Neurophysiology, Vol. 44, No. 6, December, 2012

Ontogenetic Modifications of Evoked EEG Activity in 6- to 16-Year-Old Children and Teenagers

T. A. Aliyeva,[1] E. V. Éismont,[1] and V. B. Pavlenko[1]

Received June 30, 2012.

We studied peculiarities of the age-related dynamics of amplitude/time characteristics of evoked EEG potentials (EPs) and event-related potentials (ERPs) recorded within the framework of the go/no go paradigm in 6- to 16-year-old children and teenagers. We found a number of significant correlations between age of the tested persons and characteristics of EPs and ERPs. With age, latencies of the components P1 (in the frontal and central regions), N1 (practically throughout the head surface), P2 (in the frontal, temporal, and central leads of the left hemisphere, as well as in the temporal and occipital leads of the right hemisphere), and wave P300 (in the central regions of both hemispheres) demonstrated clear trends toward shortening. On the whole, the amplitudes of P2 (in the frontal, central, and parietal regions of both hemispheres and in the right temporal region), N1-P2 (in the frontal, central, and parietal regions), and contingent negative variation (in the left central lead) increased with age; we also observed a decrease in the amplitude of the N2 component, which reached a significant value in the left occipital lead. In addition, the working efficiency increased, which was manifested in decreases in the mean delay of the sensorimotor reaction, number of errors of omission of significant stimuli, and number of erroneous pushes. Therefore, the amplitude/time characteristics of some components of EPs and ERPs in 6- to 16-year-old children and teenagers demonstrate obvious age-dependent modifications; these shifts reflect the processes of maturation of the brain and formation of cognitive functions.

Keywords: evoked potentials (EPs), P300 wave, contingent negative variation (CNV), ontogenetic changes, go/no go paradigm, children.

INTRODUCTION

Identification of peculiarities of the formation of the pattern of EEG potentials in ontogenesis in humans is an extremely urgent aspect of electroencephalographic studies, since the characteristics of this electrical activity correlate, to a significant extent, with the realization of cognitive processes and the efficacy of realized activity. Thus, these indices reflect the level of adequacy of the processes of maturation of the brain. In some studies [1-5], it was demonstrated that the parameters of evoked and event-related potentials (EPs and ERPs, respectively) are closely related to the characteristics of attention, memory, and some cognitive processes, as well as to the level of anxiety of the individual. It is believed that the most informative, from the aspect of evaluation of the peculiarities of information processing at the level of higher CNS parts, are the contingent negative variation (CNV) and P300 potential. On the basis of parameters of these potentials, some researchers constructed the so-called aging curves [6]. The data, which were accumulated in the course of studies of functional meaning of other mid- and long-latency EP components and their changes depending on different factors, are, to a great extent, fragmented and contradictory. In the literature, there is at present no common opinion on the age-related changes in the amplitude/time EP parameters in humans. In addition, the development of the EP and ERP components within each ontogenetic period is subordinated to dissimilar regularities [6, 7].

An opinion that the child's brain electrical activity (that is gradually formed) reaches on the whole a general pattern typical of adults at the beginning of the pubertal period prevailed for years, but at present this viewpoint is subjected to criticism. The data of modern studies show that age-related modifications of electrical cerebral activity are realized during the entire period from birth to adolescence, while the individually specific pattern of EEG potentials is

[1] Vernadskii Tavricheskii National University, Simferopol', Autonomic Republic of Crimea, Ukraine.
Correspondence should be addressed to
T. A. Aliyeva (e-mail: chadess@mail.ru),
E. V. Éismont (e-mail: jema07@mail.ru), or
V. B. Pavlenko (e-mail: pavlenkovb@crimea.edu).

0090-2977/12/4406-0479

formed only at 15-18 years [8]. These processes are, first of all, due to the development of the cerebral cortex; environmental influences, however, also contribute significantly to the individual specificity of the formation of EPs. From this aspect, school age is critical, since not only a significant volume of knowledge is accumulated within the above time interval, but also the processes of synthesis and analysis of information are intensely realized, and cognitive functions, such as memory and selective attention, are intensely developed [9]. Nevertheless, it is often necessary to estimate the rate of development of the above-mentioned functions in order to obtain adequate information on ranges of some pathological or borderline mental states, such as the attention deficit/hyperactivity disorder, increased anxiety, etc. There are natural difficulties in estimation of the psychophysiological state of children and teenagers because the question of reference values of objective correlates of the mental phenomena in these persons (in particular, of EP characteristics) remains open. In addition, if we take into account that the techniques of EP recording are rather different, the problem of selection of a paradigm providing most adequate estimation of the state of the cognitive sphere of examined subjects is very important.

