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Interhemispheric asymmetry of the EEG rhythms coupling accompanies cognitive awakening during bimanual performance of a psychomotor test

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Abstract Awakening is a transitional process from sleep to wakefulness. There is a certain restructuring in the work of brain structures during this period, which further allows a person to perform conscious activity. The study of interhemispheric asymmetry of amplitude–amplitude couplings of EEG rhythms was carried out. A psychomotor test was used in experiments. This test allows us to observe the moments of falling asleep and waking up when performing monotonous work. Multichannel EEG was recorded simultaneously with the test. The data of 14 subjects who reached the second stage of sleep during the experiment were analyzed. The selected 20 s EEG segments prior to awakening were processed using a continuous wavelet transform based on the "mother" complex Morlet wavelet. The Kendall correlation coefficient was used to evaluate the measure of EEG rhythms coupling. Quantitative changes in the couplings of EEG rhythms were revealed as the moment of awakening approached: in the two most distant time intervals, the total number of asymmetric connections was five to three, and in the two closest segments, there was only one coupling of EEG rhythms. This is not just a decrease in the number of connections, but also a change of EEG rhythms coupling throughout the entire 20-s segment. The dynamic nature of the EEG rhythms coupling in the hemispheres before awakening to resume the task is shown, which may indicate the dynamic relationship of structural and functional associations of the brain.

1 Introduction

Structural and functional asymmetry is one of the principles of human brain organization. Interconnections of different kinds within each hemisphere define the interhemispheric network or connectome [1].

The process of lateralization has been mostly studied when subjects perform some activity. There are known works showing the presence of asymmetry in sleep [2]. In our case, there was interest in asymmetry during awakening. Awakening is a transitional process from sleep to wakefulness. During this period, there is some rearrangement in the work of brain structures, which further allows to perform conscious activity. The question remains not completely solved—how does a person's conscious reaction to incoming stimuli and information arise? What leads to the possibility of conscious processing of information? What is the participation of the brain hemispheres in this process?

In Voss [3], the process of awakening is divided into two temporal episodes. The first (cognitive awakening) is defined as when the person reacts to external stimuli but does not respond with a motor reaction, the second (behavioral awakening)—the person can make a movement in response to an incoming stimulus.

Certain conditions influence the awakening process. Depending on these, the activity of the brain and, specifically, of the hemispheres may vary. Waking up will differ depending on whether it is night sleep or day sleep (just a nap or resulting from monotonous work). It is of interest to know if long-term tasks affect waking up? In the case of activity-related daytime sleep, the question arises—what is the impact of previous work on waking up? Since the

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person must return to the interrupted work, it is likely that the structures or structural–functional associations of the brain responsible for the activity being performed must be activated.

The registration of the encephalogram does not allow us to directly indicate all the structures activated or inhibited. Nevertheless, knowing about some binding of EEG rhythms to structural–functional associations of the brain, it is possible to assume to a certain extent the involvement of these associations in a cognitive process. If the connection of EEG rhythms is shown, it is possible to assume a certain interaction of cortical–subcortical systems of the brain. All this is reflected in various parameters of the electroencephalogram. These are amplitude, frequency, correlation coefficient, coherence and a lesser known topogram analysis [4]. The use of these parameters allowed us to characterize the performance of the brain hemispheres. Asymmetry has also been shown in default made brain networks [1]. Since the brain has two hemispheres and left–right asymmetry of subcortical structures, it is interesting to see what happens to the hemispheres on the eve of awakening, how does the brain "tune" for activity?

In our work, we used cross-frequency coupling of rhythms. According to some authors [5–7], the EEG rhythms coupling may reflect the interaction of cortical–subcortical systems.

The aim of the present study was to investigate the functioning of the brain hemispheres under the conditions of performing a psychomotor test with two hands.

The task is to investigate the amplitude–amplitude coupling of EEG rhythms during cognitive awakening.

2 Methods

2.1 Participants

Eighty-three university students participated in the study. The average age was 20 ± 1.1 years. The subjects were familiarized with the study procedure and gave written consent to participate in the study. The study complied with the ethical standards of Helsinki Declaration of the World Medical Association "Ethical principles of conducting scientific medical research with human participation" as amended in 2000, "Rules of Clinical Practice in the Russian Federation", approved by the Order of the Ministry of Health of the Russian Federation dated 06/19/2003. No. 266 and the conclusion of the Local Ethical Committee of the Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences No. 0.043 of 2019.

