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PHYSIOLOGY

Phase Interactions between EEG Rhythms during Short Time Interval Perception

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Abstract—Phase interactions between electroencephalography (EEG) rhythms in the perception of short time intervals were investigated in 27 male and 29 female university students. The study has shown that tight phase relationships are most frequently observed between gamma-rhythm and other EEG rhythms or between different gamma frequencies. We determined that the discussed phase interactions were susceptible to the effect of factors, such as "gender," "activity type," and "activity stage." Links were also detected between these phase interactions and the levels of intelligence, extraversion, neuroticism, the profile of the lateral organization of the brain, and the accuracy of time perception.

Keywords: time perception, phase interaction, EEG rhythms, individual characteristics of a subject

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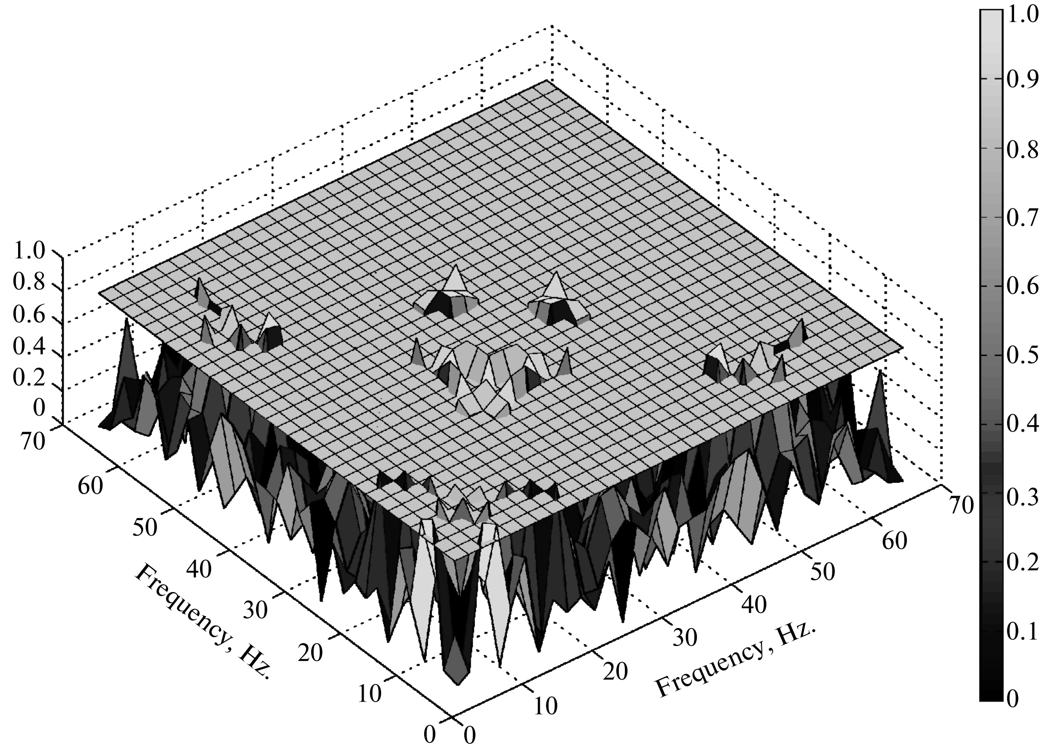
INTRODUCTION

The studies in the mechanisms supporting the functional association of neurons in realizing conscious activities are related to important topics of contemporary neurophysiology. M.N. Livanov and his students have shown in [1–3] that an important role in these processes belongs to the spatial frequency synchronization of the electrical activity of the brain. At the same time, even more popularity among researchers has been gained over recent years by the approach based on the determined chaos theory that gives an important role in the functional association of neurons and the formation of subjective images to nonlinear and phase interactions between electrical potentials of the brain [4]. The role of these interactions in the functional association of neurons and different cognitive processes remains unclear so far. Considering this, the goal of the present research was the study of phase interactions between EEG rhythms in the human perception of short time intervals. The task of this research included studying the dependence of these interactions on the type and stage of the activity performed, as well as on the individual characteristics of a subject.

MATERIALS AND METHODS

The volunteer participants in the study were a group of young students (27 males and 29 females) aged 18 to 22 from higher educational establishments of Tomsk. All the subjects gave their informed consent to their participation in the present investigation. The preliminary examination stage based on the Eysenck questionnaire [5, 6] included tests on verbal and nonverbal intelligence, as well as on the levels of extraversion and neuroticism. Using some array of standard tests, the researchers investigated the profile of the lateral organization of the brain and identified the dominant hand and the speech hemisphere [7, 8].

