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EEG Characteristics during Short-Term Spontaneous Waking Periods of Different Durations with Changes in Psychomotor Activity Induced by Falling Asleep

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Changes in EEG spectral characteristics during periods of recovery of performance in a psychomotor test during spontaneous short-term periods of waking in daytime sleep were studied in 17 healthy subjects. The test consisted of two sequentially alternating tasks: to count from 1 to 10 silently accompanied by synchronized pressing of a button, and silent counting only. The monotonous nature of the test led to a rapid decline in the level of consciousness and, in most cases, induced falling asleep. Presses serves as a behavioral indicator of the recovery of cognitive processes inhibited during sleep. Situations with small (2–5) and relatively large (6–10) numbers of button presses were compared. The start of pressing was preceded by the appearance of generalized α rhythm, which decreased during performance of psychomotor activity. The power of this rhythm was always greater in longer periods of observed behavioral activity. The end of pressing returned α-power indicators to levels seen before waking. The EEG α rhythm in decreased consciousness during short-term waking evidently characterized the action of the thalamocortical activatory mechanism and was a necessary condition for motor interaction of the body with the external environment. The absence of any differences in the frontal areas at the initial stage on performance of short-lived activity and longer-lasting activity, approaching performance of the complete cycle of presses, suggested that they are involved to the same extent during this period regardless of the number of presses. This result may provide indirect support for the notion that the observed psychomotor activity, even with a small number of presses, is not automatic and unconscious but is accompanied by reduced and fragmented consciousness.

Keywords: daytime sleep, psychomotor test, spontaneous waking, sleep inertia, EEG, α rhythm, consciousness.

Studies of transitional states in the sleep–waking cycle mainly address the processes of falling asleep and, to a significantly lesser extent, waking. The latter has been investigated mainly in experiments with nocturnal sleep and only rare cases, depending on the experimental conditions, have addressed times later than the moment of waking, which is accompanied by cognitive activity on the part of the subject.

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The features of the activation of different brain structures during waking from different sleep stages have been demonstrated [1]. As compared with the resting state before going to sleep, the default mode and hippocampal neuronal networks retain identical levels of connectivity and spectral power on waking; these parameters decreased in the sensorimotor system, and the connection between the thalamus and the neocortex was significantly strengthened. The most significant changes were seen when waking was preceded by deep sleep [1]. The leading role of the thalamus on waking and the existence of regional specificity depending on whether it was spontaneous or induced by the experimental conditions was demonstrated in studies of nocturnal sleep in

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patients with epilepsy [2]. A relationship between the frequency of the α rhythm amd the duration of waking during nocturnal sleep was demonstrated in [3]. Brief waking (less than 5 min) was accompanied by a lower α activity frequency than prolonged waking. In both cases, α-rhythm frequency in healthy subjects was decreased as compared with the state of calm waking.

The characteristics of the performance of cognitive tasks after waking have been studied mainly in the "sleep inertia" paradigm. After nocturnal sleep, its influence on the functional state of the brain has been shown to be preserved for periods ranging from 10 min to several hours in different studies. It was apparent as an increase in the power of the low-frequency EEG components (1–9 Hz) and a decrease in the power of the high-frequency components as compared with the period before going to sleep [4–7]. The most significant changes in behavioral parameters, mental activity, and functional connectivity of the brain were seen on waking from deep sleep [7]. Decreases in EEG power during performance of cognitive tasks after waking as compared with performance before sleep were demonstrated by a Japanese group [8]. We note that the transition itself from the state of sleep to activity has not been studied.

Our previous experiments on daytime sleep addressed brain activity during the period during periods preceding spontaneous waking and recovery of the performance of psychomotor activity [9]. During waking, there were increases in EEG power in the δ and α ranges which, in all probability reflected the action of the thalamocortical activatory mechanism [1, 2, 10].

The aim of the present work was to study EEG correlates directly preceding and accompanying short periods of behavioral activity on waking during daytime sleep. The tasks included analysis of the amplitude-frequency characteristics of the EEG δ and α rhythms before and during short-term periods of cognitive activity with different durations of recovery of performance in a psychomotor test.

Methods. *Subjects*. A total of 34 presumptively healthy subjects (26 women and eight men, aged 19–22 years), right-handed, students at Moscow educational institutions, took part in the study. All were familiarized with the experimental procedure and gave consent to take part. The study complied with the ethical norms of the Helsinki Declaration of the World Medical Association, i.e., the "Ethical Principles for Medical Research using Human Subjects" with the 2000 amendment.