2.2 Study protocol

Before the experiment beginning, subjects completed a sleep diary and the California Sleepiness Scale on forms.

The experiments were carried out in the daytime, starting from 13 o'clock. The experiment lasted 1–1.5 h. The experiment was conducted in a darkened, soundproof and ventilated chamber. The room was kept at a constant comfortable temperature. The subjects were placed on a couch in a comfortable position.

A monotonous psychomotor test [8] was used for the study. The subjects had to press the buttons 10 times alternately with their right and left hands. The clicks lasted until the moment of falling asleep. The instructions stipulated the immediate continuation of button pressing after awakening. The first pressing of a button with either hand after a pause was considered to be awakening and the beginning of activity.

2.3 EEG registration

EEG (19 silver chloride electrodes arranged according to the 10–20 pattern with a resistance not exceeding 5 KΩ) and EMG were recorded simultaneously when the task was performed. The mechanogram of button pressing was also recorded. The buttons were fixed between the thumbs and index fingers of the subject on each hand.

EEG registration was carried out with a sampling frequency of 500 Hz, with reference electrodes on mastoids. EEG was recorded in the range from 0.05 to 45 Hz. A 50 Hz filter was used to suppress the power line interference.

2.4 Analysis of EEG signals

The data of 14 people (11 women), all right-handed, were selected for analysis. The inclusion criterion for data analysis was (1) the achievement of the second stage of sleep and subsequent awakening (2) with pressing a button with the right hand while performing a psychomotor test. A total of 39 cases of awakening from the second stage of daytime sleep were identified, from 1 to 7 in each subject.

We examined 20-s segments of EEG before arousal during the performance of a psychomotor test.

The selected EEG segments were processed using a continuous wavelet transform based on the "mother" complex Morlet wavelet (Matlab 9.7 R2019b).

2.5 Statistical analysis

The distribution maps of the power values of the wavelet transform coefficient in the 0.5–40 Hz band with a 0.5 Hz step and a time resolution of 1 ms were constructed along acquired 20 s segments. Thus, obtained wavelet transform coefficients were averaged over the number of awakenings of each subject in the experiment. Next, we averaged coefficients in the frequency ranges of delta (0.5–3.5 Hz), theta (4–7.5 Hz), alpha (8–13.5 Hz), beta (14–19.5 Hz), and gamma (20–40 Hz). The obtained values were averaged over 4 time intervals of 5 s duration. Then, in each of the 4 intervals, coefficient values were averaged for the left and right hemisphere separately.

The Kendall correlation coefficient (KC) was used to estimate a measure of the amplitude–amplitude interaction of EEG rhythms. Statistical processing was performed using the software package "SPSS, v.12" (IBM, Armonk, NY, USA).

3 Results

Bimanual performance of the psychomotor test accompanied by the moments of falling asleep and awakening showed that cognitive awakening occurs against the background of complex dynamics of interaction of EEG rhythms in the brain hemispheres for 20 s before behavioral awakening. In general, similar EEG couplings in the hemispheres prevailed during those 20 s. Asymmetrical rhythm connections were also observed: 5 rhythm couplings were observed in the interval from 20 to 16 s and 3 couplings in the interval from 15 to 11 s. In the intervals of 10–6 s and 5–0 s, each showed one asymmetric coupling.

In the time interval of 20–16 s in the left hemisphere 7 rhythms couplings were revealed: delta-rhythm was associated with alpha-, beta- and gamma-rhythms, theta—with alpha and gamma, alpha with beta and gamma. In the right hemisphere in the same interval, 6 couplings of rhythms were shown: delta was connected with alpha- and beta-rhythms, theta with beta, alpha with beta and gamma and beta with gamma (Table 1). Among them cases of asymmetric rhythm, connections were revealed. These are delta–gamma and theta–alpha, theta–gamma connections in the left hemisphere; and theta–beta and beta–gamma connections in the right hemisphere.

In the interval of 15–11 s, 4 couplings of EEG rhythms were found in the left hemisphere: delta–alpha, theta–alpha, theta–beta and alpha–beta, and 5 couplings were in the right hemisphere: delta–theta, delta–alpha and delta–beta, theta–alpha, theta–beta (Table 2). At the same time, cases of asymmetry are shown by couplings: alpha–beta-rhythms in the left hemisphere and delta–theta, delta–beta in the right hemisphere.

