EXPERIMENTAL PAPERS

Dynamics of EEG Rhythm Interaction Preceding the Awakening Moment with Subsequent Restoration of Activity after Brief Falling Asleep Episodes

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Abstract—A study of the sleep-to-wake transition accompanied by the restoration of activity makes it possible to explore the successive activation of different levels of consciousness upon awakening. Here, we explored this process using a continuous discrete psychomotor test as an experimental model. The study was aimed to analyze the dynamics of EEG rhythm coupling over the 20-s interval that precedes the moment of cognitive awakening (the appearance of a pronounced alpha rhythm). For multi-channel EEG analysis, we used the algorithm of continuous wavelet transform based on Morlet wavelet as a mother wavelet. The amplitude interaction of EEG rhythms (delta, theta, alpha1, alpha 2, beta, and gamma) was assessed using the Kendall correlation coefficient. It was shown that the process of awakening from sleep is a prolonged phenomenon with a complex dynamics of EEG rhythm coupling. Three blocks of such couplings were identified, manifesting themselves differentially as the moment of cognitive awakening approached. Within the 20−15-s interval before awakening, the block of alpha−beta and alpha−gamma rhythm couplings was predominant, although single delta−theta, theta−alpha1 and beta−gamma couplings were also present. The next interval (15−5 s) before awakening was characterized by joining the block of theta rhythm couplings with faster rhythms to the already active block of alpha rhythm couplings. The third block of delta rhythm couplings with theta and alpha rhythms joined in the 5−0-s interval before awakening.

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INTRODUCTION

The problem of sleep−awakening−wake proportion remains relevant up to now. In this triad, the state of awakening is transitional, preceding quiet waking state or the state of activity, if there was any activity before sleep. Why is exactly the waking state of particular interest? Assuming that there is consciousness in sleep, it should certainly be different from awake consciousness [1, 2]. Therefore, it is important to understand what happens during the awakening period, which neu-

rophysiological processes contribute to consciousness transitioning to a qualitatively different level. Two types of awakening have been studied, cognitive and behavioral, with the former preceding the latter [3]. The waking state is accompanied by an increase in the number of connections in neural networks, both cortico-cortical and cortico-thalamic. The reticular activating system has been shown to be involved in the process of awakening through combining the influences from different brain structures, thus determining the general level of CNS activity. Within the first 10 min upon nocturnal awakening, an increase in the power of potentials increases in the band of 1−9 Hz and decreases in the band of 18−24 Hz. Low-frequency activity prevailed in the occipital cortex of the cerebral hemispheres [4, 5]. Spontaneous awakenings, as well as those induced by external stimulation, were studied in nocturnal sleep experiments in epileptic patients. It was found that EEG frequency characteristics during awakening differ from both waking and sleeping states. Electrical activity of the thalamus remains invariable regardless of the type of awakening, while its spectral composition corresponds to an intermediate state between sleep and wake. During non-rapid eye movement (NREM) or slow-wave sleep, it was characterized by a decrease across the entire frequency band, whereas during rapid eye movement (REM) sleep, this decline in activity was limited to delta−sigma bands. Cortical activity patterns during awakening were heterogeneous; their diverse spectral compositions were mainly related to such factors as the sleep stage, cortical area, and type of awakening (spontaneous or evoked by external stimulation) [4]. A study of the brain default mode networks (DMNs) showed that functional connectivity between brain networks was severely disrupted both 5 and 25 min after awakening from sleep compared to the pre-sleep state. Significant correlations were found between the delta EEG power and functional connectivity between the DMNs and dorsal attention networks [5]. A reduction in functional connectivity in the DMN has been shown in patients with mild cognitive impairments accompanied by nocturnal awakenings as compared to the similar patients but with intact sleep. These reductions encompassed the brain areas that play a decisive role in sleep and memory [6].

Currently, there is persisting interest in the problem of EEG rhythm interaction [7, 8], which is studied both on healthy people performing various tasks and, accordingly, being in different functional states, and on patients. Phase−amplitude, phase−phase, and amplitude−amplitude couplings of EEG rhythms are now well documented. There is an opinion that the mechanisms underlying the interaction of EEG rhythms are substantially different. Phase−amplitude rhythm coupling reflects the communication among neuronal networks [9]. Phase−phase coupling manifests itself in a phase alignment of neuronal oscillations, which may reflect the frequency-specific characteristic of interneuronal interactions [10]. EEG cross-frequency phase synchronization is based on the neuron−neuron interaction or communication among neuronal populations [11]. Rodriguez-Martinez et al. [12] suggest that amplitude−amplitude rhythm coupling is a manifestation of the functional interaction between rhythm generators. Amplitude coupling reflects a temporal co-modulation of the amplitude (or power) of neuronal oscillations, which is not only a result of neuronal interactions, but can also regulate these interactions by temporal alignment of distant processes. Amplitude coupling is expressed in well-structured cortical networks, which correspond to the known anatomical and functional connections [10].

