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Spatial Organization of Cortical Electrical Activity at Different Stages of a Visual Set in Preschool and Early School Age

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Parameters of the formation of a visual nonverbal set and the rate of its replacement with a new set were compared in children of three age groups: 5–6, 6–7, and 9–10 years. The vast majority of subjects (27 of 30 preschool children and 42 of 43 third-grade children) showed clear set effects. Age-related differences in set plasticity and the dynamics of reaction times to test stimuli were observed. The set was more rigid in children aged 5–6 years than in older children. Differences in the dynamics of the spatial organization of alpha and theta activity were seen in the anterior areas of the cortex at different stages of the set in children of different age groups. Analysis of cortical potentials coherence functions and behavioral parameters led to the hypothesis that the frontothalamic selective attention system and the corticohippocampal connection system responsible for the cortical processing of new visual information and episodic memory function are involved in organizing the visual set. A critical age (from six to seven years) was indentified in the formation of plastic types of visual nonverbal sets.

KEY WORDS: visual set, ontogenesis, frontal cortex, spatial organization of the EEG, coherence, theta rhythm, alpha rhythm.

Significant differences in the morphofunctional organization of the frontal cortex, particularly its prefrontal areas, in children of different ages allow an ontogenetic approach to be taken in identifying the roles of these structures in the cortical organization of cognitive control resulting from set formation on repeated perception of a visual stimulus and the replacement of this set by a new set when the situation changes. The key role of prefrontal cortex structures in the formation of the cognitive visual set, in its inhibition, and in its replacement by a new set appropriate to changing conditions has been demonstrated by functional scanning (fMRI) of healthy adults performing the Wisconsin test [15, 17]. Patients with organic pathology of the frontal area show impairments to the ability to sort pictures in the Wisconsin test, especially if one or another of the selection criteria they acquire is replaced by a new criterion appropriate to the altered conditions: they continue, erroneously, to solve the task as previously [18]. Studies have demonstrated that more plastic sets dominate in children aged more than six years, where replacement by a new set occurs relatively easily as compared with the situation seen in children aged 5–6 years [4]. At the stage at which the old set must be replaced by a new set (the actualization stage), children with plastic sets show significant increases in the spatial synchronization of potentials in the alpha range between the frontal areas and other cortical zones. We have suggested that the formation of a plastic visual set is associated with the maturation, at age 6–7 and particularly 9–10 years, of the frontal areas of the cortex and the resultant increases in the influence of cognitive control of the function of visual perception [3].

Data have been obtained showing that in this latter group, the morphofunctional organization of the frontal cortex comes close to that in adult humans [10, 11, 16]. By age 9–10 years, the structural organization of the frontal areas of the cortex is essentially completely formed; the mecha-

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nisms of selective attention are fully formed. This age can be regarded as "...a sensitive period in the formation of voluntary attention and the resultant development of the functional organization of various types of voluntary activity, which significantly increases the efficiency with which they are performed" [10].

The spatial synchronization of cortical potentials in the alpha range in healthy adults has been shown to change significantly at different stages of the set depending on its type (verbal, nonverbal), the nature of the additional cognitive task (for example, "What?" and "Where?"), and the subject's level of motivation [2, 5]. A specific dynamic of alpha-rhythm spatial synchronization has been demonstrated at different stages of a visual nonverbal set in children aged 5–7 years [3]. It is interesting to note that children in this group showed age-related differences in set formation which correlated with measures of the coherence function between potentials in the frontal areas and other cortical regions. These points provided grounds for the suggestion that the formation of a plastic visual set was associated with maturation of the frontal areas of the cortex, leading to strengthening and enhancement of cognitive control in visual perception.

The studies reported here sought experimental verification of this hypothesis by comparing the features of the formation of a visual nonverbal set and the rate of its replacement by a new set in children of three age groups: 5–6, 6–7, and 9–10 years.