Table 1 Intrahemispheric EEG rhythms coupling over a time interval of 20–16 s before behavioral awakening

EEG rhythms	Delta-rhythm	Theta-rhythm	Alpha-rhythm	Beta-rhythm	Gamma-rhythm
Delta-rhythm					
Left hemisphere			$r = 0.45$; $p = 0.0248$	$r = 0.6$; $p = 0.0026$	$r = 0.43$; $p = 0.0328$
Right hemisphere			$r = 0.47$; $p = 0.0188$	$r = 0.47$; $p = 0.0188$	
Theta-rhythm					
Left hemisphere			$r = 0.5$; $p = 0.01375$		$r = 0.52$; $p = 0.01$
Right hemisphere				$r = 0.43$; $p = 0.03275$	
Alpha-rhythm					
Left hemisphere				$r = 0.45$; $p = 0.0248$	$r = 0.54$; $p = 0.0073$
Right hemisphere				$r = 0.43$; $p = 0.0328$	$r = 0.52$; $p = 0.01$
Beta-rhythm					
Left hemisphere					
Right hemisphere					$r = 0.43$; $p = 0.0328$

r is the value of the Kendall correlation coefficient; p is the significance level.

Table 2 Intrahemispheric EEG rhythms coupling over a time interval of 15–11 s before behavioral awakening

EEG rhythms	Delta-rhythm	Theta-rhythm	Alpha-rhythm	Beta-rhythm	Gamma-rhythm
Delta-rhythm					
Left hemisphere			$r = 0.54$; $p = 0.0073$		
Right hemisphere		$r = 0.43$; $p = 0.0328$	$r = 0.52$; $p = 0.01$	$r = 0.43$; $p = 0.0328$	
Theta-rhythm					
Left hemisphere			$r = 0.52$; $p = 0.01008$	$r = 0.8$; $p = 0.000$	
Right hemisphere			$r = 0.52$; $p = 0.01$	$r = 0.56$; $p = 0.0052$	
Alpha-rhythm					
Left hemisphere				$r = 0.5$; $p = 0.0138$	
Right hemisphere					
Beta-rhythm					
Left hemisphere					
Right hemisphere					

r is the value of the Kendall correlation coefficient; p is the significance level.

The next time interval—10–6 s before behavioral awakening demonstrates 7 couplings in the left hemisphere and 8 couplings in the right hemisphere. A large number of symmetrical connections of EEG rhythms are observed. Only one case of asymmetry—beta–gamma-rhythm coupling in the right hemisphere was detected in this time interval (Table 3).

r is the value of the Kendall correlation coefficient; p is the significance level.

Interval the closest to behavioral awakening—5–0 s, was characterized by 10 couplings of EEG rhythms in the left hemisphere and 9 couplings in the right hemisphere. Almost all rhythm couplings were observed symmetrically

Table 3 Intrahemispheric EEG rhythms coupling over a time interval of 10–6 s before behavioral awakening

EEG rhythms	Delta-rhythm	Theta-rhythm	Alpha-rhythm	Beta-rhythm	Gamma-rhythm
Delta-rhythm					
Left hemisphere			$r = 0.58$; $p = 0.0037$	$r = 0.58$; $p = 0.0037$	$r = 0.43$; $p = 0.0328$
Right hemisphere			$r = 0.52$; $p = 0.01$	$r = 0.58$; $p = 0.0037$	$r = 0.5$; $p = 0.0138$
Theta-rhythm					
Left hemisphere			$r = 0.56$; $p = 0.0052$	$r = 0.56$; $p = 0.0052$	
Right hemisphere			$r = 0.58$; $p = 0.0037$	$r = 0.65$; $p = 0.0012$	
Alpha-rhythm					
Left hemisphere				$r = 0.65$; $p = 0.00123$	$r = 0.54$; $p = 0.0073$
Right hemisphere				$r = 0.58$; $p = 0.0037$	$r = 0.54$; $p = 0.0073$
Beta-rhythm					
Left hemisphere					
Right hemisphere					$r = 0.47$; $p = 0.0186$

Table 4 Intrahemispheric EEG rhythms coupling over a time interval of 5–0 s before behavioral awakening

