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Dynamics of the Brain's Wave Rhythms Predict the Speed of Performing Cognitive Tasks

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Abstract—Physiological and behavioral characteristics of children aged 9 to 10 are investigated in a neurophysiological experiment seeking to understand the performing of tasks based on the Sternberg paradigm. Statistical analyses are performed of wave rhythm stability and the correlation between the mean response time and wave rhythms. The analyses show that the index of brain rhythm stability can act as a biomarker of the effectiveness of performing a working memory task.

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INTRODUCTION

Research on the principles and physical laws governing brain activity is of great interest to modern science. One of the most popular and accessible ways of analyzing brain activity is to use electroencephalograms (EEGs) [1, 2]. These allow us to measure the electrical activity of the brain and provide unique opportunities to assess and analyze cognitive processes.

When analyzing EEG signals, periodic oscillations known as wave rhythms are usually identified in different ranges of frequency. These wave rhythms create distinctive patterns of electrical activity and are a product of the collective dynamics of the brain's neuron activity. It is known that changes in the amplitude and frequency of wave rhythms can reflect different states of the brain. The authors of [3] discovered a connection between theta-range energy in the frontal and central areas of the brain and the rate of success in performing an experimental task.

Changes in the energy of different wave rhythms are often used as a biomarker in developing various brain-computer interfaces [4, 5]. These changes in energy are used to analyze and extract information about the state and activity of the brain.

This work is a continuation of [6] to study a proposed biomarker in the scope of a working memory task.

EXPERIMENTAL

A neurophysiological experiment was performed to test both elementary cognitive functions and the ability to use them simultaneously in a task. A group of 24 children aged 9 to 10 without health problems was assembled. Volunteers and their parents were familiarized with the experiment's procedure in advance and given the opportunity to ask questions and have them answered. The experiment consisted of three parts, separated by 5-min breaks.

Each part of the experiment contained a block of working memory tasks based on the Sternberg paradigm [7]. Each task had an approximate duration of 10 to 12 s. Each subject was shown a set of seven elements arranged in two rows, two or three of which were two-digit numbers that needed to be memorized. The remaining elements were asterisks. A target number was shown after a pause lasting about 3 s, and the subject had to answer whether this number had been listed among those shown previously.

In this work, we investigated a biomarker based on the interconnection between wave rhythm stability and the mean response time. There are three main ways of determining the division into time intervals. One way is to split them into a predetermined number of parts. Another is to divide them into intervals of predetermined duration. The third is tying them to trials where the completion of a task corresponds to each part. In this work, we used the first approach because earlier studies confirmed it was the most effective [6].

A 64-channel EEG was recorded with electrodes positioned according to the international 10–10 scheme. The frequency of sampling the EEG signals while recording was 500 Hz. The signals were processed with a 50 Hz notch filter to eliminate noise from the electrical networks before they were recorded by a LiveAmp 64 electroencephalograph.

Table 1. RM-ANOVA p-value of wave rhythm variance while performing a working memory task

Range	Block	Channels	Block : channels
Alpha	0.00	0.00	0.29
Beta	0.01	0.00	0.90
Delta	0.15	0.01	0.80
Theta	0.02	0.00	0.17

Rhythm stability was calculated by dividing each of the three blocks of tasks into ten equal time intervals with an accuracy of 2 ms. To compensate in advance for the effect of the region of edge phenomena, we added 2 s to these intervals on both sides. Using the formulas specified in [6], we then calculated the wavelet surfaces. Wavelets were transformed separately in four ranges of frequency: 1–4 Hz (delta), 4–8 Hz (theta), 8–14 Hz (alpha), and 14–30 Hz (beta).

The resulting surfaces were next averaged over time and frequency. To avoid edge effects at both ends of the time series, we excluded 1000 points (2 s) that were additionally added in advance at the previous stage.

Frequency-averaged energies were calculated in the standard ranges from the time-frequency wavelet spectrum. To calculate the variance of the energies, each block of tasks was divided into ten parts of equal duration. Variances between these ten values were then calculated separately for each rhythm.

The resulting values were correlated with the mean response times. Spearman's correlations were used to analyze those within the first block of tasks and study connections among people. Repeated measures correlation was used to examine the dynamics of the experiment and identify interrelationships among blocks. Data on every channel of the electroencephalogram were tested separately.

RESULTS AND DISCUSSION

Due to the formulas used in calculations and their origin, the resulting values differed by orders of magnitude. A z-score calculation scheme was employed to reduce variability between the people in relation to the experimental data [8]. A repeated measures variance analysis (RM-ANOVA) [9] was then applied to the obtained results. Statistically significant differences were revealed between the channels in all ranges of frequency and between the blocks in the alpha, beta, and theta ranges (Table 1).

We next analyzed repeated measures correlations between response times and the variance of the channels. Correlations were found in all ranges except alpha (Table 2).

We also analyzed Spearman's correlations between the variance of the channels and the mean response time for the first block of tasks. It was found that a correlation for alpha frequencies existed on Channel C4 only, but there was a correlation for delta frequencies on channel CP2 (Figs. 1 and 2). We found no correlations in the other two ranges of frequency. This could allow us to predict the mean response time from the stability of the above rhythms in the corresponding channels.