The aim of the present work was to use comparative analysis of coherence functions of electrical cortical potentials to identify the age-related features of the dynamics of functional linkages between the frontal area and other parts of the cerebral cortex at different stages of a visual nonverbal set. The choice to analyze electrical activity arose, firstly, from the fact that the set is based on the tonic functional state of increased activation in frontal cortex structures [2, 15, 17] which, according to Livanov's hypothesis [6], may be apparent as an increase in the spatial synchronization of cortical potentials. Secondly, identification of the level of coherence of potentials between different cortical zones allows assessment of the existence of conditions facilitating (or hindering) the propagation of excitation between the frontal cortex and particular regions of the structural-functional visual recognition system. The concept that the level of coherence of electrical potentials in different zones of the cerebral cortex may be a measure of functional linkages between them and the level of their cooperativity at the stage of readiness for one or another cognitive activity and during execution of the activity is supported by many studies reported in the last decade [10, 12, 13, 19, 20, 23].

METHODS

Subjects. Thirty healthy children of both sexes were studied; children were from 5.3 to 6.8 years old (mean age 6.05 ± 0.75 years) and attended Nursery No. 1268 in Moscow; a further 43 healthy children of both sexes, aged from 8.7 to 10 years (mean 9.2 ± 0.05 years) and attending grade 3 at School No. 710 in Moscow, were also studied. Subjects had not previously taken part in experiments on sets. Subjects were familiarized in general terms with the nature of the study and the experimenter noted that the children understood the instructions given to them, were able and willing to follow them, and understood that participation would not be unpleasant. Thus, the children were shown the stimuli on the monitor screen several times and were trained to press a button in the right hand. All subjects took part in the experiment voluntarily, without any kind of pressure. School managers and teachers were given detailed information about the nature of the experiment and accepted that it would not harm the children.

Stimuli. Stimuli were presented at the center of an SVGA monitor (Samsung, Korea) located directly in front of the subjects at a distance of 70 cm from the eyes. A set to object inequality was formed using images of two green circles (defined by the color constant in the "Graph" 10 regime) on a dark gray background, presented simultaneously: a 15-mm diameter circle was displayed to the left of center and a 30-mm diameter circle at right of center. The distance between the centers of the circles was 45 mm; line thickness was 1 mm. The duration of exposure was 200 msec. Then, after an 800-msec pause, a green light spot 3 mm in diameter (the test stimulus) appeared at the center of the screen.

At the set formation stage, subjects were presented 15 times with unequal circles; at the following (test) stage, which followed without an interval, images of circles of identical size (30 mm) were presented 30 times. A test stimulus was presented in each trial. Pauses between groups of stimuli amounted to 3–7 sec and were varied randomly.

Apparatus and data recording and analysis. Amplification and filtration of EEG traces were performed using an MBA-32 amplifier (Medikor, Hungary), using a bandpass of 0.5–30 Hz. Signals were digitized using an L780 14-bit analog-to-digital converter (L-card, Russia) with a sampling frequency of 128 Hz. EEG traces were recorded using silver chloride electrodes (Medikor, Hungary) with a resistance of no more than 5 kΩ. Experiments were controlled and EEG traces were recorded using an IBM Pentium 1 computer. EEG recordings were made using the program "in780" based on a library of files provided by the developers of the analog-to-digital converter (L-card, Russia).

Brain bioelectrical activity was recorded from symmetrical points of the skull, projecting to six areas of the left and right cerebral cortex: occipital (*O1*, *O2*), parietal (*P3*, *P4*), posterior temporal (*T5*, *T6*), central (*C3*, *C4*), frontal (*F3*, *F4*), and frontotemporal (*F7*, *F8*), as well as from the *Cz* area, in accord with the international 10–20% scheme. EEG recordings were monopolar and the reference consisted of combined ear electrodes.

EEG traces were recorded in calm waking with the eyes closed and open and during set formation, actualization, and extinction. In calm waking, six 8-sec EEG segments were analyzed, while 3-sec EEG segments before presentation of each stimulus were analyzed in other experimental situations. Fourier transforms were used to calculate coherence functions (CoF) with a 1-Hz step using artifact-free segments in the state of calm waking and for prestimulus EEG traces, for all pairs of leads. The distribution of CoF values was normalized using Fisher's Z transformation. CoF measures from EEG segments recorded at all stages of the experiment were averaged for each subject. Mean CoF peaks were identified in the theta and alpha frequency ranges. If the function showed several peaks in the frequency range, the largest were identified. Further analysis was performed using CoF peaks of greater than 0.35. This limit was required by the statistical analysis [1].

