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RESEARCH ARTICLE

The Study of Rhythmic Component Interaction at the First Stage of Day Sleep

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Abstract—The interaction of EEG rhythms is an important indicator of the functional state of the human brain. There currently exist three theories explaining this interaction: (1) communication of neuronal populations, (2) neuronal interaction, and (3) interaction between generators of the frequencies being studied. It is known that the theta rhythm is associated with the functioning of cortico-hippocampal and alpha-rhythm-thalamo-cortical systems, and the beta rhythm can be included in the activity of both cortico-subcortical systems. The present work may clarify the features of the above-mentioned cortico-subcortical systems. There is a number of publications devoted to the study of EEG rhythm interaction in various types of psychical activity. At the same time, a concern for interaction of the rhythms at different sleep stages appeared in recent years. The task of our work included the study of the interaction between theta, alpha, and beta EEG rhythms at the first stage of sleep. The study involved 22 subjects from 18 to 22 years old. Multichannel EEG was recorded during daytime sleep of the experiment participants. EEG segments with well-expressed theta rhythm were selected for the processing since it is "dominant" at the first stage of sleep. Bandpass filtering of the EEG signal was then performed. The following rhythms were discriminated: theta rhythm (4–7 Hz), alpha rhythm (8–13 Hz), beta-1 (14–19 Hz), and beta-2 (20–25 Hz) rhythms. Afterwards, for each range at each second, the average amplitude was calculated as the square root of the EEG signal dispersion. The Pearson correlation coefficient was used as a measure to evaluate the interaction of EEG rhythms. As a result, it was established that the first stage of sleep is characterized by: (1) a lack of connections between the theta rhythm and other rhythms, (2) the presence of alpha–beta-1, alpha–beta-2, and beta-1–beta-2 links, (3) the increase in theta amplitude, and (4) the decrease in the amplitudes of alpha and beta rhythms. As was noted above, the theta rhythm is associated with functioning of the cortico-hippocampal system, and the alpha rhythm is associated with the thalamo-cortical system. In our work, two coexisting types of functioning of these systems are shown: (1) the "independent" one of the cortico-hippocampal circuit and (2) the thalamo-cortical one, connected with other rhythms, particularly with the beta rhythm. This heterogeneity is probably a condition for the first stage of sleep to be potentially unstable. An increase in theta rhythm amplitude at the first stage of sleep against the state of quiet wakefulness is shown. This is traditionally associated with the increase in ascending effects of limbic structures of the brain. Amplitudes of alpha and beta rhythms at the first stage of sleep significantly decreased, which indicates an attenuation of the influence of prefrontal cortical regions on posterior hypothalamus centers. Hence, it can be assumed that the onset of the first stage of sleep can be provided by the heterogenous character of rhythm interaction, and, correspondingly, different functioning of cortico-hippocampal and thalamo-cortical systems.

Keywords: EEG rhythm interaction, alpha rhythm, theta rhythm, beta rhythm, average amplitude of EEG rhythms, thalamo-cortical system, cortico-hippocampal system, first stage of sleep.

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The problem of EEG rhythm interaction research is of current importance. Cognitive processes of the brain require a coordinated activity of neural networks involved in the generation of EEG rhythms, which, in turn, support human's higher psychical functions. It is suggested to be reflected in EEG in the form of activity coordination in different frequency ranges [1]. In works of de Munk and Roopun [2, 3], an interaction of alpha and beta rhythms is shown. Alpha and beta rhythm oscillators "turn on and off" simultaneously; beta-1 and beta-2 rhythms can generate alpha rhythm. It is shown that there is a correlation in patients with neurogenic pain, epilepsy, and motoric disorders of theta and beta rhythms of hypothalamic nuclei's activity. The suggestion about strict functional interaction of generators of these rhythms is made [4]. In a quiet wakeful state in Alzheimer patients, an increase in the interaction of fast (beta and gamma) and slow (delta and theta) EEG rhythms as compared with healthy subjects is detected [5].

In our works considering cognitive attitude, we detected a connection of alpha and beta-2 rhythms in students with a rigid type of attitude and an interaction of beta-2 and theta rhythms in students with a flexible type attitude [6].