It is obvious that relatively simple tasks do not mobilize to the full the brain resources involved in information processing. This is why using such tasks is insufficient in studies of the process of development of higher mental functions. According to some reports [5, 10-12], the performance of the go/no go test with simultaneous recording of EPs allows researchers to relatively specifically estimate the level of development of memory and voluntary attention, as well to diagnose different neuromental disorders. Therefore, the go/no go test can be considered a situation that requires the involvement of a significant part of the brain cognitive resources.

Taking into account the above information, we examined the age-related dynamics of the characteristics of EPs recorded within the framework of the go/no go paradigm in 6- to 16-year-old schoolchildren.

METHODS

We examined 110 reasonably healthy school-age children and teenagers (6 to 16 years old). Among them, nine persons were sinistrals, while the others were dextrals. Since the number of left-handed children was relatively small, we considered the parameters of EPs and ERPs in left-handers together with the corresponding indices in other children.

Evoked potentials and ERPs were recorded according to the two-stimulus go/no go paradigm. Thirty pairs of stimuli were presented to the tested persons. These pairs included tone segments of different frequencies with 2-sec-long intrapair and 4-sec-long interpair intervals. Pairs of acoustic stimuli were presented randomly with the same (near 50%) probability of presentation of high and low tones. The task proposed to the subjects was to push the button by the finger of the leading hand to presentation of the second stimulus in the pair consisting of two tone segments of the same frequency, either high or low. The duration of the above audiomotor reaction should not exceed a standard value. At the same time, the tested children were asked to realize no reactions to pairs of segments of different tones. The initial standard time was fixed (500 msec for 6- to 9-year-old children and 380 msec for 10- to 16-year-old persons). Later on (after recording of the first and subsequent reactions of the subject), the standard time was calculated as the median of the distribution of all latencies of the sensorimotor reaction at this given moment. Therefore, the standard time was individual (calculated separately for each person and changed in the course of the task performance). After each pushing of the button, the calculated value of the standard reaction time was compared with the actual value of this time demonstrated by the subject. If this value was smaller than the standard value or equal to it, the task was considered successfully performed; if not, the performance was considered unsuccessful. Explanation of such approach for estimation of the standard latency of the sensorimotor reaction was described earlier [5].

The tested subject received a visual feedback signal informing him/her about the successful/unsuccessful performance of the proposed task; a vertical or horizontal bar was presented on the light display, respectively.

Recording of EPs and ERPs was performed according to a generally accepted technique; an automated complex consisting of an electroencephalograph, a laboratory interface, and a PC was used. As working software, we used ERP-2 (programmer V. V. Arbatov). EEG potentials were recorded monopolarly in leads F3, F4, T3, T4, C3, C4, P3, P4, O1, and O2 according to the 10-20 international system. Interconnected contacts above the mastoid processes served as a reference electrode. To record the CNV (parallel recording from C3 and C4 leads), we used two modified additional EEG channels with a broader amplifier bandwidth.

Waves P1, N1, P2, N1-P2 (vertex potential), and N2 (considered long-latency components of exogenous auditory EPs) were recorded after presentation of all warning (first in the pair) signals (bandwidth from 0.53 to 70 Hz). The P300 potential was recorded after presentation of visual feedback signals (with the same amplifier bandwidth). The CNVs appearing within time intervals between presentations of two stimuli (warning and imperative ones) and reflecting the processes of preparation for a behavioral act were recorded using the amplifier bandwidth from 0.016 to 70 Hz. The maxima of the analyzed EP components corresponded to the following time intervals: P1, 50-100 msec, N1, 100-150 msec, P2, 150-250 msec, N2, 200-300 msec, and P300, 250-500 msec after presentation of the stimuli. Time intervals between the beginning of presentation of a tonal stimulus and the peak amplitude of the corresponding EP component were considered the latencies of the analyzed components. The amplitudes of the integral CNV (CNV_i), an orientation component of the latter (CNV_o), and its terminal component (CNV_t) were measured within intervals from 300 to 2000 msec, from 300 to 1000 msec, and from 1000 to 2000 msec, respectively.

