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Features of Functional Brain Connectivity in Children during Solving Cognitive Tasks

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Abstract—The results of an analysis of phase synchronization of theta brain activity in children when solving problems that involved computational abilities, visual search, and short-term operating memory have been presented. Functional connectivity within the temporal, frontal, central, and occipital-parietal areas of the cerebral cortex using EEG data has been calculated. Significant differences in the dynamics of synchronization of neuronal structures in the frequency range of the theta rhythm, both depending on the brain area and the type of performed task have been found. Significant increases in functional connectivity within prefrontal and temporal regions during visual search tasks have been found.

Keywords: phase locking value, functional analysis, EEG, neurophysiology, theta rhythm

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INTRODUCTION

A functional analysis of the interaction of brain structures remains an important problem in the field of human neurophysiology [1], and for its study, neurophysiological studies are currently actively conducted using EEG, MEG, fBIRS, and other neuroimaging tools [2–6]. In addition to their fundamental significance, the results of these studies also have practical significance. For example, in the diagnosis of pathological processes associated with the work of functional brain networks [7], in the context of this issue, the need to study the functional networks of the brain in children for the timely detection and estimate of the severity of cognitive impairment is especially acute.

In the functional analysis, it is of interest to study the synchronicity of the bioelectrical activity of neural structures both between different areas of the brain (general synchronization) and within a separate area (the so-called local synchronization) [8].

One of the proven methods for assessing the synchronicity of neural activity is the calculation of the phase locking value or PLV [9], which is the statistical value of detecting phase synchronization between signals depending on specific time.

In this study, special attention is paid to the theta rhythm, the frequency range of which is 4–8 Hz. In the context of cognitive load, its activation in the prefrontal cortex is associated with participation in the mechanism of memorizing information and learning processes [10, 11]. However, a number of researchers point to a decrease in low-frequency activity during active work of episodic memory [12]. The features of its synchronization within individual brain structures also remain poorly understood.

Thus, this paper is aimed at studying the features of local synchronization of neurons in the theta rhythm range under different cognitive loads.

METHODS

A total of 22 children aged 11–12 years (8 girls and 14 boys) took part in the neurophysiological experiment. To study brain activity, EEG was recorded using 64 leads using the standard 10–10 scheme (BrainVision LiveAMP encephalograph with a sampling frequency of 500 Hz).

The experiment included three blocks, which included tasks of various types of cognitive load [13] (see Fig. 1). Tasks of the mental arithmetic type involved the computational abilities of the subjects: it was necessary to decide whether the shown equality was correct; visual search involved finding the previously shown number in a matrix of numbers of different dimensions; in the operating memory type tasks, the study participants had to answer whether the random number shown was found in the previously presented set of numbers. The total testing time was ~50 min.

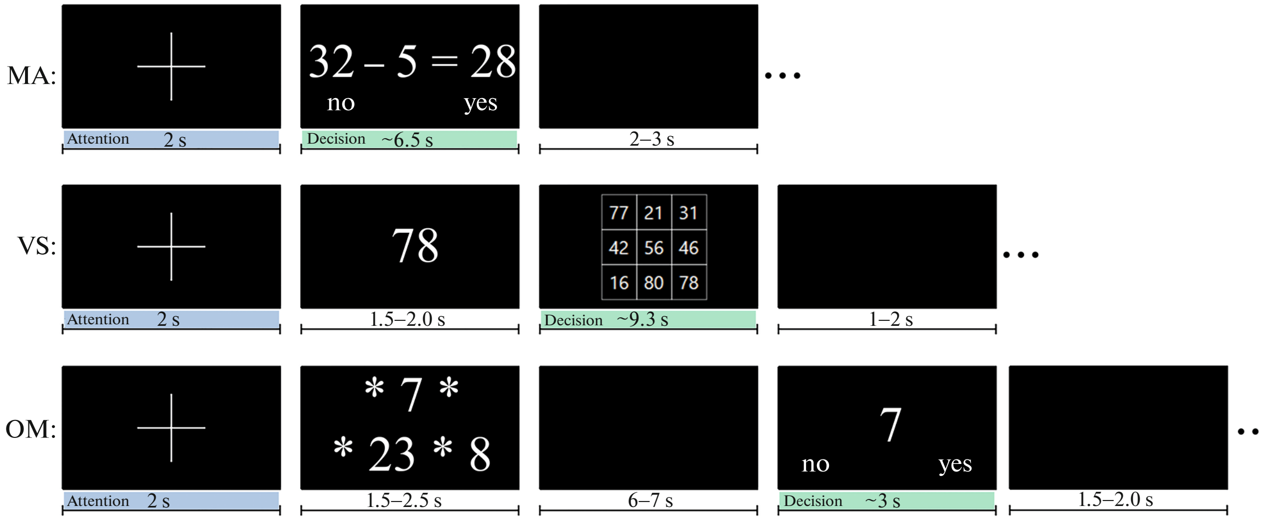

Fig. 1. Task schemes. Task types: MA, mental arithmetic; VS, visual search; OM, operating memory; the time scales indicate the types of epochs for each task: Attention covers the period of attracting the subject's attention with the help of the shown white cross before the start of the task, and Decision covers the period of completing tasks of each type.