EEG rhythms	Delta-rhythm	Theta-rhythm	Alpha-rhythm	Beta-rhythm	Gamma-rhythm
Delta-rhythm					
Left hemisphere		$r = 0.54$; $p = 0.0073$	$r = 0.47$; $p = 0.0186$	$r = 0.47$; $p = 0.0186$	$r = 0.5$; $p = 0.0138$
Right hemisphere		$r = 0.45$; $p = 0.0248$	$r = 0.47$; $p = 0.0186$	$r = 0.6$; $p = 0.0026$	$r = 0.52$; $p = 0.01$
Theta-rhythm					
Left hemisphere			$r = 0.71$; $p = 0.00037$	$r = 0.41$; $p = 0.0428$	$r = 0.52$; $p = 0.01$
Right hemisphere			$r = 0.58$; $p = 0.0037$		$r = 0.45$; $p = 0.0248$
Alpha-rhythm					
Left hemisphere				$r = 0.65$; $p = 0.0012$	$r = 0.58$; $p = 0.0037$
Right hemisphere				$r = 0.65$; $p = 0.0012$	$r = 0.69$; $p = 0.0006$
Beta-rhythm					
Left hemisphere					$r = 0.41$; $p = 0.0428$
Right hemisphere					$r = 0.56$; $p = 0.0052$

r is the value of the Kendall correlation coefficient; p is the significance level

(in both hemispheres). Similar to the previous time interval, one asymmetric connection of theta–beta-rhythms in the left hemisphere was also observed in this interval (Table 4).

Thus, during cognitive awakening from the second stage of daytime sleep, interhemispheric asymmetry in the coupling of EEG rhythms was revealed. Their quantitative changes as cognitive awakening transitions into behavioral awakening are shown: in the two most distant time segments, the total number of asymmetric connections changed from 5 to 3; in the two closest segments, there was only one EEG rhythms coupling.

4 Discussion

The study of the amplitude–amplitude coupling of EEG rhythms revealed its complex dynamics during cognitive awakening as it approaches behavioral awakening during the performance of a two-handed psychomotor test.

If we look at the change in the number of rhythm couplings, we can see an interesting pattern: a decrease in the number of couplings in the interval 15–11 s before behavioral awakening compared to the interval 20–16 s, and then at the next two intervals (10–6 and 5–0 s) a significant increase. Probably, the decrease in the number of couplings 10 s before awakening indicates a certain "dissociation" of brain structures or systems and, accordingly, a rearrangement of the spatial and temporal organization of potentials for the transition to a higher level of consciousness in relation to sleep (tuning to awakening). The subsequent significant increase in the number of connections is probably related to the generalized unification of structural and functional brain systems necessary for behavioral awakening that enables the performance of certain activities. Presumably, at this time, consciousness moves to a different, possibly "higher" level. (Fig. 1A).

The dynamics of intrahemispheric connections of rhythms follows a slightly different pattern in time compared to the dynamics of the total number of connections. The time interval farthest from behavioral awakening is characterized by the largest number of asymmetric connections. Then, as behavioral awakening approaches, this number decreases. In addition, in the 10–0 s before the button is pressed, we can find only one asymmetric coupling in each of 5 s period. Thus, in the studied parameter, the work of the hemispheres becomes more synchronized (Fig. 1B).