Other details of recording and measurement of the characteristics of EPs and ERPs were described earlier [10].

For each tested subject, we measured the mean time of the reaction. In addition, we estimated the correctness of performance of the two-stimulus test calculating the number of errors of omission of significant stimulus pairs ("low–low" or "high–high"), i.e., mistakes made through lack of attention, and also the number of "erroneous" pushes (incorrect reactions) to presentation of insignificant stimulus pairs ("low–high" or "high–low"), i.e., errors related to impulsiveness.

The data of EEG studies were quantitatively processed using standard techniques for variation statistics. Correspondence of the obtained data to the Gaussian law was estimated by the Kolmogorov–Smirnov criterion. In the course of analysis of the dependence of the EP pattern on age of the children, we used the Spearman (range) correlation coefficient. For N1, N2, and CNV, the most negative deviations of the potential were considered maxima of the amplitude. The age of the tested subjects in months was taken into account. We also analyzed age-dependent changes in the values of the mean reaction times, numbers of erroneous pushes, and errors of omission of significant stimuli.

RESULTS AND DISCUSSION

Correlation analysis of the obtained data showed that there are significant interdependences between the EP characteristics and age. As the children matured, the EP latencies, in particular those of P1 (in leads F3, F4, C3, and C4, $P < 0.05$), N1 (in leads F3, F4, T3, T4, C3, C4, P3, and P4, $P < 0.05$), and P2 (in leads F3, T3, T4, C3, and O2, $P < 0.05$), decreased. Diagrams of the correlation coefficients for values of the age and EP latencies are shown in Fig. 1. As can be seen in this figure, a maximum number of significant correlations was observed for the latencies of the N1 component. Examples of the correlation fields, which reflect negative dependences between these indices, are shown in Fig. 2. Decreases in the latencies in 6- to 16-year-old children are, obviously, due, first of all, to cyto- and fibroarchitectonic modifications in the cerebral cortex realized within this age period (gradual increase in the number of nerve fibers and complication of the system of intracortical relations), which constitute the morphological basis of the improvement of cognitive functions [13].

It is believed that the latencies of the P1 and N1 potentials correlate with the level of selective attention [14, 15]; the characteristics of the P1 potential are considered to be related to suppression of insignificant signals and intensification of perception realized in the case of attracting attention to the stimulus, while the parameters of N1 are related to the level of selective attention to the main characteristics of this stimulus and their recognition [16].

As was noted above, the latency of P2 in most leads decreased with age. At the same time, the latency of this component in the right occipital lead demonstrated, *vice versa*, an age-dependent trend toward increase ($r = 0.197$, $P < 0.05$). The latency values of the N2 component positively correlated with age of the children; such a dependence reached a significant value in the right temporal lead ($r = 0.263$, $P = 0.006$). It is obvious that interpretation of such data needs further investigations.

It should be noted that the latency of P1, N1, and P2 decreased with age in all loci of EEG recording, with the exception of occipital leads. Significant