Under the tests, the subjects were offered to reproduce and admeasure short time intervals lasting 200 and 800 ms with or without feedback signals on the results of their activities. During one series, time intervals were presented as nonverbal stimuli (a light square with 2 cm side that appeared at the center of a dark monitor screen), while numbers were used in the other series (in admeasuring the duration). The subjects reproduced and admeasured time intervals by double pressing the "space" bar. A percentage relative error in reproducing or admeasuring the specified time intervals was used as a feedback signal. The error signal appeared on a monitor screen one second after the reproduction or admeasuring of each time interval for one second. The angular dimensions of the stimuli were 2–2.3 grades in the case of presenting a square and 0.75–0.76 grades if numbers were shown. The standard DOS font was applied for numbers, and its size corresponded to 16 Word points. The stimuli lasting 200 and 800 ms were presented at random, according to the RND function, correcting a multiple "casting" of one value; each stimulus with each value of duration was presented at least 50 times.



Average per group values for the function of biocoherence between the T4 and T5 leads in young males in reproducing visual 200 ms signals without feedback.

The activity stage is 400 ms after the onset of the stimulus; horizontal plane "filters" insignificant (below 0.8) bicoherence function values.

The EEGs were recorded with a 24-channel Encephalan-131-03 encephalograph analyzer along the following leads: Cz, Fz, Pz, F3, F4, C3, C4, P3, P4, T3, T4, T5, T6, O1, O2, according to the "10–20" system. The combined reference electrode was placed on a subject's left and right earlobes, while the grounded electrode was fixed to the right wrist. To exclude artifacts related to eye movements, electrooculargraphies (EOG) were recorded. The electrodes to record EOGs were placed on a subject's left upper and lower eyelids. EEGs and EOGs were recorded at rest with open and closed eyes (during 20 s) and at time perception. The frequency of discretization accounted for 250 Hz at entering analogue signals into a PC. To control the cortical origin of the gamma-rhythm, the dipole localization method was used [9]. In studying phase interactions between high-frequency (30–70 Hz) and low-frequency (0.5–30 Hz) EEG rhythms, the wavelet bispectral analysis was used and the bicoherence function was counted [10]. This function takes on the 0 to 1 values and is the measure of the phase link in the time interval T between the frequency signal constituents f_1, f_2, f_3, which meet the condition $f_3 = f_1 + f_2$. If the phases of one of three components are the sum or difference of the other two, the bicoherence function significantly differs from zero, while this evidences that the phases of the three frequencies are interconnected. When studying the intrahemispheric phase relationships, the bicoherence function values were counted between different frequency constituents of the same EEG signal, whereas these values in studying the interhemispheric phase relationships were counted between different frequency constituents of two EEG signals simultaneously recorded in the same subject along the left-hemispheric and right-hemispheric leads. A half-sum of the values for this function in the investigated EEG frequency range (0.5–70 Hz) was used as an integral characteristic of the EEG rhythm phase interactions.

Analyzing correlational relationships between the investigated indicators, we counted Spearman's rank correlation coefficient. To evaluate the effect of the investigated factors (gender, activity stage, and activity type) on the phase interactions, we used multifactor dispersion analysis. The statistical data were treated using the applied Statistica v. 6.0 and MatLab v. 6.5 software.

RESULTS AND DISCUSSION

A bicoherent analysis allowed us to detect close intra- and interhemispheric phase relationships between the EEG rhythms in both the background and time perception. The phase relationships have

Combined effect of the gender and activity type factors on the interhemispheric phase interactions between the EEG rhythms at the first pressure on the space bar activity stage

Leads	Fisher's test values (F)	Significance level (p)
O1–T6	3.72	0.02
F3–C4	3.75	0.01
F3–T6	3.22	0.03
P3–P4	3.69	0.02
P3–T6	3.04	0.03
T5–P4	3.30	0.02
T5–T6	3.16	0.03

appeared to be more frequently observable (in approximately 60–70% cases) between gamma-rhythm and low-frequency EEG constituents (0.5–30 Hz), as well as between different gamma-rhythm frequencies. The bicoherence function values reach 0.8 and higher at the indicated frequencies.

Average per group bicoherence function values between the T4 and T5 leads in males in reproducing visual 200 ms signals without feedback are presented in figure.

It is seen from this figure that the closest phase relationships are observed between low-frequency EEG constituents (0.5–20 Hz), between the gamma-rhythm at 40–60 Hz and the rhythms at a frequency of 5–20 Hz, and between different gamma-rhythm frequencies (30–36, 38–44 Hz).

A dispersion analysis has shown that the gender and activity stage factors when reproducing the duration of nonverbal visual stimuli produce a statistically significant effect on the level of phase relationships between EEG rhythms in the C4 ($p = 0.02$) and T3 ($p = 0.03$) leads. In particular, the influence of the gender factor on the level of phase relationships is manifested in women as higher mean bicoherence function values than in men in the C4 lead. There are no differences in the levels of phase relationships in other leads between males and females.

