

Research Article

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Coupling of EEG Rhythms in the Cerebral Hemispheres as a Neurophysiological Basis for Awakening

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Abstract

Introduction. The study of interhemispheric asymmetry during awakening from different sleep stages remains relevant. This study is the first effort to identify interactions of cortical-subcortical systems that function simultaneously. This study aims to detect interhemispheric asymmetry during awakening from Stage 2 daytime sleep using amplitude-amplitude coupling of EEG rhythms. We examined cognitive awakening with varying task performance using a psychomotor test model. **Methods.** A multichannel EEG was recorded simultaneously with task performance. The EEG was evaluated using the complex Morlet wavelet. The Kendall correlation coefficient was as a measure of the amplitude-amplitude coupling of EEG rhythms. **Results.** A large area of asymmetric processes was observed in the left hemisphere during full performance recovery (compared to partial recovery) in the segment closest to the onset of button pressing. Awakening, accompanied by full performance recovery, was characterized by a predominance of delta-range coupling in both hemispheres in the interval of 8-5 sec. The theta and gamma rhythms became dominant in the interval of 4-1 sec. During partial performance recovery, an increase in the number of delta-range coupling was observed in the interval of 4-1 sec compared to the interval of 8-5 sec. **Discussion.** Cognitive awakening, accompanied by varying task performance, is characterized by interhemispheric asymmetry as measured by EEG rhythms coupling. This asymmetry is determined by both different localization areas of coupling patterns across the cerebral cortex and different sets of coupling

patterns. In two experimental situations, different coupling patterns of EEG rhythms were revealed. Therefore, in a number of regions, unequal interactions between the thalamocortical and cortico-hippocampal systems were found.

Keywords

interhemispheric brain asymmetry, awakening, psychomotor test, amplitude-amplitude coupling of EEG rhythms

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Introduction

The human circadian cycle consists of sleep and wakefulness during the day. Wakefulness includes various activities, sometimes interspersed with sleep. Based on his observations, A.R. Luria formulated the concept of three structural and functional blocks of the brain. Various mental functions are supported by the combined dynamic work of these blocks in both hemispheres of the brain. Block 1 is the “energetic” block, which maintains an optimal level of mental activity. This block regulates, in particular, the sleep-wake cycle and consciousness (Luria, 1973). Daytime sleep improves cognitive abilities and promotes performance restoration (Ficca et al., 2010). Sleep disturbances, manifested in particular by the need to work at night, as well as in conditions of sleep deprivation during the day, can lead to drowsiness and falling asleep. In emergency or spontaneous awakenings, performance recovery occurs in the context of slower motor reactions and decision-making, which affects its effectiveness. The period immediately preceding the onset of activity during sleep inertia (Santhi et al., 2013), as well as the accompanying objective neurophysiological characteristics, have been insufficiently studied. However, uneven recovery may be observed, leading to varying task performance. What manifestations of brain activity underlie this phenomenon? Awakening is a prolonged process. During this period, some changes in brain function occur, allowing the continuation of activity that began before being interrupted by sleep.

U. Voss (2010) divides awakening into two stages: (a) Stage 1—cognitive awakening, when a person perceives incoming information but is not yet able to perform a motor response; (b) Stage 2—behavioral awakening, when a person not only perceives stimuli but also performs a motor response. Awakening is associated with the transition of consciousness from the level observed during sleep to the level of wakefulness. The authors (Horton, 2017; Windt, 2020) hypothesize the existence of consciousness during sleep. (Liu, Li & Bai, 2023) examined EEG parameters in the frontal and parietal regions, which, in their opinion, demonstrated high relevance to consciousness. The authors argue that a decrease in consciousness is accompanied by an increase in low-frequency rhythms, a suppression of high-frequency rhythms, a decrease in dynamic complexity, and the destruction of networks. Thus, the study of the neurophysiological basis of the cognitive awakening stage to some extent answers the question of what performance will be after awakening. At the same time, it is necessary to consider the contribution of the cerebral hemispheres to the awakening process. (Casagrande & Bertini, 2008) in their work on the studied parameters demonstrated a sustainable advantage of the right hemisphere during awakening from both REM and NREM sleep, as well as during the transition from sleep to wakefulness. Results (Aritake et al., 2012) demonstrate a correlation between spontaneous awakening and a preceding increase in hemodynamic activation in the right prefrontal cortex, suggesting this structure's contribution to time estimation.