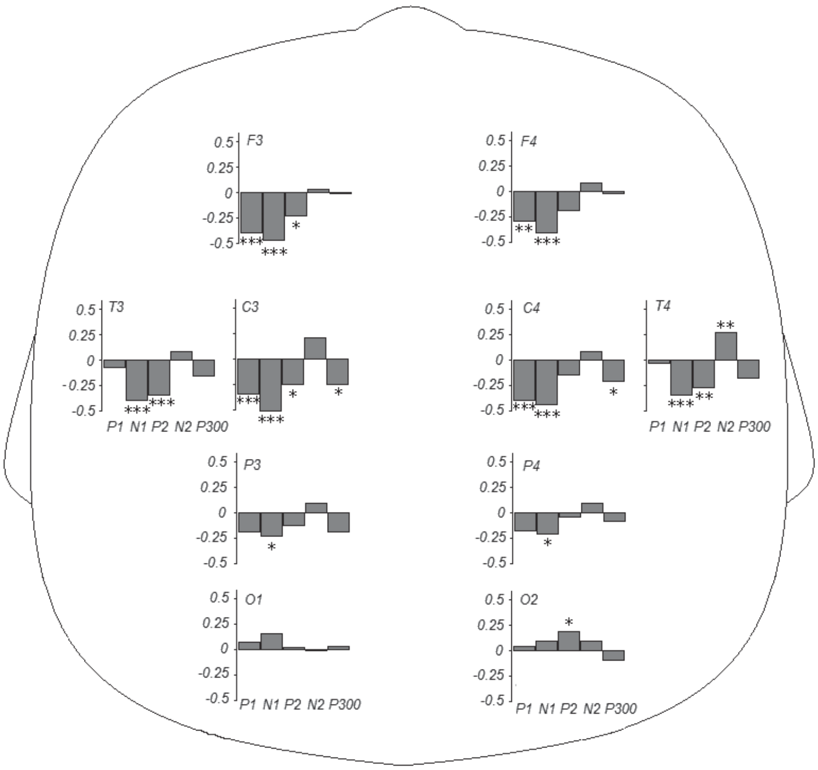

Fig. 1. Diagrams of correlation coefficients between the age of tested subjects and latencies of the components of evoked potentials (EPs) and P300 wave in 110 children and teenagers (6 to 16 years old). Horizontal scale) Components of EPs; vertical scale) correlation coefficients. F3, F4, T3, T4, C3, C4, P3, P4, O1, and O2 are loci of the leads according to the 10-20 system. In this and other figures, one, two, and three asterisks indicate cases of significant correlations of the age and latencies of EP components and P300 wave with $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

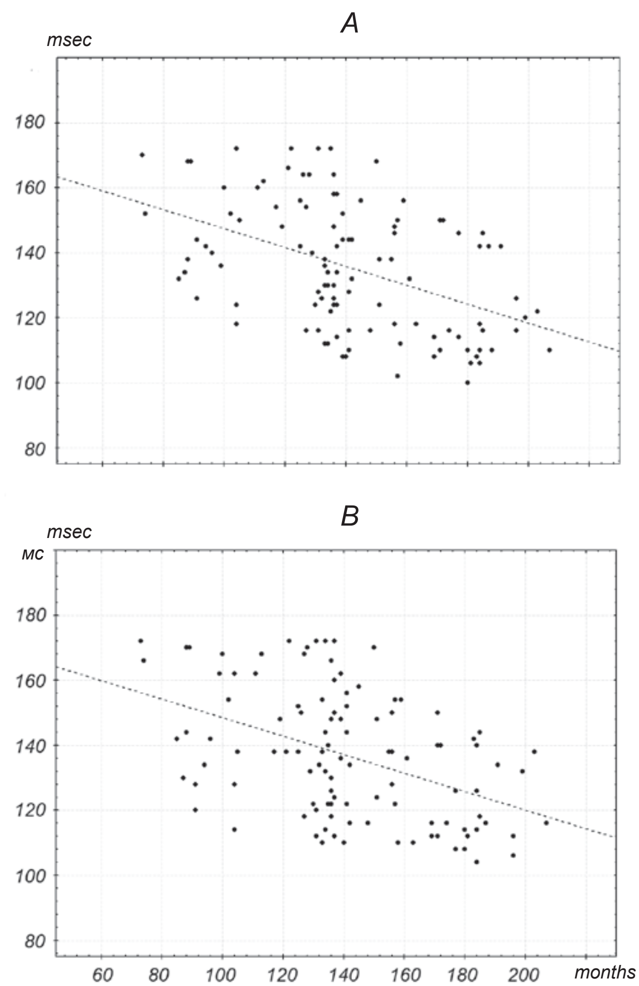

Fig. 2. Correlation fields of the age of tested subjects (months) and latencies of the N1 component (msec) recorded at the left (A) and right (B) frontal leads in 110 children and teenagers (6 to 16 years old). Dotted lines show the regression functions.

correlations of the considered characteristics were, however, observed only in the frontal and central leads. This fact can be related to the following circumstance. According to the available published data, the P1 component evoked by presentation of stimuli of the acoustic modality develops with the minimum latency precisely in the above-mentioned cortical regions [17].