Dispersion analysis (ANOVA) was performed for each pair of leads. This analysis allows sets of different sizes to be compared, which was important for the present study because there were different numbers of children in the different age groups. The influences of the "stage" factor on CoF peak values in the theta and alpha ranges were analyzed. Data obtained in the state of calm waking with the eyes open were compared pairwise with each subsequent experimental stage (set formation, actualization, and extinction). Comparison results were plotted on map diagrams. If a parameter value was significantly ($p < 0.05$) greater in the state of calm waking than in the experimental stage, this was recorded on the map diagram as a thin line joining the relevant pair of leads; a thick line was used when it was smaller.

RESULTS

Set plasticity (behavioral data). The vast majority of subjects (27 of 30 of preschool age and 42 of 43 third-graders) showed the visual nonverbal set effect as contrast illusions in which the size of the circle to the left of the fixation point (the location at which the smaller circle had been presented at the previous stage of the experiment) was identified as larger, when in reality the circles were of the same size. This stage, in which erroneous assessments of the relative sizes of the circles were recorded, was designated, as by Uznadze [9], the "set actualization" stage. The number of trials with erroneous assessments at this stage was used to evaluate the plasticity properties of the set, i.e., the ability of the formed set to be replaced by a new set appropriate to the altered conditions. As shown in Fig. 1, children of the youngest age group experienced contrast illusions in a larger number of trials, i.e., the set in these children was more inert than that in children aged 6–7 and 9–10 years (Mann–Whitney test, $p < 0.04$). Figure 1 also shows that there was no significant difference in the numbers of contrast illusions in children aged 6–7 and 9–10 years.

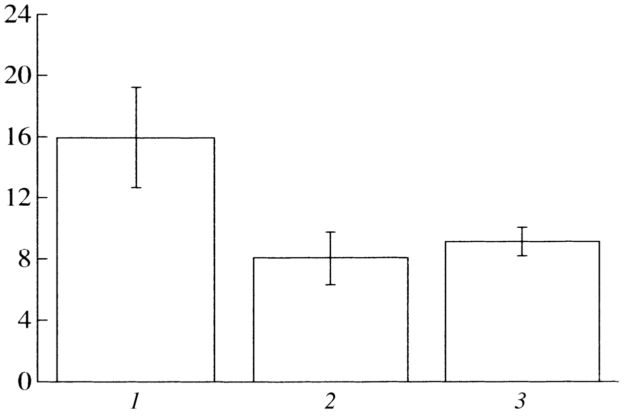

Fig. 1. Set rigidity in subjects of preschool and early school age. The vertical axis shows the number of trials with contrast illusions; the horizontal axis shows: *1*) children aged 5–6 years; *2*) children aged 6–7 years; *3*) children aged 9–10 years. Significant differences between groups, Mann–Whitney test, $p < 0.04$.

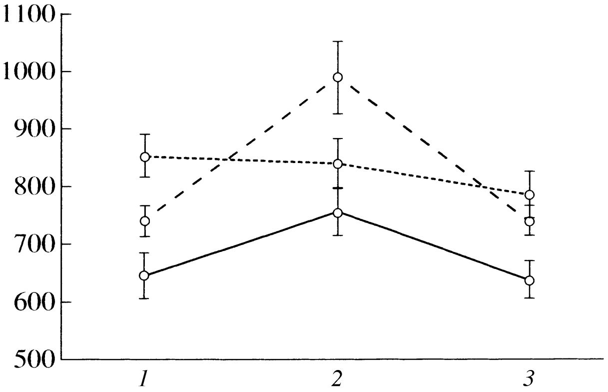

Fig. 2. Reaction times to the test stimulus at different stages of the set in children aged 5–6, 6–7, and 9–10 years. The vertical axis shows time, msec; the horizontal axis shows the stage of the experiment: *1*) formation; *2*) actualization; *3*) extinction of the set. The dotted line shows children aged 5–6 years; the dashed line shows children aged 6–7 years; the continuous line shows children aged 9–10 years. Bars show errors of the mean.