Cross-frequency interaction of EEG rhythms can serve as a mechanism to transfer information from the large brain networks to the local ones, integrating thereby functional systems [13].

Recently, there have been carried out some studies on the interaction of EEG rhythms during sleep [14, 15]. Based on cross-frequency EEG rhythm coupling, attempts have been made to generate classifiers for automatic sleep stage scoring [16, 17]. Animal studies have revealed the coupling of fast and slow rhythms during stage 3 sleep in primates [18], as well as that of theta and gamma rhythms at the paradoxical (REM) sleep stage in mice [19]. When studying rhythm interaction during stage 1 sleep, there have been demonstrated the absence of theta rhythm coupling with other rhythms and the presence of

alpha–beta1, alpha–beta2, and beta1–beta2 rhythm coupling [20]. However, we failed to find in the literature an analysis of the coupling between rhythms upon awakening.

The present work aimed to study the process of awakening that precedes the psychomotor test. Our specific goal was to analyze the amplitude–amplitude interaction (cross-frequency coupling) of EEG rhythms at the stage of cognitive awakening during daytime sleep preceding the implementation of the above test.

MATERIALS AND METHODS

Subjects. Twenty-three people (16 females and 7 males, aged 19–22 years, all students, right-handers) were involved in the experiment. All subjects were acquainted with the research procedure and gave their written consent to participate in the study. The experimental protocl complied with ethical standards of the Declaration of Helsinki of the World Medical Association "Ethical Principles for Conducting Medical Research Involving Human Subjects", as amended in 2000, and the "Rules for Clinical Practice in the Russian Federation", approved by the Order of the Ministry of Health of the Russian Federation no. 266 of 19 June 2003. The daytime sleepiness level was assessed using the KSS (Karolinskaya Sleepiness Scale) questionnaire.

Research procedure. Time of the experiment: from 1 to 4 PM; duration: from 55 min to 1 h. The subjects were placed on a couch in a darkened, soundproof and ventilated chamber at a constant comfortable temperature.

A continuous-discrete psychomotor test developed by V.B. Dorohov was used in the experiment [21]. The subjects were to count in their heads from 1 to 10. Simultaneously, at each count, they were to press the button attached to the index finger with the right hand thumb. Next, they kept counting in the same way from 1 to 10, but without pressing the button any more. The alternation of counting with and without pressing the button was continued until the subjects fell asleep or stayed awake until the end of the experiment. In the case of falling asleep and subsequent spontaneous awakening, they were to resume the psychomotor test immediately. The test instruction

particularly emphasized that, upon awakening, one must first perform the count with and only then without pressing the button.

Monopolar EEG recording was carried out from the surface of the head via 17 electrodes placed according to the international 10–20% system (F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4, P3, P4, Pz, T5, T6, O1, O2), using the ipsilateral combined auricular electrode as a reference. Electrooculogram (EOG), electromyogram (EMG), and mechanogram (MG) of button pressing were recorded in parallel with EEG. A pneumatic button, sensitive to the force of pressing, was used to record the pressings. Simultaneously with MG of pressing the button, we recorded EMG of the short muscle abducting the right hand thumb (*musculus abductor pollicis brevis*). All indicators were recorded using Neocortex-Pro system (Neurobotics, Russia). The sampling frequency was 250 Hz; frequency bandwidth was 0.5–70 Hz. EEG was recorded using a special helmet with chlorosilver electrodes (resistance ≤ 5 KOhm).

Before psychomotor testing, the subject's EEG was recorded for 5 min in the quiet waking state with eyes shut.

Data analysis. Twenty-s EEG segments preceding the awakening were analyzed.