The fact that correlations between the age and latency of EPs were most clearly pronounced in the frontal, temporal, central, and parietal leads attracts special attention. In the occipital regions, the correlation coefficients were smaller and did not reach the significance level. This peculiarity can be due to predominant specialization of the occipital cortical regions on processing of visual information. In this relation, the above regions are not involved actively in processing of acoustic stimuli, and this circumstance noticeably affected the characteristics of the recorded auditory EPs and peculiarities of their age-related dynamics.

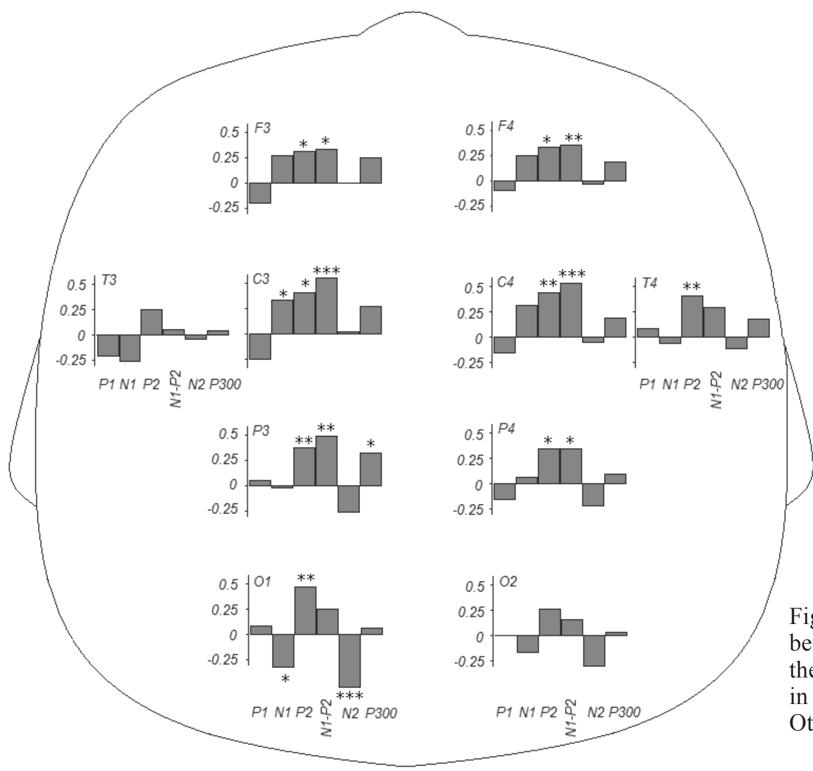

Fig. 3. Diagrams of the correlation coefficients between the age of tested persons and amplitudes of the components of evoked potentials and wave P300 in 110 children and teenagers (6 to 16 years old). Other designations are the same as in Fig. 1.

The amplitude of components P2 and N1-P2 (vertex potential) demonstrated positive correlations with age (Fig. 3). In other words, the older a child, the higher, usually, the amplitude of such waves. Significant correlations for the P2 amplitude were found in the frontal, central, and parietal leads of both hemispheres, as well as in the right temporal lead ($0.196 < r < 0.289$, $0.002 < P < 0.040$).

According to the published data [16], the characteristics of P2 can be considered an indicator of the level of recognition and classification of the stimuli and also modulation of attention with respect to standard (non-target) stimuli. Hence, the following assumption seems logical: The observed age-related changes correspond to the process of sophistication of selective attention in children and teenagers. Our own data agree with findings made in the studies of auditory EPs in children of different age groups under conditions of the oddball paradigm. It was found that the amplitude of the P2 component increases with age; the level of this increase seems to reflect the level of maturation of the brain [7, 18]. Significant correlations of the amplitude of the vertex potential in children with their age were found in the frontal, central, and parietal regions of both hemispheres. Since the amplitude of the N1-P2 complex is interpreted as a rather direct index of the efficiency of work of the tested subjects in the processing of different types of information [10], increase in this parameter with age also reflects a greater successfulness in the performance of the proposed task.