Currently there exist three explanations of interaction between different EEG rhythms: (1) communication of neuronal populations, (2) neuronal interaction, and (3) interaction of generators of frequencies under study [7]. Based on the first explanation, we made a prediction that, at the increase of correlations between rhythms, there is an interaction between different neuronal populations, generating different rhythms, inside one subcortical system, integrating its different structures or integrating structures of two or more cortico-subcortical systems.

Recently, a number of studies on EEG rhythm interaction in sleep appeared [8–10]. The fact of interaction between fast and slow rhythms at the third stage of sleep is detected [11]. The interaction of theta and gamma rhythms in the paradoxical stage of sleep is shown [12]. In our work conducted on students with sleep disorders, we revealed no coherence of alpha and theta rhythms with beta rhythm in performing an emotional facial expression recognition task [13].

The first sleep stage is transitional from wakefulness to sleep. It is interesting by the fact that both EEG characteristics of quiet wakefulness and sleep-typical EEG features may remain in it. Classically, the first stage of sleep is characterized by the alpha power decrease and the increase in theta rhythm [14]. In this connection, a reasonable interest into the features of EEG rhythm interaction on the first sleep stage appears.

The purpose of the performed work was to estimate the amplitude interaction of theta, alpha, and beta rhythms on the first stage of sleep, and also to study changes in rhythmical coherences in a quiet wakeful state.

MATERIALS AND METHODS

The experiment involved 22 subjects, medical students (12 men and ten women from 18 to 22 years old, whose mean age was 19.8 ± 0.8 years). Before the commencement of the experiment, the "FAM" (feeling-activity-mood) inventory was offered to the subjects to record their functional condition; the quality of night sleep was estimated with the help of the Carolina sleepiness scale. The participants signed informed consent for participation in the experiment. The experiment was carried out in daytime, from 1:00 to 4:00 p.m. The data of 16 of 22 persons were used for distinguishing sleep phases. In six subjects, the first sleep stage did not come or the EEG failed to be recorded without artefacts. A subject was placed in a sound-damping, lightproof room at the stable temperature of 24°C. During the experiment, the recording was performed with a sampling rate 500 Hz of 16 EEG channels located on the scalp according to the 10–20 layout and two channels of an electrooculogram (EOG), with the help of the wireless hardware-software complex Neuropolygraph 24 (software by Neurotech, Russia). The EEG derivation was monopolar.

After the application of the electrodes, a subject made himself comfortable on a couch. After that, a background recoding of EEG and EOG was performed during 3 min with the subject's eyes closed. The sleep EEG was then recorded during 20 min. Over this time, the subjects developed the first sleep stage, which started at different times. The first and the second stages of sleep were detected by the standard criteria [15]. Each 20 sec of recorded EEG were analyzed. The first stage of sleep is characterized by the alpha power decrease and the increase in theta rhythm. For the control of temporal limits of the first stage of sleep, we determined the beginning time of the second stage of sleep, characterized by the presence of no less than one sleep spindle, which is the main criterion of its onset. This, in turn, was the ending of the first stage. Duration of the first stage was very variable in different subjects. We looked for the lowest duration of the first stage, and 20–30-s artifactless EEG fragments of the first sleep stage were studied. Since it was longer in most of the subjects, EEG fragments of the mentioned duration were taken for the statistical analysis. EEG fragments with the most expressed theta rhythm were chosen, since it is "dominant" at the first sleep stage. The bandpass filtering of the EEG signal was then performed: theta rhythm (4–7 Hz), alpha rhythm (8–13 Hz), beta-1 (14–19 Hz), and beta-2 (20–25 Hz) rhythms were discriminated. Separately, for the filtration, the average amplitude was calculated by each range at each second as the square root of the EEG signal dispersion. This method of estimation of amplitude by range is more economical in the amount of required calculations in comparison with the wavelet transform we used earlier [6].

For the statistical analysis, we used amplitudes' mean values for the studied EEG rhythms. They were calculated by the function values of corresponding rhythms' variation, averaged by 20–30 1-s EEG fragments. The averaging by all registered EEG derivations was also performed.