The criterion for spontaneous awakening was the moment when an alpha rhythm appeared in most EEG leads with subsequent resumption of the psychomotor test. This criterion of EEG activation during sleep has been used in a number of works [4, 21]. Notably, the appearance of a pronounced alpha rhythm preceded the onset of button pressing, with this interval varying from 1 to 8 s, averaging 3–4 s. The above criterion meets the criteria of the American Sleep Disorders Association (ASDA). Awakenings were defined as abrupt EEG frequency shifts arisinging after at least 10 s of stable sleep and lasting 3–15 s [22]. A total of 65 EEG segments were selected for analysis, with sleep time (microsleep) before awakening ranging from 1.5 to 14 min. The number of spontaneous awakenings in the analyzed sample varied from 1 to 8, averaging 3.47 ± 0.58.

The pre-awakening EEG characteristics for the appropriate segments of EEG records were assessed using a continuous wavelet transform

Table 1. Coupling of EEG rhythms as revealed by the Kendall correlation coefficient in the quiet waking state (20 s)

EEG rhythms		theta	alpha1	alpha2	beta	gamma
delta	R	0.53	0.36			0.33
	p	< 0.01	< 0.05			< 0.05
theta	R		0.57	0.52	0.56	0.48
	p		< 0.001	< 0.01	< 0.001	< 0.01
alpha1	R			0.77	0.6	0.59
	p			<0.001	< 0.001	< 0.001
alpha2	R				0.79	0.76
	p				< 0.001	< 0.001
beta	R					0.84
	p					< 0.001

R—Kendall correlation coefficient; p—significance level.

(CWT) based on the Morlet mother wavelet (Matlab 78.01; script parameters were taken from [23]). For all the selected pre-awakening EEG segments, there were plotted the distribution maps of the wavelet transform coefficient (WTC) absolute values in the 0.5–40 Hz band with a pitch of 0.5 Hz and a time resolution of 1 ms. For each subject, the WTC was averaged over the number of his/her awakenings per experiment.

Then, the WTC was averaged in the delta (0.5–3.5 Hz), theta (4–7.5 Hz), alpha-1 (8–10.5 Hz), alpha-2 (11–14.5 Hz), beta (15–19.5 Hz), and gamma (20–40 Hz) frequency ranges. The resultant values were averaged over time: for the whole 20-s interval and separately for 4-s and 5-s intervals. Next, individually for each subject, time-averaged WTC values were re-averaged across all of the recorded leads for each of the selected EEG ranges. Thus, each subject's EEG for each of the four pre-awakening time intervals was described by six frequency characteristics (by the number of the six frequency ranges selected for analysis).

The Kendall correlation coefficient (KC) was chosen as a measure of interaction between two EEG rhythms. For example, to determine the strength of interaction between delta and alpha-1 rhythms, we took the calculated delta and alpha-1 EEG indicators for each subject ($n = 23$) and calculated the KC in between. This procedure was performed for all pairs of rhythms, both for the entire 20-s pre-awakening time interval and individually for each of the 4-s and 5-s intervals into which the former interval was divided.

Based on the assumption that intra- and inter-subject estimates measure a comparable construction, in order to increase the statistical significance of the estimates, the intra- and inter-subject correlations were pooled into a single general sample. At the same time, we suppose that averaging makes it possible to level off individual characteristics of the subjects and to reveal against their background an overall correlation of EEG rhythms.

Data were statistically processed using an SPSS v.12 software package.

RESULTS

In this work, we investigated the interaction of EEG rhythms within a 20-s period before cognitive awakening when performing a psychomotor test and in the quiet waking state with eyes shut before the onset of the experiment. The quiet waking state was characterized by a largest number of significantly coupled EEG rhythms (13 pairs, Table 1).

A study of EEG rhythm coupling during the 20-s pre-awakening period revealed 8 pairs of statistically significant couplings between EEG rhythms (Table 2).

Table 2. Coupling of EEG rhythms as revealed by the Kendall correlation coefficient during the whole 20-s pre-awakening period

EEG rhythms		theta	alpha1	alpha2	beta	gamma
delta	R	0.421				
	p	< 0.01				
theta	R		0.674	0.347		
	p		< 0.001	< 0.05		
alpha1	R			0.653	0.516	0.516
	p			< 0.001	< 0.01	< 0.01
alpha2	R				0.7376	0.484
	p				< 0.001	< 0.01
beta	R					0.705
	p					< 0.001

R—Kendall correlation coefficient; p—significance level.