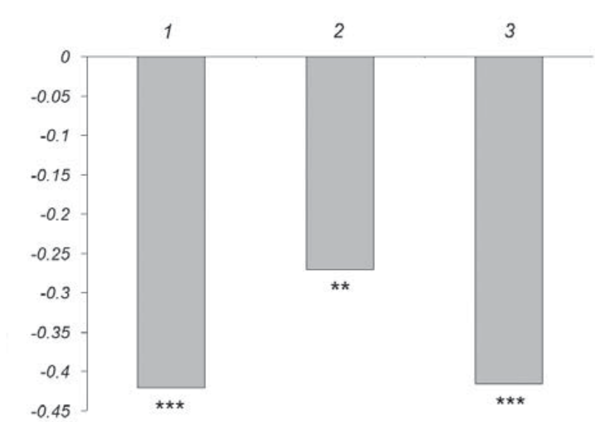

Fig. 4. Diagram of the correlation coefficients between the age and mean time of the sensorimotor reaction (1), number of errors of omission of significant stimuli (2) and errors of erroneous pushes (3) in 110 tested persons (6 to 16 years old). Other designations are the same as in Fig. 1.

We found a significant trend toward decrease with age in the amplitude of the N2 component in the occipital lead (r = –0.314, P = 0.0009). In studies carried out in our laboratory [4], it was found that the amplitude of the N2 component of EPs recorded within the framework of the oddball paradigm is higher in 5- to 7-year-old children than that in 10- to 12-year-old ones; in turn, this parameter in the latter group was greater than that in 15- to 16-year-old teenagers. It was hypothesized that a decrease in the N2 component in the course of maturation is, to a significant extent, related to the development of the mechanisms of selective attention. With age, separation of relevant information is realized within earlier stages of information processing corresponding to the generation of components N1 and P2; this, probably, is reflected in a decrease in the amplitude and an increase in the latency of the later component (N2).

The age of children and the ERP characteristics also demonstrated certain correlations. The amplitude of different phases of the CNV positively correlated with age; in other words, higher CNV amplitudes were in general typical of senior schoolchildren. In this case, significant correlations for CNV_i and CNV_t were found in the left central lead (r = 0.233, P = 0.014 and r = = 0.237, P = 0.012, respectively). It is believed [19] that the CNV reflects the readiness for a reaction to presentation of the stimulus. As Bekhtereva supposed [20], precisely this ERP adequately reflects the process of formation of the readiness for action (activity of the subject in a situation of interaction with the environment). There are also data according to which higher amplitudes of the CNV_i and CNV_t are related to optimal characteristics of attention [10]. Correlation between the age and amplitude of different CNV phases recorded just in the left hemisphere can be due to the improvement of voluntary attention; the formation of the latter is, to a significant extent, based on resources of the left hemisphere [21].

Ontogenetic changes in the P300 potentials appeared, first of all, as a decrease in the latency of this wave with age. Significant correlations of these indices were observed in loci C3 (r = –0.22, P = 0.019) and C4 (r = –0.207, P = 0.031). Age-dependent maximum shortening of the P300 latency in the above leads is, probably, related to the fact that the P300 topographically prevails just in the frontal/central regions [13]. The P300 potential is usually considered a reflection of "triggering" of the events related to information processing and construction of neurocognitive models. Some authors believe that the dynamics of time characteristics of the P300 component depend not on the influence of biological age *per se*, but on the level of development of cognitive functions (in particular, memory) in children [1-3]. Correspondingly, the above-mentioned decrease in the latency of the P300 within the framework of the paradigm used in our study is, most probably, related to acceleration of the analysis of adopted decisions, as well as to changes in the characteristics of short-term memory. This is confirmed by parallel alterations of the indices of working efficacy; the mean latency of the sensorimotor reaction, the number of erroneous pushes, and that of errors of omission of significant stimuli demonstrated obvious decreases with age (Fig. 4). Therefore, in general, inattention and high impulsivity are typical of older schoolchildren to a lesser extent.