A difference between these latter groups was seen on analysis of reaction times (RT) to the test stimulus, which served as a measure of the function of switching selective attention from one cognitive task to another. Figure 2 shows that RT to the test stimulus did not change at different stages of the experiment in children of the youngest age group. At the same time, RT was initially (at the set formation stage) significantly greater than in older children. RT in these showed a clear increase at the set actualization stage, i.e.,

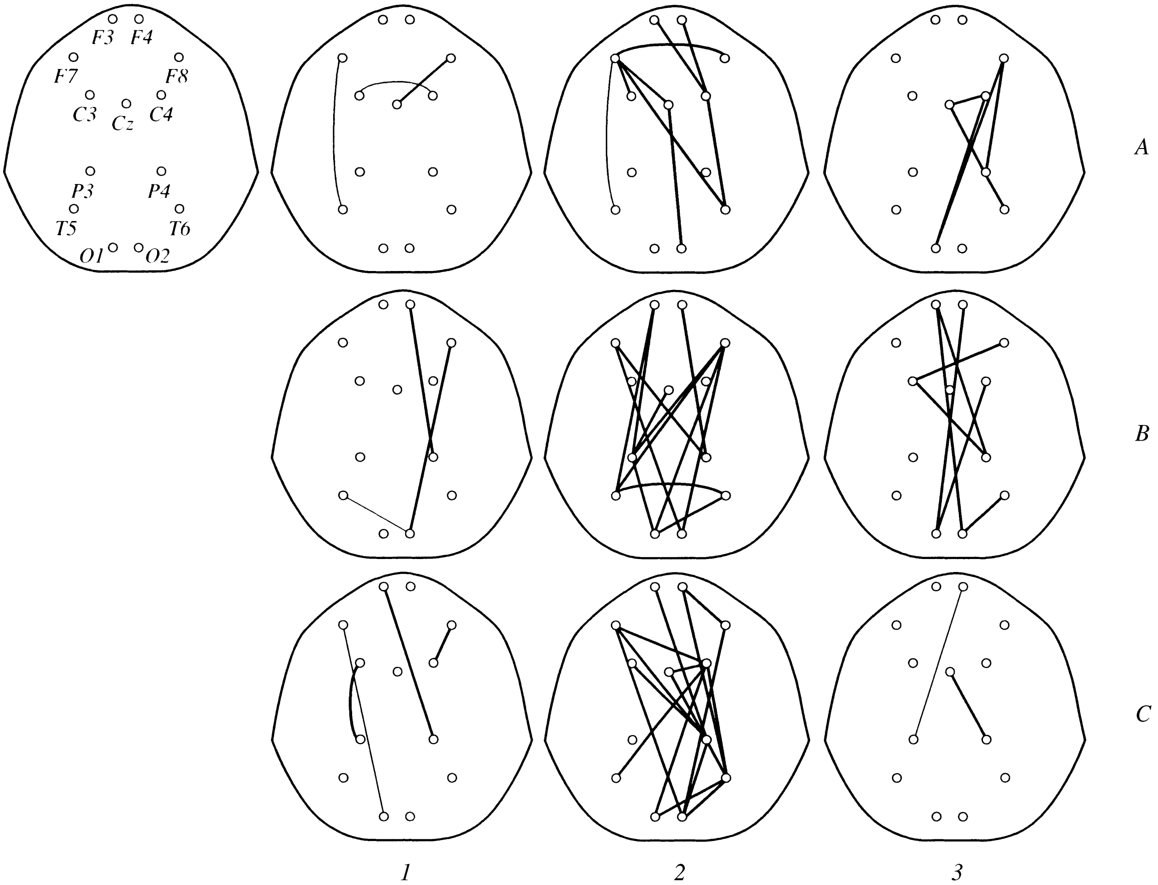

Fig. 3. Topography of differences in theta-rhythm CoF function peaks at different stages of the set compared with the state of calm waking with the eyes open in children aged 5–6 (*A*), 6–7 (*B*), and 9–10 (*C*) years. Thick lines show increases in values, thin lines show decreases; *1*) set formation; *2*) set actualization; *3*) set extinction.

when there was discordance between the old set and the new stimuli, reverting at the set extinction stage to the value seen at the set formation stage. Changes in RT at different stages of the experiment were particularly marked in children of the middle age group (6–7 years) (Fig. 2).

