, 24, 25]. This evidences joint activity of many cortical areas of the left and right hemispheres during verbal–mental activity, with the predominant involvement of Wernicke's area. At the same time, children, as compared with adults, more often showed an additional intensification of distant relations of bioelectric potentials of Broca's center, probably due to the activation of expressive speech, even during passive listening to verbal material.

Active participation of the sensory speech (Wernicke's) center in all three types of tasks (especially distinct in the results of EEG correlation analysis), which was also observed in this work, is evidence for a significant contribution of this cortical area to verbal activity not only at the phonological level, but also at the syntactic and semantic levels [1, 3].

Quantitative comparison of the patterns of spatial interactions of cortex bioelectric potentials observed during the performance of tasks connected with the analysis of verbal material at different linguistic levels shows a high degree of statistical similarity (table). The statistical similarity coefficients between the patterns of interregional interaction of potentials typical of different tasks exceeded 0.70 in all cases, both in children and in adults.

However, it should be noted that, in spite of rather high similarity coefficient values for the patterns of interregional interaction of potentials corresponding to different tasks, they were below 0.90 in all cases (table). This is evidence for a significant effect of the specific features of the verbal task on the degree of involvement of individual cortical areas interacting during the performance of a given task.

The tasks were selected in such a way that each particular task entailed preferential analysis of those aspects of a speech utterance mainly belonging to a specific linguistic level. For example, the cross-correlation analysis of the EEG in adults showed much greater involvement of prefrontal areas of both hemispheres in the recognition of phonemes in words and semantic mistakes in sentences than in the recognition of grammatical mistakes (Figs. 1–3).

Regarding the data presented in the table, it should be noted that particularly similar changes in the spatial structure of interactions of cortical areas (as compared with the background state) were found when we compared the results obtained during recognition by subjects of semantic mistakes in sentences and during recognition of phonemes in words. Such a high coefficient of similarity of the spatiotemporal organization of the EEG during phonemic analysis and during recognition of semantic mistakes by subjects of all three age groups (up to 0.85–0.87) is probably due to the fact that phonemes also have a distinctive function, which makes it possible to differentiate between similar-sounding words. For example, a change in one phoneme may completely change the meaning of a word.

Problems connected with the two basic concepts of language architecture and its possible cerebral organization are a topic of heated debate among neurolinguists [5, 6]. The concept of a modular approach is based on the assumption that linguistic levels are represented in the brain by relatively independent generative systems connected with one another by interfaces [34]. The other concept is based on the notion of a decisive role of associative memory at different linguistic levels, which requires differential participation of the entire neural network.

The approach based on the idea that brain activity is rooted in continuous interactions of various cortical and subcortical areas interconnected by the gradient principle deserves particular attention. Such a system can maintain highly complicated processes, and transition from one constellation of relations to another is characterized by a dynamic topology [35].

Analysis of our results shows that they may cast doubt on the concept of the modular principle of organization of the central mechanisms of different linguistic levels in the brain. These data suggest that the existence of different linguistic levels and their distributive central mechanisms are based on topologically close constellations of interacting cortical areas and on relatively similar organization of their regional interactions. Our findings also suggest that the observed relationships between the spatial organizations of cortical

Statistical similarity coefficients between the patterns of changes in regional interactions of cortex bioelectric potentials during the performance by children and adults of the verbal tasks connected with particular linguistic levels

Compared groups	Similarity coefficients between					
	GR and SM		GR and PA		SM and PA	
Adults	0.73	+ 0.061 – 0.075	0.76	+ 0.055 – 0.068	0.87	+ 0.031 – 0.040
Eight- to nine-year-old children	0.74	+ 0.059 – 0.072	0.75	+ 0.057 – 0.070	0.86	+ 0.033 – 0.042
Five- to six-year-old children	0.80	+ 0.046 – 0.058	0.78	+ 0.050 – 0.063	0.85	+ 0.035 – 0.045

Notes: GR, recognition of grammatical mistakes in auditory presented sentences; SM, recognition of semantic mistakes in sentences; PA, recognition of phonemes in auditory presented words. Confidence intervals of the mean similarity coefficients for $p = 0.05$ are indicated.

mechanisms of different linguistic levels are present not only in adults, but also in children of primary school and even preschool age.

CONCLUSIONS

(1) Performance by adults and children of verbal tasks that require increased attention to aspects of a speech utterance largely related to a specific linguistic level (phonemic, syntactic, or semantic) is ensured by coordinated activity of both cerebral hemispheres with a marked intensification of interhemispheric interactions, particularly of the inferior frontal and temporal areas.

(2) The findings suggest that the relative immaturity of neurophysiological mechanisms of different linguistic levels in children of both age groups studied, especially the younger ones, is expressed in a lesser involvement of the frontal areas of both hemispheres as compared with adult subjects and in a partial decrease (relative to the background state) in intrahemispheric relations of bioelectric potentials of the temporal areas of the cortex of both hemispheres.

(3) In children of both preschool and primary school ages, the neurophysiological mechanisms underlying phonemic analysis are characterized by a relatively higher maturity as compared with the central mechanisms of other aspects of the speech function, namely, grammatical processing of a verbal utterance and the semantic content of a phrase.

(4) Although the specific character of the performed verbal tasks is demonstrated by the peculiarities of the spatial organization of interregional interaction of bioelectric potentials of different cortical areas, the results show that the central mechanisms of different linguistic levels depend on topologically close constellations of interacting cortical areas. Evidently, these data support the criticism of the concepts assuming a modular principle of organization of the central mechanisms of different linguistic levels in the brain.

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