In addition, correlation analysis allowed us to find interdependences between the EP characteristics, values of the mean reaction time, and the number of erroneous pushes. Significant correlations with the value of the mean reaction latency were observed for the amplitudes of components P2 ($-0.201 < r < -0.370$, $0.00007 < P < 0.040$), P300 ($-0.228 < r < -0.34$, $0.0003 < P < 0.019$), N1-P2 ($-0.228 < r < -0.285$, $0.003 < P < 0.016$), and CNV ($-0.286 < r < -0.213$, $0.002 < P < 0.025$). In other words, the higher the amplitudes of the above-mentioned EEG potentials, the more rapidly the children coped with the task. The presence of correlations between these indices corresponds to functional importance of the EPs considered above and again confirms the existence of age-related mechanisms underlying the improvement the characteristics of voluntary attention, memory, and analytical processes.

The number of erroneous pushes demonstrated significant correlations with the latency of the P1 ($0.196 < r < 0.263$, $0.005 < P < 0.040$) and N1 ($0.200 < r < 0.338$, $0.0002 < P < 0.036$). Therefore, the greater the latencies of these EP components, the higher the level of impulsivity determined by insufficiently successful suppression of insignificant stimuli, and the lesser the efficacy of the processes of selective attention typical of the children.

When analyzing topographical distribution of the cases of significant correlation between the age and amplitude/time characteristics of EPs and ERPs, we did not observe clearly pronounced interhemisphere asymmetry. The exception was the CNV, whose amplitude increased predominantly in the left hemisphere. The data obtained in studies of the age-related dynamics of EPs recorded within the framework of the oddball paradigm [22] differ significantly from our findings. As was reported, there is a trend toward higher amplitude values of the greater part of the considered EPs in the right hemisphere; this is explained by the appreciable emotional importance of the resolved task. We hypothesize that the absence of such asymmetry in our tests is related to a significant involvement of not only emotional but also cognitive resources of the brain in processing of the signals obtained by children in the course of the task performance within the framework of the go/no go paradigm.

Based on these data, we conclude that the intensity of cognitive processes realized in the neocortex in children and teenagers in the course of task performance corresponding to the go/no go paradigm are nearly equal in both hemispheres. Incomplete development of the neocortex and, consequently, some of the cognitive functions of the brain in children of the tested age range are probable reasons for such a peculiarity. It is believed that lateralization of cerebral functions is formed in the course of ontogenesis within an interval between 14 to 16 years [23]. Dubrovinskaya et al. [9] mentioned that final formation of the system of ranging analysis is related to structural/functional maturation of the anterior associative cortical divisions. In this relation, interhemisphere specialization of the processes of recognition is clearly manifested only at the age of 16 to 17. Moreover, in the review of Hiscock [24] no convincing proofs were mentioned in favor of ontogenetic increase in the lateralization of auditory, visual, tactile, and motor spheres in 2- to 12-year-old children; in addition, the cited author called into question the data of those studies where such increases were found.

Our own data allow us to conclude that the measurement of characteristics of the EP components in children of school age helps, to a considerable extent, to estimate the level of cognitive maturation of the brain. We believe that the data obtained with the use of the go/no go paradigm (in which the complexity of the tasks is greater than that in the oddball paradigm) are more correct and objective in the course of estimation of the age-related changes in EPs and ERPs. The observed changes affected both long-latency components of EPs/ERPs and indices of the working efficiency, such as the mean latency of the sensorimotor reaction and the number of erroneous motor responses and errors of omission of significant stimuli. The maximum number of significant correlations was found for the latencies of the P1, N1, and P2 components, as well as for the amplitudes of the P2 component and vertex potential. Age-related modifications of ERPs were expressed in a clearly pronounced trend toward decrease in the latency of the P300 and an increase in the amplitudes of the CNV phases. With age, schoolchildren also become less inclined to impulsivity and inattention during the performance of the proposed tasks and are able to focus their attention more successfully.

It is believed that the characteristics of EP reflect various processes of selective attention, while ERPs are mostly related to the mental processes. In this relation, we believe that the characteristics of voluntary attention and rate of analytical processes within the examined age period change rather intensely. This fact should be taken into account for estimation of age-related norms of the EP characteristics and also in studies directed toward investigation of correlations between the EP characteristics and different psychophysiological functions in children and teenagers.

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