Analysis of cortical potential coherence functions in the theta range (4–7 Hz). Hemisphere asymmetry was seen at individual stages of the experiment in all subjects, these being particularly marked in children aged 5–6 years. In these subjects, coherence of theta potentials at the set formation stage showed little change as compared with calm waking with the eyes open (Fig. 3, *A*). However, at the set actualization stage, coherence clearly increased in the anterior cortical areas and, interestingly, between the anterior areas of the two hemispheres and the posterior zones of the right hemisphere, i.e., the posterior temporal and occipital areas. An increase in the interhemisphere coherence linkage was also noted between the frontotemporal zones (*F7* and *F8*). At the set extinction stage (no contrast illusions, subjects correctly assessing relative circle sizes), coherence linkages persisted mainly in the right hemisphere or, more precisely, between the anterior areas (*F8*, *Cz*, and *C4*) and the temporal zones (*T4* and *T6*) of the right hemisphere, as well as the frontotemporal (*F8*) zone of the right hemisphere and the occipital area of the left hemisphere (*O1*).

In children aged 6–7 years (Fig. 3, *B*), increases in the coherence of potentials in the theta range were seen as early as the set formation stage and these were clearly lateralized: statistical significance was reached only in the right hemisphere, between the frontal (*F4*) and temporal (*T4*) leads and between the frontotemporal (*F8*) and occipital (*O2*) leads. At the set actualization stage, as shown in Fig. 3, *B*, there was a significant enhancement in the coherence of theta potentials between the anterior and frontal areas of the cerebral cortex and the posterior – temporal and occipital – areas, both within hemispheres and between hemispheres. At this stage of the experiment, there was no hemisphere asymmetry in the coherence function of potentials in the theta range; changes were more generalized in nature. However, at the set extinction stage, coherence linkages in