Table 1. Correlation of EEG rhythms by their average amplitude in a quiet wakeful state with eyes closed

Stages of the study	EEG rhythms	Statistical values
Quiet wakefulness	theta – beta-1	$r = 0.63$; $P = 0.012$
	theta – beta-2	$r = 0.69$; $P = 0.005$
	alpha – beta-1	$r = 0.72$; $P = 0.002$
	alpha – beta-2	$r = 0.73$; $P = 0.002$
	alpha – theta	$r = 0.74$; $P = 0.001$
	beta-1 – beta-2	$r = 0.85$; $P = 0.000$

Table 2. Correlation of EEG rhythms by their average amplitude in the first sleep stage

Stages of the study	EEG rhythms	Statistical values
First sleep stage	theta – beta-1	
	theta – beta-2	
	alpha – beta-1	$r = 0.73$; $P = 0.001$
	alpha – beta-2	$r = 0.83$; $P = 0.000$
	alpha – theta	
	beta-1 – beta-2	$r = 0.90$; $P = 0.000$

The analysis of variance (ANOVA RM) was implemented to estimate statistical significance of the results. The “condition” factor was considered an intragroup factor (two levels: quiet wakefulness and the first sleep stage). The significance of its influence was estimated individually for each studied rhythm. The difference of amplitudes was also studied using a pairwise t-test.

The Pearson correlation coefficient was used as a measure to estimate the interaction of two subranges of beta rhythm with theta and alpha rhythms. The correlation coefficient of the studied rhythmic ranges was calculated individually for different studied situations: quiet wakeful; first sleep stage). The statistical processing was performed with the help of SPSS v.13 software kit (SPSS Inc. IBM, United States).

RESULTS

A comparison of interactions of theta, alpha, beta-1, and beta-2- EEG rhythms in a quiet wakeful state (background with eyes closed) and on the first sleep stage was conducted. The highest number of rhythm coherencies in the experiment was revealed in a quiet wakeful state with eyes closed: the theta rhythm interacted with the alpha rhythm and both subranges of the beta rhythm, the alpha rhythm interacted with theta and beta rhythms, an also both beta subranges between themselves (Table 1).

On the first sleep stage, a significant decrease in the number of rhythm coherencies as compared to quiet wakefulness is shown. Three coherent pairs are revealed: alpha-beta-1, alpha-beta-2, and beta-1-beta-2 (Table 2). The cause of the reduction in coherencies is an absence of links between the theta rhythm with the fast rhythms.

The analysis of variance (ANOVA RM) showed that the “condition” factor exerts a significant influence on the total amplitude values of theta ($F(1;12) = 7.42$; $P = 0.018$), alpha ($F(1;12) = 14.01$; $P = 0.003$), beta-1 ($F(1;12) = 14.91$; $P = 0.002$), and beta-2 ($F(1;12) = 36.00$; $P = 0.0001$) rhythms. Thus, the amplitude indices of the studied rhythms significantly change in the transition from a background state with eyes closed to the first sleep stage.

To clarify the character of changes in EEG amplitude characteristics, we conducted a pairwise comparison (by t-criterion) of mean amplitude values of the studied rhythms in a quiet wakeful state and in the first sleep stage (Table 3). The significant differences of amplitudes of the rhythms in the studied states are shown. A significant increase in theta rhythm amplitude at the first stage of sleep is revealed. At the same time, a decrease in amplitudes of alpha rhythm and beta subranges is noted.

Thus, the first stage of sleep was characterized by: (1) the lack of connections of theta-rhythm with other rhythms, (2) the increase in the theta rhythm amplitude, and (3) the decrease in amplitudes of alpha and beta rhythms.