Table 3. Coupling of EEG rhythms as revealed by the Kendall correlation coefficient within the 20−15-s pre-awakening interval

EEG rhythms		theta	alpha1	alpha2	beta	gamma
delta	R	**0.495**				
	p	**< 0.01**				
theta	R		**0.442**			
	p		**≤ 0.01**			
alpha1	R			**0.674**	**0.463**	
	p			**< 0.001**	**< 0.01**	
alpha2	R				**0.705**	**0.4**
	p				**< 0.001**	**0.01**
beta	R					**0.589**
	p					**< 0.001**

R—Kendall correlation coefficient; p—significance level. Bold—delta rhythm couplings (1st block of EEG rhythm couplings); bold underlined—theta rhythm couplings (2nd block of EEG rhythm couplings); bold double-underlined—alpha and beta rhythm couplings (3rd block of EEG rhythm couplings).

A more detailed analysis carried out across each 5-s interval within the studied 20-s period showed a complex dynamics of EEG rhythm coupling during awakening. First, the number of significant rhythm couplings increased from the most distant 5-s interval to the closest to awakening. While 6 pairs of EEG rhythm couplings were detected within the farthest 5-s interval, 10 of them were revealed within the closest one. Second, the pattern of rhythm couplings changed, as expressed in their formation or disruption as the awakening moment approached.

The first 5-s pre-awakening EEG segment (20−15 s) was characterized by the presence of 6 pairs of rhythms (Table 3).

Within the second 5-s interval (15−10 s), theta−beta EEG rhythm coupling joined the pre-existing couplings (Table 4).

Within the 10−5-s interval, alpha1−gamma EEG rhythm coupling appeared, while delta−

Table 4. Coupling of EEG rhythms as revealed by the Kendall correlation coefficient within the 15−10-s pre-awakening interval

EEG rhythms		theta	alpha1	alpha2	beta	gamma
delta	R	**0.589**				
	p	**< 0.05**				
theta	R		_0.558_	**0.4**	**0.347**	
	p		_≤ 0.001_	**< 0.05**	**< 0.05**	
alpha1	R			0.611	_0.516_	
	p			< 0.001	_≤ 0.01_	
alpha2	R				_0.674_	_0.337_
	p				_≤ 0.001_	_≤ 0.05_
beta	R					_0.6_
	p					_≤ 0.001_

R—Kendall correlation coefficient; p—significance level. Bold—delta rhythm couplings (1st block of EEG rhythm couplings); bold underlined—theta rhythm couplings (2nd block of EEG rhythm couplings); bold double-underlined—alpha and beta rhythm couplings (3rd block of EEG rhythm couplings).

Table 5. Coupling of EEG rhythms as revealed by the Kendall correlation coefficient within the 10−5-s pre-awakening interval

EEG rhythms		theta	alpha1	alpha2	beta	gamma
delta	R					
	p					
theta	R		_0.6_	_0.337_		
	p		_≤ 0.001_	_≤ 0.05_		
alpha1	R			0.611	_0.495_	_0.389_
	p			< 0.001	_≤ 0.01_	_≤ 0.05_
alpha2	R				_0.737_	_0.484_
	p				_≤ 0.001_	_≤ 0.01_
beta	R					_0.684_
	p					_≤ 0.001_

R—Kendall correlation coefficient; p—significance level. Bold—delta rhythm couplings (1st block of EEG rhythm couplings); bold underlined—theta rhythm couplings (2nd block of EEG rhythm couplings); bold double-underlined—alpha and beta rhythm couplings (3rd block of EEG rhythm couplings).

theta EEG rhythm coupling disappeared (Table 5).

The closest time segment to the moment of awakening, namely the fourth 5-s interval (5−0 s), was significantly different from the previous one. There appeared delta rhythm couplings with slow (delta−theta, delta−alpha) and theta−gamma rhythms, which was not observed within the previous time interval (Table 6).

A closer attention to changes in EEG rhythm coupling during the 20-s pre-awakening period revealed three blocks of couplings. The first block was characterized by the coupling of both alpha rhythm sub-bands with beta and gamma rhythms, as well as beta with gamma. These couplings were pooled into a single block because they occurred (sometimes in a reduced form) throughout the entire 20-s period (Tables 2−5, bold double-

Table 6. Coupling of EEG rhythms as revealed by the Kendall correlation coefficient within the 5−0-s pre-awakening interval