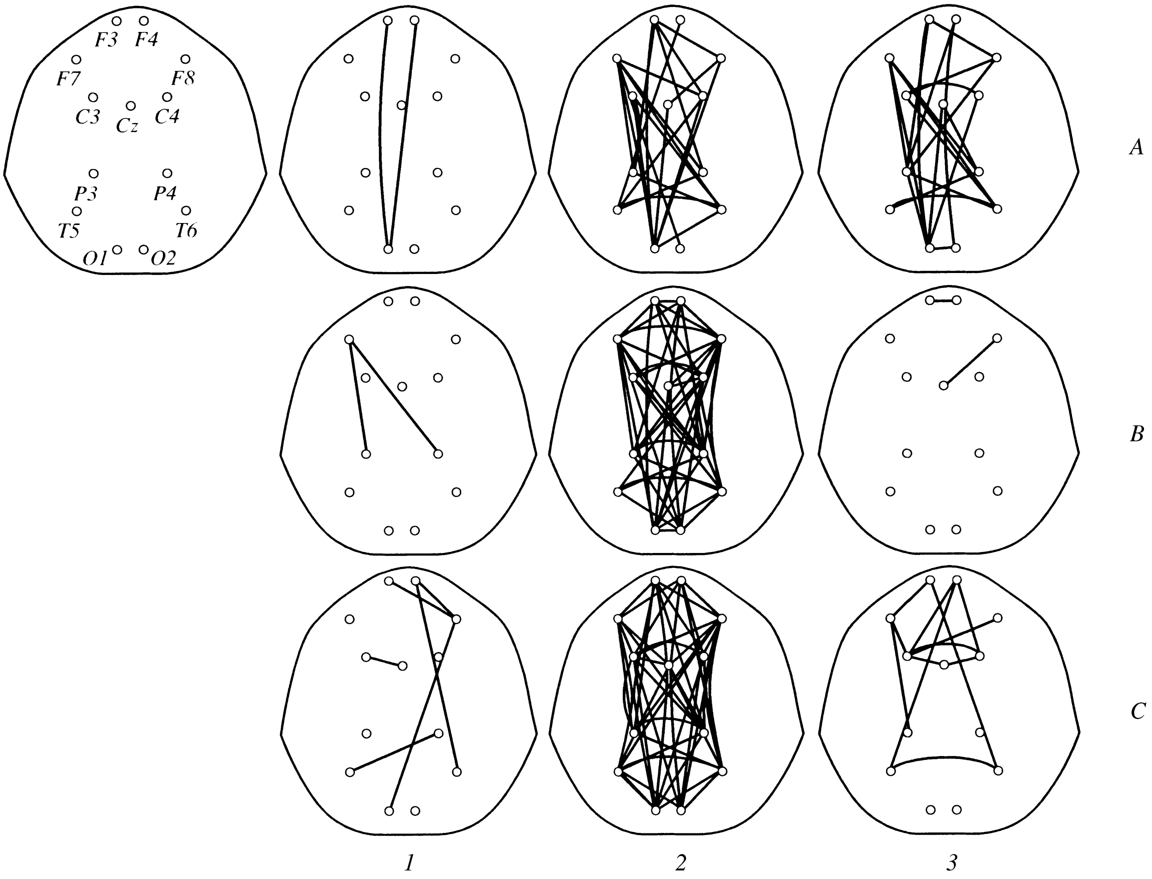

Fig. 4. Topography of differences in alpha-rhythm CoF function peaks at different stages of the set compared with the state of calm waking with the eyes open in children aged 5–6 (*A*), 6–7 (*B*), and 9–10 (*C*) years. For further details see caption to Fig. 3.

the left hemisphere weakened, though they were significantly persistent in the right hemisphere, leading to hemisphere asymmetry in this function. At this stage, there were long interhemisphere coherent linkages between the frontal leads (*F3* and *F4*) and the occipital zones (*O1* and *O2*), as well as between the left frontal area (*F3*) and the anterior temporal zone (*T4*) of the right hemisphere.

In young school-age children (9–10 years old), the set formation stage showed (Fig. 3, *C*) an increase in the coherence of theta potentials between the left frontal area (*F3*) and the anterior temporal area of the cortex of the right hemisphere (*T4*). Hemisphere asymmetry in the coherence function was seen at the set actualization stage. As shown by Fig. 3, *C*, the coherence linkage between the frontal areas of the left hemisphere (*F3*, *F7*) reached statistical significance mainly with the posterior areas of the right hemisphere (*O2*, *T6*, *T4*). Thus, this stage of the experiment showed increases in interhemisphere coherence linkages in theta-range potentials in the anterior cortical zones of the left hemisphere with the temporal and occipital areas of the right hemisphere. Intrahemisphere spatial synchronization between the anterior and posterior areas of the right hemisphere was also clearly evident (Fig. 3, *C*). These data suggest that the coherence function of cortical potentials in the theta range is asymmetrical in children aged 9–10 years at the set actualization stage: the posterior zones of the right hemisphere are linked by coherence linkages with the frontal areas of both the ipsilateral and the contralateral hemispheres. It is interesting to note that these coherence linkages were not seen at the set extinction stage (at the level of significance used here), except for one – between the vertex and the right temporal area (*T4*).

Analysis of coherence functions of cortical potentials in the alpha range (7–13 Hz). The spatial organization of alpha potentials changed depending on the stage of the experiment and the subjects' age (Fig. 4). Long coherence linkages were seen between the frontal zones (*F3*, *F4*) of both hemispheres and the left occipital zone (*O1*) at the set formation stage in children aged 5–6 years. There was a significant enhancement of alpha-range potential coherence between the anterior and posterior areas of the cerebral cortex at the actualization stage (Fig. 4, *A*). This involved increases in both intrahemisphere and interhemisphere linkages. It was interesting to note that most of these linkages also persisted at the set extinction stage, when the children's verbal responses indicated that they started to make correct identifications of the ratio of circle sizes.

Coherence linkages between alpha-range potentials between the left frontal area (*F7*) and the posterior temporal (*T5*, *T6*) zones of both hemispheres appeared at the set formation stage in children aged 6–7 years (Fig. 4, *B*). This plot also shows that the actualization stage showed a general increase in coherence of cortical potentials – both intrahemisphere and interhemisphere. This was associated with coherent linkages both between neighboring cortical areas and between symmetrical zones, as well as between the anterior and posterior parts of the cerebral cortex. In contrast with the youngest group, coherence linkages almost completely disappeared at the extinction stage of the set effect, when children aged 6–7 years started to identify the ratio of new stimulus sizes correctly.