This study **aims** to detect interhemispheric asymmetry during awakening from Stage 2 daytime sleep.

The **objective** of the study is to identify cross-frequency coupling of EEG rhythms in the cerebral hemispheres when awakening with varying task performance.

Methods

This study complies with the ethical standards of the World Medical Association Declaration of Helsinki, Ethical Principles for Medical Research Involving Human Subjects, as amended in 2000, and was approved by the Ethics Committee of the Institute of Higher Nervous Activity and Neurophysiology, Russian Academy of Sciences (Protocol No. 2, dated June 3, 2019).

In our experiment, 83 students participated. The participants in the study were apparently healthy young adults aged 18 to 22. The selection criteria for this study were: a) awakening from Stage 2 daytime sleep, b) the onset of button pressing with the right hand after awakening, and c) situations of full and partial recovery of psychomotor activity in the same subject. Fifteen subjects were recruited, and the number of situations studied varied from 2 to 8.

The experiment was conducted during the daytime, from 1:00 PM to 2:00 PM. It was conducted in a darkened, soundproof room. The subject was positioned on a couch. The experimental model was a bimanual psychomotor test (Dorokhov et al., 2021). The subject was instructed to press buttons 10 times with his/her right and left hands, alternately, until falling asleep. It was specified that if the subject fell asleep and was spontaneously awakened, he/she would continue to press the buttons.

During the task, an EEG was recorded from 19 silver chloride electrodes using a 10–20% scheme (reference electrodes were placed on the mastoids, impedance up to 5 kOhm, sampling frequency 500 Hz, amplifier bandwidth 0.5–40 Hz). An electrooculogram and mechanograms of button presses were also recorded.

The EEG was analyzed before awakening, followed by partial and full recovery of task performance. In the partial condition, the subject pressed the button with the right hand, then the left, 7 to 9 times; in the full condition, the subject pressed the button 10 times each. Two 4-second epochs of analysis were identified prior to awakening.

Based on the complex Morlet wavelet (Matlab 78.01), the absolute value of wavelet transform coefficients (AWTC) was calculated. The resulting parameter was considered the amplitude characteristic of the EEG. The AWTC was calculated in the range of 0.5–40 Hz with the 0.5 Hz step size and a time resolution of 0.01 sec. The delta (1–3 Hz), theta (4–7 Hz), alpha-1 (8–10 Hz), alpha-2 (11–13 Hz), beta (14–20 Hz), and gamma (21–40 Hz) spectral ranges of individual EEG leads were analyzed.

We used cross-frequency coupling of EEG rhythms, which enabled us to assess the functional interactions of brain structures or systems (Knyazev et al., 2019; Salimpour & William, 2019; Siems & Siegel, 2020; Schanze & Eckhorn, 1997; Rodriguez-Martinez et al., 2015; Canolty & Knight, 2010; Yakovenko et al., 2022; Yakovenko et al., 2024). The Kendall rank correlation coefficient (KC) was a measure of the amplitude-amplitude coupling of EEG rhythms. This calculation was performed for all pairs of rhythms.