EEG rhythms		theta	alpha1	alpha2	beta	gamma
delta	R	**0.6**	**0.6**			
	p	**< 0.001**	**< 0.01**			
theta	R		_0.579_	_0.358_		_0.347_
	p		_< 0.001_	_< 0.05_		_< 0.05_
alpha1	R			0.737	_0.505_	_0.516_
	p			< 0.001	_< 0.01_	_< 0.01_
alpha2	R				_0.705_	_0.547_
	p				_< 0.001_	_< 0.001_
beta	R					_0.716_
	p					_< 0.001_

R—Kendall correlation coefficient; p—significance level. Bold—delta rhythm couplings (1st block of EEG rhythm couplings); bold underlined—theta rhythm couplings (2nd block of EEG rhythm couplings); bold double-underlined—alpha and beta rhythm couplings (3rd block of EEG rhythm couplings).

underlined). The second block reflected the changes in theta rhythm coupling with other rhythms. A single theta−alpha1 coupling was observed within the 20−15-s pre-awakening interval. A quantitative jump in EEG rhythm coupling was observed within the 15−10-s pre-awakening interval. Here, there was detected a theta rhythm coupling with alpha1 and alpha2 rhythms, as well as with beta rhythms. Immediately before cognitive awakening (5−0-s interval), theta rhythm couplings with alpha1 and alpha2 rhythms persisted, but theta−gamma coupling appeared instead of theta−beta one (Tables 2−5, bold underlined). The third block reflected delta rhythm couplings (Tables 2−5, bold double-underlined). This block was rather conventional, because delta rhythm couplings with other EEG rhythms were only occasional.

Thus, it was found that the maximum number of EEG rhythm couplings forms immediately prior to cognitive awakening. Temporal changes were revealed in EEG rhythm coupling as the moment of cognitive awakening approached.

DISCUSSION

A study of the coupling of EEG rhythms during 20 s before cognitive awakening followed by a psy-chomotor test revealed an interesting dynamics of these couplings, which changed as the moment of awakening approached. Within the 20−15-s pre-awakening interval, we detected the couplings of both alpha rhythm sub-bands with beta and gamma rhythms. Traditionally, the thalamo-cortical cortico-subcortical system is associated with the appearance of an alpha rhythm in the EEG. Apparently, the inclusion of the beta rhythm in the beta−alpha complex allows maintaining the required level of activation of this system during sleep. Single delta−theta, theta−alpha, and beta−gamma rhythm couplings were also shown. Since the period under study refers to the second stage of sleep, which is characterized by the presence of a theta rhythm, K-complex and spindles, it can be assumed that single couplings of slow rhythms are their characteristic features. It was shown that the K-complex is characterized by an increased signal (by MRI data) in the thalamus, hippocampus, and various cortical regions [24]. The spindles are thought to be associated with the activity of the bilateral thalamus, shell, and individual cortical areas.

Within the 15−10-s interval, there was an expansion of theta rhythm couplings with both alpha rhythm sub-bands, as well as with the beta rhythm. It is commonly believed that the theta

rhythm reflects the activity of the cortico-hippocampal cortico-subcortical system. Based on these data, we can assume that this structural/functional coalescence reaches some higher level of activation and also begins to interact more extensively with the thalamo-cortical system. Interestingly, alpha–beta and alpha–gamma rhythm couplings are retained at this stage.

The next pre-awakening time interval (10–5 s) was characterized by a disruption of delta–theta and theta–beta couplings and the addition of alpha1–gamma coupling.

Five seconds before awakening, delta–theta and delta–alpha couplings occurred while retaining the couplings observed during the previous time intervals. There is evidence that broad functional connections change after sleep, with the default mode network, as well as delta and beta bands, playing a crucial role in network changes during the transition from sleep to waking [25]. The delta rhythm of both quiet wakefulness and sleep is associated with the activity of the medial frontal cortical regions [24]. The delta rhythm is also provided by the thalamo-cortical system [26].

Our study shows delta rhythm coupling with theta and alpha rhythms during the 5-s period before awakening, suggesting not merely a concurrent, but concerted involvement of the thalamo-cortical and cortico-hippocampal structural/functional systems in the process of awakening. The coupling of these systems differs from that in the 20–15-s interval, where their involvement was most likely confined to the K-complex and spindles. Here, however, the coupling is rather vast and perhaps of a different nature (spatiotemporal organization of potentials), although it may also incorporate these indicators of the second stage of sleep. In fact, we observe a gradual increase in the number of rhythm couplings before cognitive awakening. Importantly, the emergence of couplings is by no means chaotic.