Study procedure. Experiments ran from 13:00 to 16:00. Duration ranged from 55 min to 1 h 10 min. Before experiments assessing sleep parameters, the subjects kept a sleep diary during the night before the study and assessed drowsiness using the Karolinska Sleepiness Scale (KSS).

Subjects lay on a couch in a darkened, soundproofed room at a comfortable temperature. EEG traces were recorded for 5 min in the state of calm waking with the eyes closed. A series of sequential periods of falling asleep and waking was obtained using a continuous psychomotor test, as in our previous suggestion [9, 11, 12]. The subject silently counts from 1 to 10, simultaneously pressing a button with the right thumb with every count (phase 1 of the test), the button being attached to the index finger. The subject then continues to count silently from 1 to 10 but without pressing the button (phase 2). Alternating counts with and without pressing (phases 1 and 2) continue until the subject falls asleep or until the end of the experiment. When falling asleep with subsequent spontaneous waking occurs, the subject has to restart the psychomotor test task. The instructions given after EEG recording with the eyes closed emphasized that on waking the subject should start by counting with button presses (phase 1) and only then proceed to counting without presses.

During the experiment, the EEG was recorded from the head surface using 17 leads positioned according to the 10–20% scheme (F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4, P3, P4, Pz, T5, T7, O1, and O2). Leads were monopolar and the reference electrode was a combined ear electrode. The electrooculogram (EOG) and myogram (EMG) were also recorded, along with the mechanogram for button presses. All parameters were recorded using a Neocortex-Pro system (Neurobotics, Russia). The sampling frequency was 250 Hz. The frequency bandpass was 0.5–70 Hz. The EEG was recorded with a cap with silver chloride electrodes with resistance not exceeding 5 kΩ.

Data collection and analysis. Subjects who on spontaneous waking from the second stage of sleep and performed phase 1 of the psychomotor test, even if only once, with smaller (2–5) or larger (6–10) numbers of presses, were identified. Use of an approach based on repeat observations of the same subject for comparison of the properties of the α rhythm accompanying these different-duration behavioral patterns avoided the results being influenced by differences in power in subjects' EEG recordings. This approach also provided for comparison of the time interval from the onset of a widespread cortical α rhythm to the moment of the start of pressing, which varied from subject to subject and depended on the number of presses.

Situations in which the sequences of presses were recorded on the mechanogram for one minute or more were considered. Cases in which the difference between shorter and longer episodes of performance of phase 1 of the test after waking was by less than three presses were excluded. Subsequent analysis in each subject used one performance with a smaller or larger number of presses such that the difference was maximal. Thus, to some extent we separated subjects' activation levels in episodes of recovery of activity after waking. A total of 17 subjects (13 women and four men aged 19–22 years) were selected on this basis. The mean duration of nocturnal sleep on the night before the experiment was 6.0 ± 0.5 h, and its quality and wellbeing after morning waking were assessed by subjects as good and satisfactory (3.8 ± 0.3 and 3.2 ± 0.3, respectively,

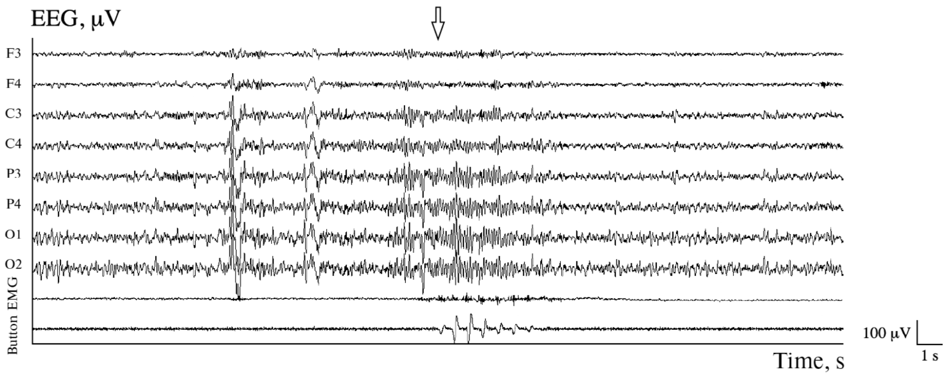

Fig. 1. Example EEG, EMG, and mechanograms on waking and renewed performance of the psychomotor test. From above: EEG, EMG, and mechanogram leads. Vertical bars show 1-sec time intervals. The arrow shows the beginning of presses.