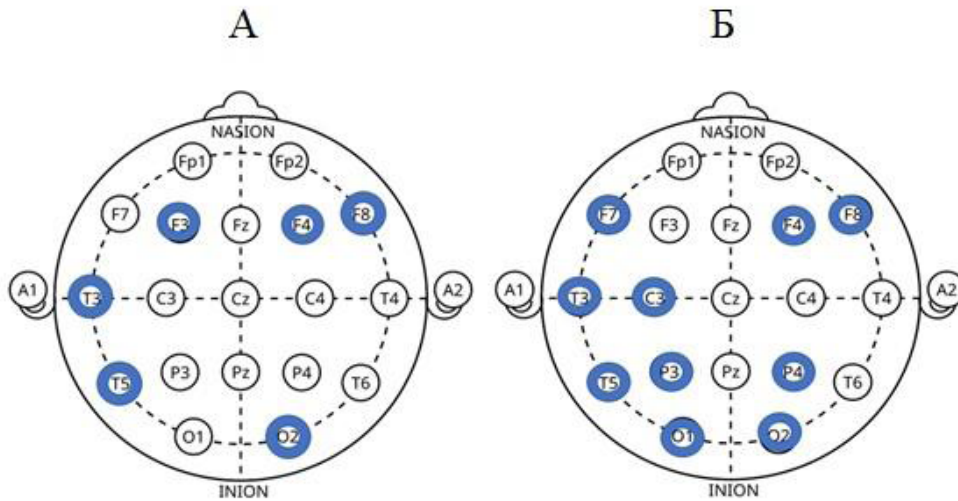
Data were analyzed using the statistical software package SPSS v. 12

Results

Cognitive awakening with full performance recovery, characterized by 10 button presses with both hands, was accompanied by the presence of asymmetric coupling in both the left and right hemispheres in the two time periods studied. Despite similar localization in the hemispheres, the coupling patterns are asymmetrical in their content – EEG coupling patterns are not duplicated. In the interval of 8-5 sec before the onset of button pressing, the asymmetry of coupling patterns is formed in the frontal and temporal regions of the left hemisphere, and in the frontal and occipital regions of the right hemisphere. Moreover, a somewhat greater distribution of coupling patterns of EEG rhythms in the frontal regions is observed in the right hemisphere compared to the left one. Coupling patterns are observed in the temporal regions in the left hemisphere, which are not observed in the right one. Coupling patterns in the occipital region are also noted in the right hemisphere. Leads F3 and F4 deserve special attention. They are symmetrical in localization but asymmetrical in their sets of EEG coupling patterns. In the interval of 4-1 sec, the distribution area of asymmetric coupling increases – coupling patterns in the central region of the left hemisphere and the parietal regions of both hemispheres are added to the existing coupling patterns of EEG rhythms (Figure 1).

Figure 1

Asymmetric coupling patterns of EEG rhythms in the cerebral hemispheres during full cognitive awakening

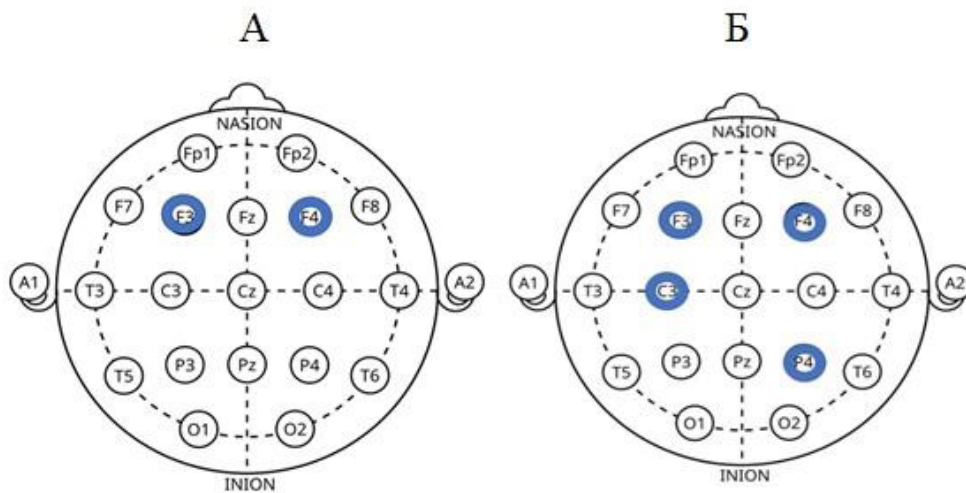


Notes: A – full awakening in the interval of 8-5 sec; B – full awakening in the interval of 4-1 sec. Circles with borders indicate the presence of reliable coupling patterns of EEG rhythms. The EEG leads are shown on the schematic maps.