DISCUSSION

The interaction of EEG rhythms is an informative characteristic for determining the functional state of subjects. In our earlier work [6], a connection of the beta rhythm with alpha and beta rhythms in cognitive attitude formation is shown. In a work conducted on students with sleep disorders, no coherence of alpha and theta rhythms with the beta rhythm in the forma-

Table 3. Statistical differences of mean amplitude values in ranges of theta, alpha, and beta rhythms at different stages of the experiment

EEG rhythms	Quiet wakefulness	First sleep stage	Statistical values
theta	6.24 + 0.36	7.31 + 0.36	$t = 4.21$; $P = 0.001$
alpha	11.82 + 1.42	6.66 + 0.82	$t = -3.83$; $P = 0.002$
beta-1	4.98 + 0.48	3.71 + 0.31	$t = -3.23$; $P = 0.007$
beta-2	3.44 + 0.22	2.50 + 0.23	$t = -5.77$; $P = 0.000$

tion of cognitive attitude is revealed [13]. It is known that the beta rhythm can be recorded not only in the big hemisphere cortex but also in thalamic and hypothalamic structures [16, 17]. Traditionally, thalamocortical and cortico-hippocampal cortico-subcortical systems are associated with the appearance of alpha and theta rhythms, correspondingly, in EEG. Perhaps, the inclusion of the beta rhythm in "beta-alpha" and "beta-theta" complexes makes it possible to maintain the required activation level of these cortico-subcortical systems for the implementation of psychical activity. In a work on rhythm interaction in sleep [8], it was shown that the highest number of coherencies between rhythms is observed in the third sleep stage, while the lowest one is in the paradoxical sleep stage, both in healthy subjects and in epilepsy patients. In the work of Li [10], a significant interaction of slow oscillations (0.1–1.5 Hz) and spindles (12–16 Hz) from the first to the fourth sleep stage is shown.

In our work, the interaction of rhythms at the first sleep stage was studied. A substantial reduction in coherencies was revealed against a quiet wakeful state with eyes closed. The first stage of sleep is characterized by an alpha amplitude decrease and an increase in theta rhythm in EEG [14]. It seemed logical that the "dominant" theta rhythm in our study would be somehow related to other rhythms. Our expectation proved to be incorrect. At the same time, the coherencies of alpha and beta rhythms were preserved. Why does it happen this way? In the work by Yeh [18], there is a notion that the decrease in the number of rhythm coherencies makes allowance to release a reserve for combining the studied rhythms into some other pairs. In further sleep stages, theta rhythm will perhaps be integrated with some other rhythm. The first sleep stage includes EEG characteristics both of sleep and wake. That is possibly why, in the decrease of alpha and beta amplitudes, their connection is preserved, which, in the following sleep stages, may be transformed into a more stable mode, which can result in awakening, and into less stable mode as well, which, in turn, would result in the deepening of the sleep.

As noted above, the theta rhythm is associated with the functioning of the cortico-hippocampal system, and alpha rhythm is associated with the thalamo-cortical system. In our work, two coexisting types of functioning in these systems are shown: the "independent" one of the cortico-hippocampal circuit and the thalamo-cortical one connected with other rhythms, particularly with the beta rhythm. This heterogeneity is probably a condition for the first stage of sleep to be potentially unstable.

A study of the dependency of the dynamics of studied EEG rhythms on a stage of the experiment was conducted. The anticipated increase in theta rhythm amplitude is shown at the first stage of sleep against the state of quiet wakefulness. This is traditionally associated with an increase in ascending effects of limbic structures. Amplitudes of alpha and beta rhythms at the first stage of sleep significantly decreased, which indicates an attenuation of the prefrontal cortical regions' influence on posterior hypothalamus centers. These data, to a certain degree, correspond with results obtained in the work by Yeh [18], where a decrease in beta power with the deepening of sleep is noticed.

As a conclusion, it can be said that the first stage of sleep was characterized by: (1) the lack of connections of the theta-rhythm with other rhythms, (2) the presence of alpha–beta-1, alpha–beta-2, and beta-1–beta-2 rhythm links, and (3) the increase in theta rhythm amplitude, and the decrease in the amplitudes of alpha and beta rhythms. Based on this, it can be assumed that the onset of the first stage of sleep can be provided by the heterogeneous character of rhythm interaction, and, correspondingly, different functioning of cortico-hippocampal and thalamo-cortical systems.

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CONFLICT OF INTERESTS

All the participants signed informed consent for participation in the experiment. The protocol of the study was approved by the ethical committee of the Institute of Higher Nervous Activity and Physiology. The authors declare no conflict of interests.

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