In the oldest group, the set formation stage (Fig. 4, *C*) showed the appearance of long coherence linkages between the frontal zones of the right hemisphere (*F4*, *F8*) and the posterior areas of the cortex (*O1* and *T6*). The actualization stage produced a generalized increase in the coherence of potentials, affecting both "short" linkages, i.e., between neighboring cortical areas, and "long" linkages, i.e., between the anterior and posterior areas, affecting both intrahemisphere and interhemisphere linkages. The set extinction stage showed a significant weakening of spatial coherence of alpha-range potentials as compared with the preceding stage (actualization). However, Fig. 4, *C* shows that coherence linkages between neighboring areas in the anterior cortical areas persisted, as did those between the anterior frontal zones (*F3*, *F4*) and the posterior temporal zones of the opposite hemisphere, i.e., between the left frontotemporal area (*F7*) and the anterior temporal area of the same hemisphere (*T3*), and an interhemisphere linkage between the posterior temporal zones (*T5*, *T6*). Thus, in children aged 9–10 years, spatial synchronization of alpha-range potentials at the set extinction stage weakened less significantly than in children aged 6–7 years: coherence linkages involving the anterior areas of the cerebral cortex persisted in the oldest group.

DISCUSSION

Comparative analysis of behavioral and bioelectrical data leads to several conclusions regarding the ontogenetic development of the visual set function and its regulatory influence on human cognitive activity. We have identified grounds for regarding the short period from six to seven years as a critical period in the development of the visual set to nonverbal stimuli. At this age, the set acquires plastic properties and its replacement by a new set occurs as in children aged 9–10 years, while the set is significantly more rigid in children of the youngest group (5–6 years). This is indicated, firstly, by the larger number of contrast illusions at the test stage of the experiment in this group, i.e., the presence of a longer-lasting set actualization phase. Secondly, in subjects aged 5–6 years, the set extinction stage showed persistence of most of the coherence linkages between potentials in the alpha and theta ranges which had appeared at the actualization stage, which appears to be associated with the inertness of the set. We believe that this assertion is correct, as when preschool children were grouped in terms of having a plastic or rigid set in our previous studies [3], the level of alpha-rhythm synchronization in the rigid-set group not only did not decrease at the extinction stage, but increased. This provided grounds for suggesting that in children with rigid sets, its action was incomplete despite the fact that the subjects' verbal responses indicated they had started to solve the cognitive task correctly. It is interesting to note that at this stage of the experiment, this group of children showed no reduction in the RT to the test stimulus.

In older preschool children (6–7 years), as we have noted, replacement of the set occurred more quickly, i.e., it was more plastic than in children of the youngest age group. These two groups also showed significant differences in the dynamics of the spatial synchronization of alpha potentials. In children aged 6–7 years, synchronization of cortical activity increased significantly at the set actualization stage, though in contrast to the youngest group, synchronization was not seen at the extinction stage, i.e., coherence linkages almost completely disappeared. It is important to note that the RT to the test stimulus decreased strongly.

We believe that the diffuse increases in the synchronization of alpha potentials, especially involving the anterior cortical areas, and the sharp increase in the RT to the test stimulus provide evidence that activation of the cerebral cortex – both its generalized and local forms – increases in children aged 6–7 years during the period of discordance between incoming information and the old set, which occurs on solution of the new cognitive task. It should be noted that the increase in the RT to the test stimulus is a good indicator of the subject's attention to solving the main task; it may be the result of difficulty in switching selective attention to a stimulus not associated with the main task. The correctness of our suggestion is supported by data obtained in this group of children at the set extinction stage, when the subjects solved the cognitive task and substitution of the set occurred: synchronization of potentials almost completely disappeared and the RT to the test stimulus decreased strongly. This change in cortical activity, as well as the consequently greater (than in the youngest children) plasticity of the cognitive set, probably resulted from increases in the functional capacity of cortical structures to interact. This occurs as a result of qualitative changes in the maturation of the frontothalamic selective attention system after age six years [7, 8], which is consistent with data on the completion of the development of voluntary attention at this stage of ontogenesis [21].