Cognitive awakening, followed by full performance recovery (the subject pressed the button with the right hand, then the left hand, 7 to 9 times), is characterized by a similar localization (leads F3 and F4) of asymmetric coupling patterns of EEG rhythms in the interval of 8-5 sec before the onset of button pressing with the right hand. The interval closest to awakening (4-1 sec) demonstrates the activation of the left central and right parietal regions of the brain (Figure 2).

Figure 2

Asymmetric coupling patterns of EEG rhythms in the cerebral hemispheres during partial cognitive awakening



Notes: A – partial awakening in the interval of 8-5 sec; B – partial awakening in the interval of 4-1 sec. Circles with borders indicate the presence of reliable coupling patterns of EEG rhythms. The EEG leads are shown on the schematic maps.

Therefore, different types of cognitive awakening are associated with different hemispheric localization of asymmetric coupling patterns of EEG rhythms and differ in the extent of these interactions across the cortex.

Which coupling patterns of EEG rhythms create this asymmetry? Table 1 shows that the vast majority of delta-range coupling patterns are observed in both hemispheres during the interval of 8-5 sec before the onset of button pressing during full awakening. During partial awakening, asymmetric coupling patterns of EEG rhythms are fewer and more varied – in addition to delta-range coupling, there are theta-gamma and beta-gamma coupling.

Table 1

Reliable coupling patterns of EEG rhythms in individual leads of the left and right hemispheres during different types of awakening in the interval of 8-5 sec

Full cognitive awakening		Partial cognitive awakening	
Leads	Coupling of EEG rhythms	Leads	Coupling of EEG rhythms
F3	Δ - α 1	F3	Δ - γ , θ - γ
F4	Δ - β , α 2- γ	F4	β - γ

Full cognitive awakening Leads Coupling of EEG rhythms	Partial cognitive awakening Leads Coupling of EEG rhythms
F8	Δ - β , Δ - γ
T3	Δ - γ
T5	Δ - α 2, Δ - β , Δ - γ
O2	Δ - β

Notes. Δ , θ , α 1, α 2, β , γ – delta, theta, alpha1, alpha2, beta, and gamma EEG rhythms, respectively.

Therefore, in the interval of 8-5 sec before the onset of button pressing, the types of awakening differ in the set of coupling of EEG rhythms.

In the interval of 4-1 sec, with full awakening, theta and alpha rhythm coupling predominate, almost always associated with the gamma rhythm in both hemispheres. Delta-range coupling is somewhat less common. The asymmetry is formed primarily due to the greater number of theta, alpha, and gamma coupling in the left hemisphere. With partial awakening, delta-range coupling predominates. The asymmetry is formed due to both the qualitative difference in coupling patterns and their localization (see Table 2).

Table 2

Reliable coupling patterns of EEG rhythms in individual leads of the left and right hemispheres during different types of awakening in the interval of 4-1 sec

Full cognitive awakening Leads Coupling of EEG rhythms	Partial cognitive awakening Leads Coupling of EEG rhythms
	F3 Δ - α 1, Δ - α 2
F4 θ - β , θ - γ	F4 α 2- γ
F7 θ - β , θ - γ , α 1- γ	
F8 β - γ	
C3 α 1- γ , α 2- γ , β - γ	C3 Δ - α 1, Δ - α 2, θ - α 1, α 1- γ , α 2- γ
T3 Δ - γ , θ - γ , α 2- γ	
T5 Δ - γ , θ - γ	