The MNE-Python toolkit [14] was used to process the obtained data. Preprocessing included filtering (0.1–40 Hz) to remove noise and the independent component analysis (ICA) to remove artifacts (e.g., extracerebral activity caused by eye, muscle, electrode movements, etc.). Segmentation (the process of forming epochs, individual fragments of a recording associated with a specific activity of the subject) was performed so that there were two epochs for each task (see Fig. 1):

(1) Attention. The period of preparation for execution. The start and end times of each epoch were [–0.5; 2] s relative to the start time of showing the white cross to the subject to attract the subject's attention;

(2) Decision: the period of task execution. The start and end times of the epochs were different for each type of task and varied depending on the average duration of the subjects' response in the sample: mental arithmetic, [–0.5; 6.5] s relative to the stimulus (display of the arithmetic expression); visual search, [–0.5; 9.3] s relative to the matrix display time, and operating memory, [–0.5; 3] s relative to the number display. Epochs with excessively long responses (subjects' responses outside the 95th percentile in response duration for each task type) were defined as statistical outliers and excluded from further analysis.

The "MNE-connectivity" package was employed to calculate the phase synchronization values. PLV were calculated and averaged for each category of epochs in the frequency range from 4 to 8 Hz. Unlike the common method of the coherence analysis based on calculating the spectral power of signals, PLV does not take into account the amplitude of the studied signals, but relies only on the difference in their phases and is calculated as follows [9]:

$$PLV_t = \frac{1}{N}\sum_{n=1}^{N} \exp(j\theta(t,n)), \quad (1)$$

where $\theta(t, n)$ is the phase difference of signals $\varphi_1(t, n) - \varphi_2(t, n)$, N is the number of trials, j is the imaginary unit, n is the trial number, and t is the trial time.

For subsequent statistical processing, the differences in PLV values in the epochs of attention fixation (preparation for the next task) and the subsequent period of task performance (separately for each type) were calculated for each subject. The obtained ΔPLV values were averaged over the zones in which each pair of electrodes were located (see Fig. 2).

Statistical processing using the repeated measures analysis of variance (RM-ANOVA) was used to identify differences in the comparison groups, after which a posteriori analysis was performed: a paired t-test with Holm's correction for multiple comparisons.

RESULTS AND DISCUSSION

During the analysis of the differences in the phase synchronization coefficients within each of the brain zones for the studied frequency range, changes in theta rhythm synchronization associated with the cognitive load of a certain type of task were obtained. The obtained data on the bioelectrical activity of the brain were subjected to statistical processing: repeated measures analysis of variance (ANOVA) and Student's T-test, including Holm's correction for multiple comparisons (p_{Holm}).

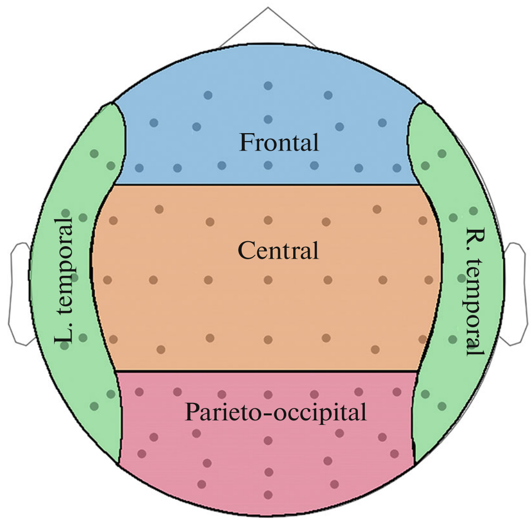

Fig. 2. Scheme of the arrangement of the "10–10" electrodes with the indicated combined zones.

It was found that the degree of theta rhythm synchronization differs within the studied areas of the cerebral cortex on average for all tests (RM-ANOVA: $p < 0.001$, see Fig. 3a). The post-hoc test showed significant differences between the groups: frontal–central ($p_{\text{Holm}} = 0.01$), left temporal–central ($p_{\text{Holm}} < 0.001$), right temporal–central ($p_{\text{Holm}} < 0.001$), and occipito–parietal–central ($p_{\text{Holm}} < 0.001$).