In children aged 9–10 years, the plasticity of the set, as assessed from the verbal responses during solution of the task consisting of comparative evaluation of the sizes of two circles, was no different from that seen in children aged 6–7 years. The dynamics of the RT to the test stimulus at different stages of the experiment in these two groups of subjects were also very similar, though the absolute value of the RT in the oldest children was clearly less at all stages. However, there were also differences. In children aged 9–10 years, spatial synchronization of alpha potentials in the anterior cortical areas did not weaken as significantly at the set extinction stage as in younger children (6–7 years). It can be suggested that third-graders, in contrast to older preschool children, continue to analyze the situation after the set replacement event has occurred. As a result, selective attention to new stimuli in these children remains elevated, and this is manifest in the synchronization of potentials in the anterior cortical areas and their linkages to the posterior temporal zones, which play an important role in processing visual information. The roles of these areas in information processes at the extinction stage is apparent as the increase in interhemisphere linkages of the symmetrical posterior temporal zones.

Analysis of significant coherent linkages in the theta range demonstrated lateralization: spatial synchronization of potentials in the youngest children was more marked in the right hemisphere at all stages of the experiment. In all three groups, spatial synchronization was more marked at the set actualization stage, i.e., when there was discordance between ongoing visual information and the previously formed set. In addition, there was an identifiable difference between groups at this stage: coherence linkages between theta potentials were weaker in children of the youngest group and strongest in children aged 9–10 years. There were increases in coherence between theta potentials recorded from the anterior frontal areas and the posterior zones of the cortex and, an observation which we believe is important, this occurred both within hemispheres and between hemispheres. At the set extinction stage, when the set was replaced and the subject correctly solved the cognitive task, conversely, coherence linkages almost completely disappeared in children of the oldest group, while they decreased but persisted, mainly in the right hemisphere, the youngest children.

Recent years have seen the appearance of the concept that synchronization of potentials in the theta rhythm developing as a result of the action of recurrent corticohippocampal connections is functionally closely associated with the processing of new information and visual (episodic) memory [14, 21, 22]. These concepts suggest an explanation for the differences in the dynamics of spatial synchronization of theta activity in children of different age groups. In children aged up to six years, the involvement of the left hemisphere in solving the main cognitive task is significantly smaller, these children solving the task predominantly using visual memory and not using semantic types of memory to the same extent as older children. This leads to an understanding of the clear lateralization of coherence linkages favoring the right hemisphere in the youngest children and its absence in the older age groups, particularly at the set actualization stage. We note that this is the stage at which discordance between ongoing visual information and the old set leads to the need for replacement of the latter by a set more appropriate to the new stimuli. At this stage, older children show significant bilateral synchronization of theta activity, probably because of successful solution of the cognitive task. It is interesting to note that replacement of the set in children of preschool age was followed by lateralization of spatial synchronization of theta activity to the right hemisphere, while synchronization in children aged 9–10 years was almost completely absent. It is possible that third-graders recognize changes in the situation of the cognitive task more than younger children do.

CONCLUSIONS

The behavioral and electrophysiological data obtained in the present study suggest that two brain systems play significant roles in the functional organization of the visual set: the frontothalamic selective attention system and the system of recurrent corticohippocampal connections. The significance of the selective attention system is indicated by changes in reaction times to the test stimulus and the spatial synchronization of potentials in the alpha range at different stages of the set (formation, actualization, and extinction). The involvement of a second brain system is indicated by the results obtained from analysis of coherence in the theta range. Changes in the spatial synchronization of theta-range potentials at different stages of the visual set provide grounds to regard age-related differences in the properties of the visual set as resulting to some extent from the development of corticohippocampal recurrent connections in children, these being involved in the organization of the cortical processing of new sensory information and in the functioning of episodic memory. Our data show that the critical period of maturation of both brain systems is at age 6–7 years. This relates to their involvement in supporting the plasticity of cognitive visual sets.

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