Full cognitive awakening	Partial cognitive awakening	Leads	Coupling of EEG rhythms
P3	$\theta-\gamma, \alpha1-\gamma, \alpha2-\gamma$		
P4	$\Delta-\alpha1, \theta-\alpha1, \theta-\alpha2,$ $\theta-\beta$	P4	$\Delta-\alpha1, \Delta-\alpha2, \Delta-\beta,$ $\theta-\alpha2$
O1	$\theta-\alpha1, \theta-\alpha2, \theta-\gamma$		
O2	$\Delta-\alpha2$		

Notes. $\Delta, \theta, \alpha1, \alpha2, \beta, \gamma$ – delta, theta, alpha1, alpha2, beta, and gamma EEG rhythms, respectively.

Therefore, in addition to the different localization areas of the coupling patterns of EEG rhythms in the cerebral hemispheres, differences in the coupling structure have also been shown for different types of cognitive awakening.

Discussion

Full awakening is accompanied by a broader distribution of asymmetric coupling patterns across the cortex compared to partial awakening. In the interval of 4-1 sec, reliable coupling patterns of EEG rhythms involve the frontal and temporal regions of the left hemisphere cortex, as well as the frontal and occipital regions of the right hemisphere. These data are somewhat consistent with the results of (Yang et al., 2015). The time interval closest to the onset of button pressing (4-1 sec) is characterized by a greater involvement of the cerebral cortex. With partial awakening, asymmetry in the interval of 8-5 sec is observed only in the frontal regions. In the interval of 4-1 sec, asymmetric coupling patterns were observed not only in the frontal regions, but also in the left central and right parietal regions. We can assume that the presence of a greater number of asymmetric coupling patterns of EEG rhythms across broader areas of the cerebral cortex is associated with the possibility of a fuller awakening and readiness for task performance. In partial awakening, the presence of a smaller number of asymmetric coupling patterns of EEG rhythms probably prevents the maintenance of the level of structural activation necessary for successful task performance.

A comparison of the distribution of coupling patterns of EEG rhythms during full and partial awakenings at the cognitive and behavioral stages (Yakovenko et al., 2024) suggests the involvement of the frontal lobes of both hemispheres in any type of awakening. In both full and partial cognitive awakenings, the frontal lobes of both hemispheres are symmetrical in localization but asymmetrical in their coupling patterns. During full behavioral awakening, the

same distribution of coupling patterns of EEG rhythms is maintained. The frontal lobes of the two hemispheres are involved in partial cognitive awakening, while only the left hemisphere frontal lobe is involved in behavioral awakening. This indicates the involvement of the right frontal lobe not only in awakening, but also in maintaining wakefulness for longer periods of time. A study (Aritake et al., 2012) reported a link between voluntary awakening and a preceding increase in hemodynamic activation in the right prefrontal cortex. These data are somewhat consistent with our results.

Let us consider which coupling patterns of EEG rhythms are involved in the formation of interhemispheric asymmetry during cognitive awakening. Awakening with full performance recovery is accompanied by a large number of delta-range coupling patterns in both hemispheres 8-5 s before the onset of button pressing. The study (Hilditch et al., 2021) suggests that the delta and beta bands play a decisive role in network changes during the transition from sleep to wakefulness. The delta rhythm reflects the functioning of the thalamocortical system (Steriade, 2006; Faber & Novak, 2011; Manyukhina et al., 2020). Moreover, in the left hemisphere, it is associated not only with high-frequency (beta and gamma) rhythms, but also with the alpha rhythm. The alpha rhythm, like the delta rhythm, reflects the functioning of the thalamocortical system (Faber & Novak, 2011). Based on this, it can be assumed that delta-range coupling with high-frequency rhythms may indicate greater activation of the aforementioned cortical-subcortical system. Delta-range coupling with the alpha rhythm probably indicates a greater involvement of this system in the awakening process. The delta rhythm is characteristic of both sleep and wakefulness (Harmony, 2013). Perhaps a "transfer of authority" occurs here from the part of the thalamocortical system involved in sleep to the part that ensures wakefulness. The interval of 4-1 sec before the onset of button pressing demonstrates the predominance of theta-range coupling in both hemispheres, mainly with beta and gamma rhythms. The theta rhythm reflects the functioning of the cortico-hippocampal system, which is involved in memory processes (Vertes, Hoover & Di Prisco, 2004; Barnett et al., 2021). This suggests greater activation of this cortical-subcortical system and the retrieval of instructions from memory. During the same time interval, a greater representation of theta, alpha, and gamma coupling patterns in the left hemisphere can be observed. All this may indicate preparation for button pressing with the right hand. A study (Dos Santos Lima et al., 2019) described a dynamic pattern of hippocampal and cortical activation associated with microarousal during sleep in mice. An increase in cortico-hippocampal coherence was noted, in the delta and theta ranges and peaks (2.5–5.5 Hz).