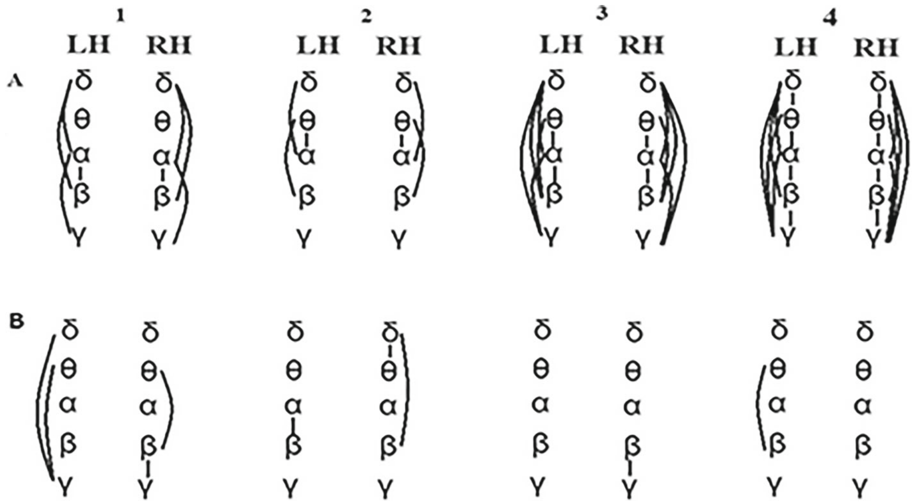

Fig. 1 Schematic maps of significant correlations between EEG rhythms in the left and right hemispheres separately during cognitive awakening before resuming the bimanual psychomotor test. From left to right on the schematic maps—the left (LH) and right (RH) hemispheres; **A** matching EEG rhythms couplings observed in both hemispheres; **B** EEG rhythms couplings that occur unilaterally; 1, 2, 3 and 4—time intervals for 20–16, 15–11, 10–6 and 5–0 s before awakening, respectively; Δ, θ, α, β and γ are delta-, theta-, alpha-, beta- and gamma-rhythms, respectively; significant correlations are marked by lines between the rhythm icons ($p < 0.05$)

Let us concretize the nature of interrelations of EEG rhythms in the hemispheres. It is believed that delta- and alpha-rhythms reflect the work of the thalamo-cortical cortical–subcortical system, theta corresponds to cortico-hippocampal interactions, and beta-rhythm can be observed both in the cortex and subcortical structures (nonspecific nuclei of the thalamus and hippocampus). The greatest number of asymmetric couplings is found in the delta- and theta-rhythm connection groups and one asymmetric coupling each in the fast rhythm group at intervals of 20–16 and 15–11 s prior to the onset of activity. We can suppose that 20 s before awakening during the periods of dissociated hemispheric activity in the aforementioned systems of their separate structures some rearrangements take place, accompanied by processing of the available information in separate hemispheres, which proceeds differently in them.

Let us consider each time interval separately. There is the greatest "disconnection" in the work of the hemispheres of the brain in the interval of 20–16 s. Preparation for future activity in the hemispheres occurs in different ways. The left hemisphere probably has a wider coverage of brain structures and their greater activation (delta–gamma, theta–alpha and theta–gamma connections). There is probably greater activation of both thalamo-cortical and cortico-hippocampal cortical–subcortical brain systems. In the right hemisphere, the cortico-hippocampal system is presumably activated (theta–beta connections). Since we observe connections of the theta-rhythm with faster rhythms in both hemispheres, we can assume that already 20 s before behavioral awakening the hippocampus was activated, and therefore, the instruction to perform the activity is activated.

The group of delta-rhythm connections demonstrates cases of interhemispheric asymmetry mainly in the interval of 15–11 s. The cases of "dissociation" may affect the thalamo-cortical system to a greater extent. The right hemisphere has more connections (delta–theta and delta–beta) and hence more connections of the thalamo-cortical circle with the cortico-hippocampal circle, which is in agreement with the works [9, 10] that delta- and beta-rhythms are essential for changes in default networks during the transition from sleep to wakefulness. The left hemisphere is restricted to alpha–beta connectivity, which may also indicate activation of the thalamo-cortical cortical–subcortical system, but it may have a different spatiotemporal organization.

Asymmetry is minimized in the interval of 10–6 s before awakening. There is a single beta–gamma coupling of EEG rhythms in the right hemisphere, which is not observed in the left hemisphere. In Ref. [11], it is suggested that the increase in power in the beta- and gamma-bands of the EEG may reflect a subconscious desire to restore the interrupted activity.

The time interval of 5–0 s before awakening we found the presence of a of theta–beta-rhythms coupling in the left hemisphere. Since we analyzed only cases of awakening from the second stage of sleep accompanied by right-handed button press, perhaps here once again the instruction is "replayed". In addition, since the pressing is done with the right hand, the left hemisphere is activated accordingly.

We obtained integral indices of the interaction of EEG rhythms inside the hemispheres. However, the question of regional changes in such interaction remains open. Nevertheless, we considered it possible to demonstrate preliminary data on the nearest time interval to the moment of awakening.