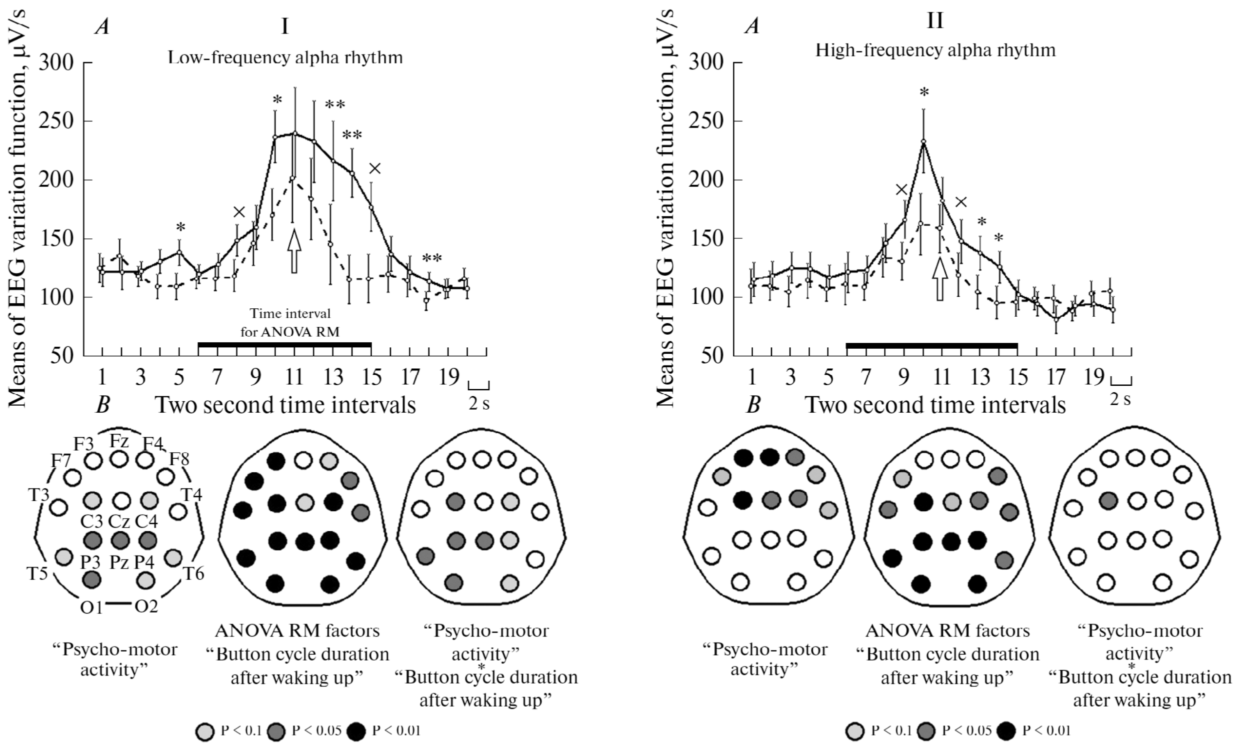

Fig. 2. Spectral characteristics of the low-frequency and high-frequency α rhythm for different durations of the button-pressing period during recovery of psychomotor test performance after spontaneous waking. *I*) Low-frequency α rhythm; *II*) high-frequency α rhythm; *A*) *total* for all EEG leads; the dotted line shows 2–5 presses and the continuous line shows 6–10 presses; the vertical axis shows spectral power, μV/sec and the horizontal axis shows time in 2-sec segments; the arrow shows the start of pressing after waking; ×, *, ** – differences ($p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively); the interval during which analysis of variance was run is indicated; the error of the mean is shown; *B*) results of analysis of variance for individual EEG leads; maps showing significant differences for individual factors and their combinations; light gray, dark gray, and black show leads – $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively.

5-point scale, where 5 is the best score). Sleepiness levels before the experiments were elevated (5.3 ± 0.5, 7-point scale, where 7 is the highest level of sleepiness).