The activity stage factor in admeasuring time intervals produce a statistically significant effect on the level of phase relationships between EEG rhythms only in the C3 ($p = 0.008$), T5 ($p = 0.003$), and T6 ($p = 0.022$) leads. The effect of this factor is manifested in the increased mean bicoherence level in the indicated leads from the first (digital stimulus presentation) to the final stage of admeasuring the specified time interval (the second pressure on the bar). No effect of the gender factor on the level of the same relationships has been established.

Similar data were also obtained studying interhemispheric phase interactions between the investigated EEG rhythms. A dispersion analysis allowed us, in particular, to detect a statistically significant combined effect of the gender and activity type factors on the interhemispheric phase interactions.

The dispersion analysis results characterizing a combined effect of the gender and activity type on the investigated phase interactions at the stage of the "first pressure on the space bar" are presented in the table.

We see from the table that the gender and activity type factors in question produce their statistically significant combined effect on the level of interhemispheric phase relationships between occipital and temporal, frontal and central, frontal and temporal, parietal, temporal, parietal and temporal cortices of the left and right hemispheres at the first pressure on the space bar activity stage. These interhemispheric phase relationships reflect the interaction of the "interested" corteces at the stage of preparing and realizing the motor action (pressing the computer bar).

In addition, the conducted investigations allowed us to detect the presence of statistically significant correlations between the level of intra- and interhemispheric phase interactions and the indicators for verbal and nonverbal intelligence, extraversion and neuroticism, the profile of the lateral organization of the brain, and the time perception accuracy. The value of the found Spearman's correlation coefficients varied from 0.56 to 0.98 ($p = 0.05 + 0.003$) in absolute values. The found correlations evidence that the phase interactions between the EEG rhythms substantially depend on the individual psychophysiological characteristics of a subject and interfere with the time perception accuracy.

It has been established that the character of the indicated correlations is different in males and females and depends on the type and the stage of the activity performed. For example, negative correlations were found between the level of interhemispheric phase relationships and the indicators of extraversion ($r = -0.63$–0.84, $p < 0.01$) and neuroticism ($r = -0.59$–0.63, $p < 0.01$), while positive correlations were detected between the mentioned level and the right ear ($r = 0.55$, $p < 0.05$) coefficient in females when reproducing the duration of stimuli with feedback at the stage of 100 ms before the onset of a stimulus. In young men in the same period of activity, positive correlations were found between the level of interhemispheric phase relationships and the indicators of intelligence ($r = 0.76$–0.90, $p < 0.01$) and manual preference ($r = 0.78$, $p < 0.03$), and the right ear coefficient ($r = 0.82$, $p < 0.02$).

Thus, the conducted investigations have shown that the discussed phase interactions are informative and reflect the type and stage of the activity performed, as well as individual characteristics of a person. The dependence of phase interactions on the gender factor is probably, in fact, explained by the gender-specific profile of the lateral organization of the brain, which is most brightly manifested in the interhemispheric relationships [11]. Positive different gender-specific correlations found by us in males and females between the level of interhemispheric phase relationships and the manual preference indicator and the right ear indicator evidence in favor of the stated suggestion.

A special interest is stirred by the found correlations between the level of phase interactions and the time perception accuracy, as well as the indicators for intelligence, extraversion, neuroticism, and the lateral organization of the brain, on which the efficiency of intellectual activity is known to depend [12]. Considering the data that the phase interactions between the EEG rhythms can provide the functional association of neurons [4], as well as encoding, pressurization, and coordination of neural messages throughout the brain [13], we can expect that these interactions play an important role not only in time perception but also in other cognitive processes.

The obtained data indicate a special role of gamma-rhythm in the formation of the discussed phase relationships, since close intra- and interhemispheric phase relationships are most frequently (approximately in 60–70% of cases) observed between the gamma-rhythm and other EEG rhythms or between different gamma frequencies. It may be associated with the fact that gamma-rhythm provides an increased efficiency of synaptic inputs [14] and thus contributes to the functional association of neurons.

CONCLUSIONS

(1) There are close intra- and interhemispheric phase relationships between EEG rhythms. These relationships are most frequently (in 60–70% of cases) observed between gamma-rhythms and low-frequency EEG rhythms, as well as between different gamma frequencies.

(2) The following factors have a significant effect on phase interactions: a subject's gender and the type and stage of the activity performed.

(3) Statistically significant correlations have been found between the level of phase interactions and the time perception accuracy and the indicators of intelligence, extraversion, neuroticism and the lateral organization of the brain. The character of these correlations is different in young males and females and depends on the type and stage of the performed activity.

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