Based on the aforesaid, we formulated a hypothesis of three blocks of rhythm coupling that precede awakening.

The first block comprises alpha rhythm couplings with fast rhythms, as well as with beta and gamma rhythms. These couplings persist throughout the whole 20-s pre-awakening period, which partially includes the second stage of sleep and preparation for awakening. Our previous work has shown that similar couplings are present at the first stage of sleep and during quiet wakefulness [20]. Classically, the amplitude of alpha rhythm oscillations during the quiet waking period is higher than during the first stage of sleep [27]. Based on our present data, it can be suggested that alpha rhythm couplings with beta and gamma rhythms provide a certain basal level of activation (tone or arousal) of the thalamo-cortical system, which allows the brain to quickly restore a working level after awakening during daytime sleep. Probably, this basal level of activation allows a person to respond in sleep to some, perhaps relevant, stimuli.

The second block is a block of theta rhythm couplings, which reflects the performance of the cortico-hippocampal cortico-subcortical system. The number of theta rhythm connections with alpha, beta, and gamma rhythms begins to increase 15 s before awakening. We can assume the existence of a certain level of activation of the cortico-hippocampal system through combining with fast rhythms that engage the thalamo-cortical system and probably additional brain regions or additional neural networks within the same cortico-subcortical system. In a certain sense, this is the awakening preparatory block. Since here we observe various couplings of the theta rhythm, which is known to be connected with the activity of the hippocampus, we can hypothesize that it is in this time interval when the instruction is retrieved from memory to subsequently trigger the subject's activity.

The third block is a block that couples delta with theta and alpha rhythms. In our previous work, we noted an increase in the amplitude values of these rhythms [20]. Delta and alpha rhythms are conventionally associated with the performance of the thalamo-cortical system, while the theta rhythm, as we have already written above, with that of the cortico-hippocampal system. Due to the presence of couplings of delta with alpha and theta rhythms, we can assume that the above two cortico-subcortical systems are united. The reticular activating system is involved in the process of awakening by combining influences from different brain structures, thus deter-

mining the overall level of CNS activity [28]. Apparently, the above-mentioned coupling of slow rhythms and, hence, cortico-subcortical systems occurs with the involvement of the brainstem reticular formation, which may lead to an even higher integration, including hypothalamolimbic and neocortical structures.

So, having tried to describe what conditions can lead to awakening, we have revealed quite a complex dynamic system of coupling between EEG rhythms.

In the present work, there is one more remarkable aspect, namely, getting back to the activity interrupted by falling asleep, which has not been considered here. This aspect relates to the second, behavioral, type of awakening and requires further investigation. Nevertheless, yet now, we can argue for the involvement of the reticular formation, thalamus and hypothalamus, which exert an ascending activating influence on the cortex of the cerebral hemispheres. Such an influence is well known not to cease even in sleep, and it is the functioning of the reticular structures that enables getting back to the initial state of consciousness. In our opinion, it is exactly the first block of couplings, namely, alpha rhythm couplings with faster rhythms, that is a manifestation of the work of activating systems, since we observed this block at both the first and second stages of sleep, as well as during the preparation for awakening.

CONCLUSION

The process of awakening is a lengthy process with a complex coupling dynamics of EEG rhythms. Within the 20−15-s pre-awakening interval, alpha rhythm couplings with beta and gamma rhythms are mainly predominant (first block of EEG rhythm couplings), although single delta−theta, theta−alpha1 and beta−gamma couplings also happen to occur. Within the 15−5-s pre-awakening interval, the number of theta rhythm couplings with faster rhythms increases (second block of EEG rhythm couplings). Lastly, within the 5−0-s pre-awakening interval, delta rhythm couplings with theta and alpha rhythms join the pre-existing rhythm couplings (third block of EEG rhythm coupling). A coaction of these three blocks leads to cognitive awakening.

This may indicate a functional unity of the thalamo-cortical, cortico-hippocampal, and reticular formation, with the latter, most likely, playing a unifying role toward the two cortico-subcortical systems.

AUTHORS' CONTRIBUTION

Conceptualization and experimental design (V.B.D.); data collection, primary analysis of EEG data, statistical data processing (N.E.P.); data collection and processing (E.A.Ch.); idea to analyze EEG rhythmic interactions, data interpretation, writing the first manuscript version and its subsequent revision (I.A.Ya.).

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest, both evident and potential, related to the publication of this article.

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