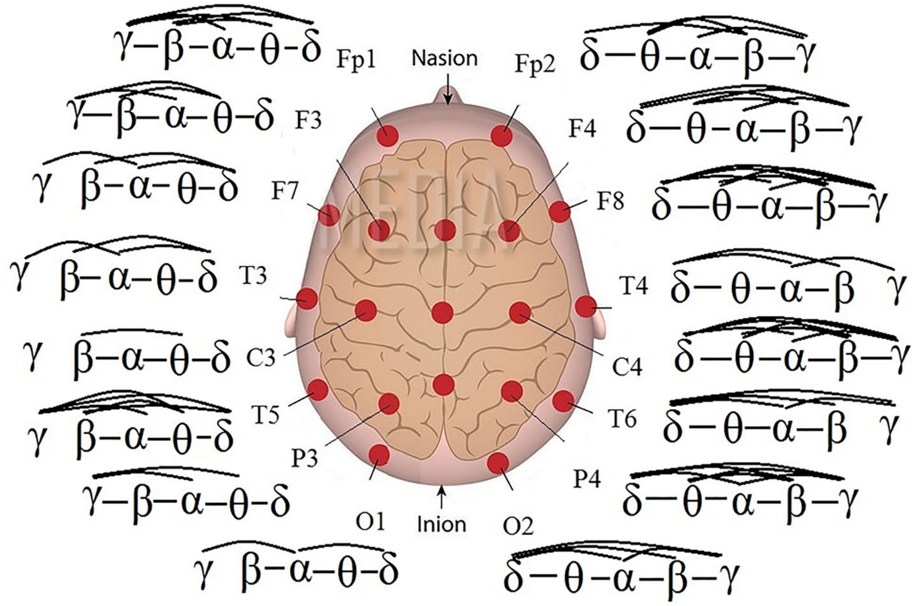

Fig. 2 Interhemispheric asymmetry of EEG rhythms couplings in cortical areas. In the center—schematic representation of the investigated EEG leads; around the scheme—significant ($p < 0.05$) couplings between rhythms; δ, θ, α, β and γ—delta-, theta-, alpha-, beta- and gamma-rhythms, respectively

To identify regional features of the interaction of EEG rhythms, we used cross-correlation matrices (5 × 5—according to the number of rhythm bands) between the main frequency ranges of EEG oscillations: Δ—0.5–3.5 Hz, θ—4.0–7.5 Hz, α—8.0–14.5 Hz, β—15–19.5 Hz and gamma (20–40 Hz) for symmetrical cortical areas.

Figure 2 clearly shows a greater number of connections of EEG rhythms in the right hemisphere at the time interval of 5–1 s before behavioral awakening. This is probably due to the greater activation of the hemisphere regions, which allows waking up and returning to the activity interrupted by sleep. This is consistent with the view that the right hemisphere dominates during the transition from sleep to wakefulness in the morning [12].

The greatest difference in the interaction of rhythms is noted in leads C3–C4, P3–P4 and O1–O2. There are significantly more connections in the corresponding leads in the right hemisphere. The difference is achieved by reducing the number of connections of delta-rhythm with beta- and gamma-rhythms in the left hemisphere. The work [13] shows an increase in interhemispheric interaction in Fp1–Fp2, C3–C4 and P3–P4 leads in all stages of sleep compared to the state of quiet wakefulness. Interhemispheric connections in leads O1–O2 remained practically unchanged in the same conditions. Interestingly, both in sleep and on awakening, changes in similar brain regions are observed, but with deepening sleep interhemispheric interaction in these regions increases, while on the contrary, according to our data, asymmetry increases on awakening.

The analysis of the total index of interaction between EEG rhythms and regional changes in rhythm couplings yielded intriguing findings. While the overall index showed significant similarity in both hemispheres, the regional features revealed interhemispheric disparities during the same time period. Evidently, global bioelectrical processes that affect the entire hemisphere originate from a distinct source than the spatially restricted ones.

Thus, the presence of interhemispheric asymmetry of amplitude–amplitude coupling of EEG rhythms during awakening while performing the psychomotor test was shown.

This article presents preliminary results of the study. Our work will be continued, as the criteria chosen to include data in the analysis significantly limited the sample of subjects.

5 Conclusions

1. Interhemispheric asymmetry of the amplitude–amplitude coupling of EEG rhythms during cognitive awakening while performing a bimanual psychomotor test was revealed.
2. As the moment of awakening approached, both the nature of the EEG rhythm couplings and their number changed.
3. The greatest number of asymmetric connections of EEG rhythms in our study was found at the interval 20–16 s prior to the moment of awakening.