Awakening with partial performance recovery demonstrates significantly fewer asymmetric coupling patterns between the hemispheres, which are observed only in the frontal regions in the interval of 8–5 sec before the onset of button pressing. Here, only two coupling patterns are noted: delta-gamma and theta-gamma in the left hemisphere and beta-gamma in the right hemisphere. We can assume that in the frontal regions a more constrained activation process of the thalamocortical and cortico-hippocampal systems is observed. The next interval (4-1 sec) was accompanied mainly by delta-alpha and alpha-gamma coupling patterns. At this time, greater involvement of the cerebral cortex by asymmetric processes

is observed. The increase in the number of delta-alpha coupling may indicate a broader involvement of the thalamocortical system in the awakening process. Theta range coupling patterns, which ensure the reproduction of instructions, are less represented.

Gamma range coupling deserves special attention. A comparison of gamma range coupling during full and partial cognitive awakening revealed its greatest presence in the interval of 4-1 sec in the left hemisphere during full performance recovery. The authors (Danilova et al., 2002) describe the presence of the gamma rhythm in various brain structures. They believe that this rhythm is a functional building block associated not only with various cognitive processes but also with consciousness. The study (Doesburg et al., 2009) suggests that conscious perception is accompanied by the presence of large-scale ensembles of gamma-synchronous neuronal populations associated with the theta rhythm. Based on these studies, we can assume that during this time interval, consciousness reaches a new level. In other words, preparation for task performance occurs.

Cognitive awakening, accompanied by varying task performance, is characterized by interhemispheric asymmetry by coupling patterns of EEG rhythms. This asymmetry is determined by both different localization areas of coupling patterns across the cerebral cortex and the set of coupling patterns within cortical regions. We hypothesize that these results characterize different levels of consciousness manifested during cognitive awakening.

Conclusion

Cognitive awakening with full and partial performance recovery differs in the range of asymmetric processes in the hemispheres. A greater area is observed in the left hemisphere with full performance recovery in the segment closest to the onset of button pressing. The types of awakening differ in the number of coupling patterns. The number of coupling patterns of EEG rhythms is significantly greater during full awakening compared to partial awakening. The greatest number of coupling patterns is observed in the left hemisphere in the interval of 4-1 sec before awakening with full performance recovery. Awakening, accompanied by full performance recovery, was characterized by a predominance of delta-range coupling in both hemispheres in the interval of 8-5 sec. Theta- and gamma-range coupling became dominant in the interval of 4-1 sec. With partial performance recovery, an increase in the number of delta-range coupling was noted in the interval of 4-1 sec compared to the interval of 8-5 sec.

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Author Contribution

Irina Anatol'evna Yakovenko conducted a theoretical analysis of the research problem, interpreted and described quantitative and qualitative results

Evgenii Alekseevich Cheremushkin performed quantitative and qualitative data processing and presented the results in figures and tables

Vladimir Borisovich Dorokhov contributed to the research concept and prepared the text of the manuscript.

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Conflict of Interest Information

The authors have no conflicts of interest to declare.