Table 2. Repeated measures correlations between RT and variance in different channels

Range	Channels, r
Alpha	Undetected
Beta	FT7, $r = -0.41$
	FT8, $r = -0.40$
Delta	Oz, $r = 0.50$
	F8, $r = 0.50$
	POz, $r = 0.49$
	TP10, $r = 0.40$
	FT8, $r = -0.46$
Theta	Fz, $r = -0.47$
	TP9, $r = -0.42$
	F4, $r = -0.41$
	AF3, $r = -0.43$
	AFz, $r = -0.43$
	F1, $r = -0.41$
	AF4, $r = -0.41$
	F2, $r = -0.40$

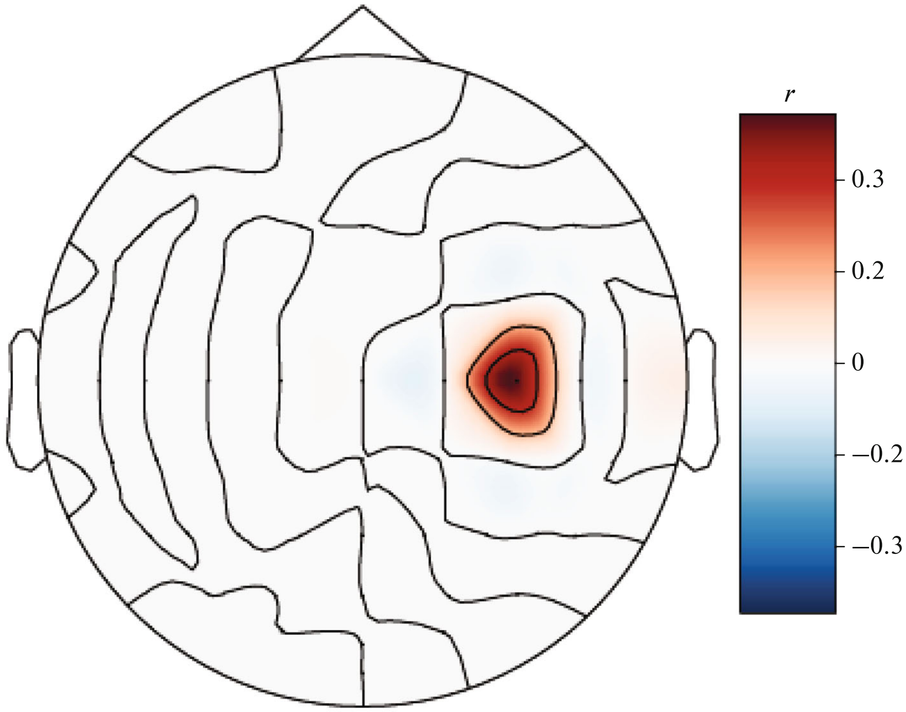

Fig. 1. Topographic map of correlations between alpha-rhythm stability and the mean response time.

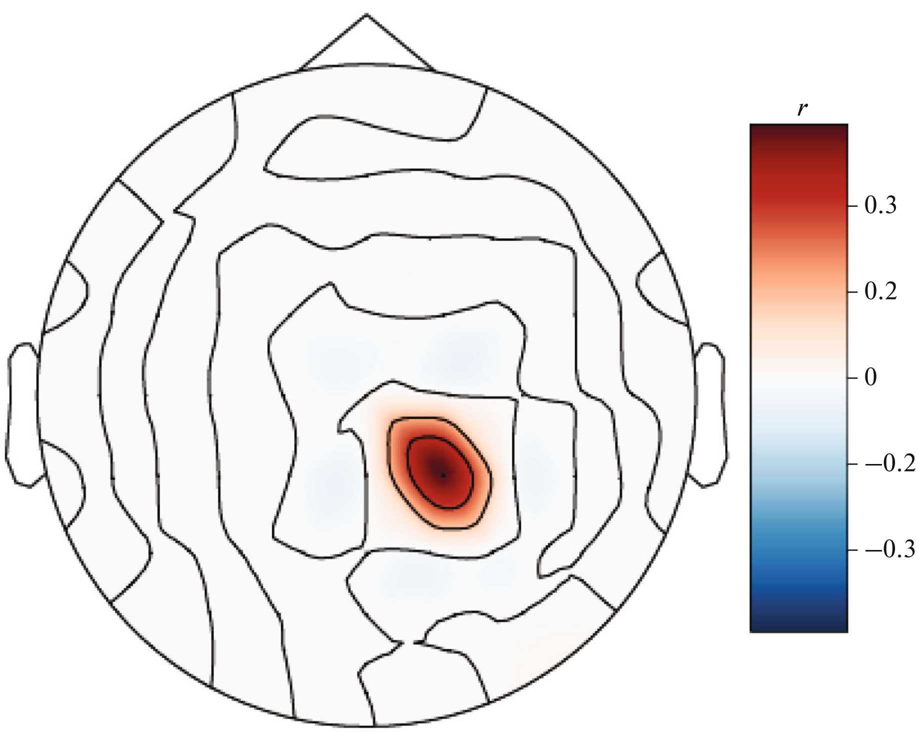

Fig. 2. Topographic map of correlations between delta-rhythm stability and the mean response time.

CONCLUSIONS

In certain ranges of frequency, the stability of the brain's activity correlates with the mean response time when performing a working memory task. It therefore acts as a biomarker that could allow us to predict a decline in cognitive abilities, based on wave rhythm dynamics. These dynamics were also studied during our experiment, and it was shown that this marker can be used in real time. Because the experiment dealt with working memory and not attentiveness, this work (as a continuation of [6]) demonstrates the universal character of the biomarker for different types of cognitive tasks.

FUNDING

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ETHICS APPROVAL AND CONSENT TO PARTICIPATE

All procedures performed in studies with human participants were in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki Declaration and its amendments or comparable ethical standards. They were also approved by the Independent Ethics Committee of the Clinical Research Center, Immanuel Kant Baltic Federal University, protocol No. 32 dated July 4, 2022.

Each participant in the study provided a voluntary written informed consent after receiving an explanation of the potential risks and benefits, as well as the nature of the upcoming study.

CONFLICT OF INTEREST

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

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