4. Immediately before awakening, a single asymmetric connection of EEG rhythms was present.

Author contributions

Conceptualization: VBD; data curation IAY, ONT, NEP; formal analysis IAY, ONT, NEP, ANP; investigation: EOG; methodology: VBD, IAY, ONT, NEP; project administration VBD; supervision: VBD; visualization: NEP; writing—original draft VBD; writing—review and editing: IAY.

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Data availability The data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests. The funders had no role in the design of the study, the collection, analyses, or interpretation of data, the writing of the manuscript, and the decision to publish the results.

References

1. B. Wang, L. Yang, W. Yan et al., Brain asymmetry: a novel perspective on hemispheric network. Brain Sci. Adv. **9**(2), 56–77 (2023). https://doi.org/10.26599/BSA.2023.9050014
2. D.-H. Park, C.-J. Shin, Asymmetrical electroencephalographic change of human brain during sleep onset period. Psychiatry Investig. **14**(6), 839–843 (2017). https://doi.org/10.4306/pi.2017.14.6.839
3. U. Voss, Change in EEG pre and post awakening. Int. Rev. Neurobiol. **93**, 23–55 (2010). https://doi.org/10.1016/S0074-7742(10)93002-X
4. I.A. Yakovenko, E.A. Cheremushkin, Interhemispheric asymmetry of the spatiotemporal organization of the human brain cortical potentials under different conditions of formation of the verbal set. Zhurnal vysshei nervnoi deyatelnosti imeni I.P. Pavlova. **54**(2), 216–224 (2004). (**researchgate.net/publication/292709681**)
5. G.G. Knyazev, A.N. Savostyanov, A.V. Bocharov et al., Cross-frequency coupling in developmental perspective. Front. Hum. Neurosci. **13**(article: 158), 1–10 (2019). https://doi.org/10.3389/fnhum.2019.00158
6. G.G. Knyazev, Motivation, emotion, and their inhibitory control mirrored in brain oscillations. Neurosci. Biobehav. Rev. **31**, 377–395 (2007). https://doi.org/10.1016/j.neubiorev.2006.10.004
7. A. Morillas-Romero, M. Tortella-Feliu, X. Bornas, P. Putman, Spontaneous EEG theta/beta ratio and delta–beta coupling in relation to attentional network functioning and self-reported attentional control. Cogn. Affect. Behav. Neurosci. **15**(3), 598–606 (2015). https://doi.org/10.3758/s13415-015-0351-x
8. V.B. Dorokhov, O.N. Tkachenko, V.L. Ushakov, A.M. Chernorizov, Neuronal correlates of spontaneous awakening and recovery of psychomotor performance, in *Advances in Cognitive Research, Artificial Intelligence and Neuroinformatics. Advances in Intelligent Systems and Computing*. ed. by B.M. Velichkovsky, P.M. Balaban, V.L. Ushakov (Springer International Publishing, 2021), pp.429–435. https://doi.org/10.1007/978-3-030-71637-0_4924
9. C.J. Hilditch, K. Bansal, R. Chachad et al., Reconfigurations in brain networks upon awakening from slow wave sleep: Interventions and implications in neural communication. Netw Neurosci. **7**(1), 102–121 (2023). https://doi.org/10.1162/netn_a_00272.eCollection2023
10. M. Caporro, Z. Haneef, H.J. Yeh, A. Lenartowicz, C. Buttinelli, J. Parvizi, J.M. Stern, Functional MRI of sleep spindles and K-complexes. Clin. Neurophysiol. **123**, 303–309 (2012). https://doi.org/10.1016/j.clinph.2011.06.018
11. M.H. Zaky, R. Shoorangiz, G.R. Poudel, Y. Le, C.R.H. Innes, R.D. Jones, Increased cerebral activity during microsleeps reflects an unconscious drive to re-establish consciousness. Int. J. Psychophysiol. **189**, 57–65 (2023). https://doi.org/10.1016/j.ijpsycho.2023.05.349
12. M. Casagrande, M. Bertini, Night time right hemisphere superiority and daytime left hemisphere superiority: a repatterning of laterality across wake-sleep-wake states. Biol. Psychol. **77**(3), 337–342 (2008). https://doi.org/10.1016/j.biopsycho.2007.11.007
13. A.N. Shepovalnikov, M.N. Tsitseroshin, L.G. Zaitseva, E.I. Galperina, Features of cortex areas system interactions in the left and right brain hemispheres during different human sleep stages. Russ. J. Physiol. **98**(10), 1228–1241 (2012)