A difference in the change in synchronization depending on the type of task was revealed (RM-ANOVA: $p < 0.001$, see Fig. 3b). The post-hoc test showed significant differences between the groups: mental arithmetic–visual search ($p_{\text{Holm}} < 0.001$) and visual search–operating memory ($p_{\text{Holm}} < 0.001$).

Differences between the groups when considering factors Brain area and Task type simultaneously were revealed (RM-ANOVA: $p < 0.001$, see Fig. 3c). The post-hoc test showed significant differences: for the frontal area, mental arithmetic–visual search ($p_{\text{Holm}} = 0.01$); for the left temporal area, mental arithmetic–visual search ($p_{\text{Holm}} < 0.001$) and visual search–operating memory ($p_{\text{Holm}} < 0.001$); for the right temporal area, mental arithmetic–visual search ($p_{\text{Holm}} < 0.001$) and visual search–operating memory ($p_{\text{Holm}} < 0.001$); for the central area, mental arithmetic–operating memory ($p_{\text{Holm}} < 0.001$); and for the occipital-parietal zone, mental arithmetic–visual search ($p_{\text{Holm}} = 0.003$).

CONCLUSIONS

As a result of this study, the phase synchronization of the theta activity of neurons in the frontal, central, occipital-parietal, and left and right temporal zones of the children's brain when solving cognitive problems of various types has been analyzed.

It has been found that when solving problems on visual search of elements in a matrix, the phase synchronization of the theta rhythm increases in the frontal, left and right temporal, as well as the occipital-parietal areas of the brain in comparison with the cognitive load when performing other types of tasks. In addition, the degree of synchronization of the theta rhythm on average for all tasks significantly decreases only in the central zone of the brain (including mainly the motor and somatosensory cortex) in comparison with other areas.

In future studies, it is planned to analyze the phase synchronization for higher-frequency brain rhythms, as well as their ratios. In addition, of interest is a com-

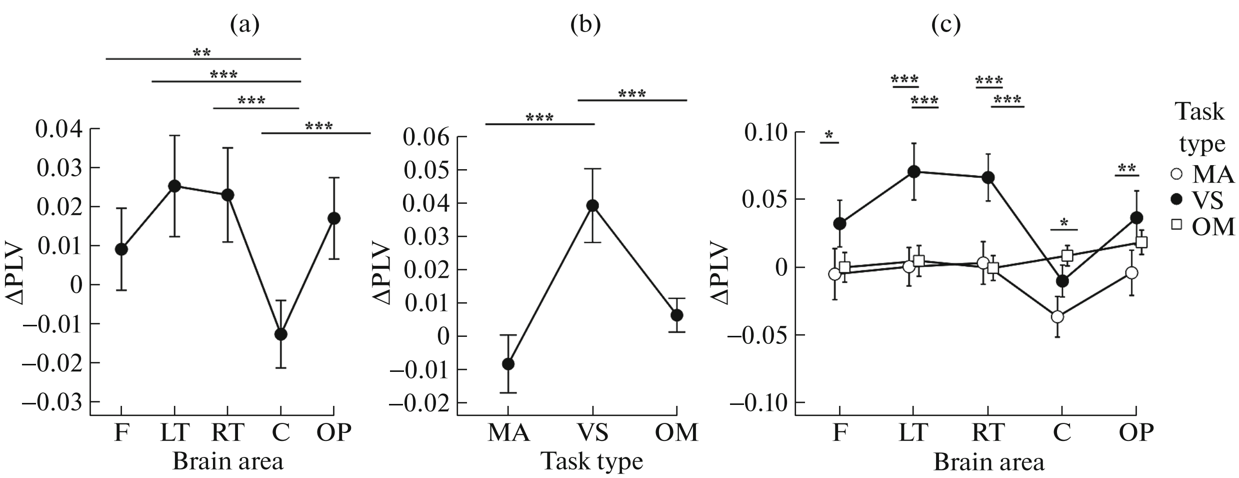

Fig. 3. Dynamics of changes in ΔPLV during problem solving depending on (a) the area, (b) task type, and (c) zone-task type. 95%-confidence intervals are indicated. Significant differences are indicated based on the results of the post-hoc test (Holm's correction for multiple comparisons was used). Abbreviations of brain zones: F, frontal; LT, left temporal; RT, right temporal; C, central; and OP, occipito-parietal.

parative analysis of the results of different age groups using the described approach to identify age-related features of phase synchronization of electrical activity of the brain.

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

All studies were conducted in accordance with the principles of biomedical ethics as outlined in the 1964 Declaration of Helsinki and its later amendments. They were also approved by the Ethics Committee of the Baltic Center for Artificial Intelligence and Neurotechnology of the Immanuel Kant Baltic Federal University (Kaliningrad), protocol no. 32 dated July 4, 2022.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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