EEG segments of 40 sec, with onset of button pressing in the middle, were analyzed. Amplitude changes in electrical oscillations were evaluated using variance curves [13]. Initial Fourier transformation was used to filter selected segments in the ranges 0.5–3.5, 4–7.5, 8–10.5, and 11–13.5 Hz (the δ, θ, low-frequency α, and high-frequency α rhythms). Then, 1-sec intervals with a sliding window of 100 msec and shift 10 msec were used on each EEG lead to determine the variance functions, which were averaged. Variance curves were defined by the product of the amplitude of a potential and its frequency. However, considering the small changes in the frequency structure of electrical oscillations in relatively small periods of time (1 sec), it can be regarded as a power indicator of the amplitude type [13]. It was then found that selection of relatively short (1 sec)

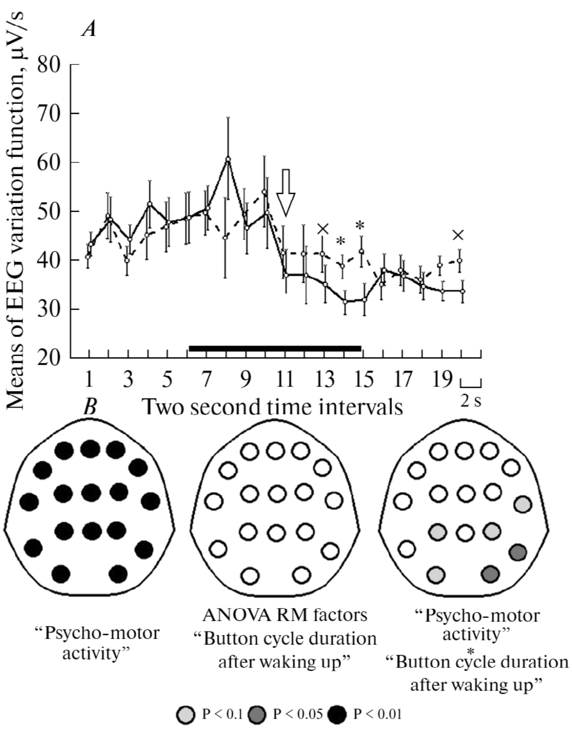

Fig. 3. Spectral characteristics of the δ rhythm for different durations button-pressing during recovery of psychomotor test performance after spontaneous waking. For details see caption to Fig. 3.

time intervals as analysis epochs for statistical evaluation of changes in EEG amplitude characteristics was excessive for this study. Thus, values of the variance function were averaged for 2-sec periods. This did not affect the results, though curves smoothed in this way shown in the illustrations provide a better reflection of the trends in these measurements. The resulting values for each frequency range were evaluated by analysis of variance for repeat measures (ANOVA RM). Attention was focused on the time interval comparable with the duration of performance of the first phase of the test (10 sec, or five 2-sec intervals), i.e., the period of pressing the button after waking. The influences of the factors Psychomotor activity (two levels – before the start of button pressing and after button pressing), Duration of pressing (two levels – 2–5 and 6–10 presses), and Time (five levels – five 2-sec time segments) on EEG amplitude-power characteristics were assessed. Analyses were run using both average amplitudes for all EEG leads for each subject (i.e., total) and separately for each lead. Evaluation of the results in this analysis of variance design was followed by additional processing for regional features. Influences of the Region (two levels – anterocentral and caudal) and EEG lead (six levels – F3, F4, F7, F8, C3, and C4 for the anterocentral region and P3, P4, T5, T6, O1, and O2 for the caudal region) factors on numerical EEG power characteristics were also evaluated. Statistical results were obtained using the Greenhouse–Geisser correction. At each time interval, the paired Wilcoxon test was used to compare the characteristics of the EEG rhythms of interest. All statistical computations were run in SPSS 13.0.

Results and Discussion. Overall for all leads, the Psychomotor activity factor influenced the power of the δ rhythm ($F(1,16) = 20.0$, $p < 0.001$) and, at the level of a tendency, that of the α rhythm in both ranges ($F(1,16) = 3.7$, $p = 0.07$ and $F(1,16) = 3.7$, $p = 0.07$, respectively); the Duration of pressing factor influenced the power of the EEG low-frequency and high-frequency α rhythms ($F(1,16) = 11.0$, $p = 0.004$ and $F(1,16) = 9.4$, $p = 0.007$, respectively). The low-frequency α rhythm was also influenced at the level of a tendency by the combination of the Psychomotor activity and Duration of pressing factors ($F(1,16) = 3.8$, $p = 0.07$). Mean total EEG power for all leads in the α subranges is shown in Fig. 2, *A* and that for the δ rhythm is shown in Fig. 3, *A*. We did not find any significant influence for these factors on the power characteristics of the θ rhythm, which was therefore excluded from further analysis.

Results on influences of the Psychomotor activity and Duration of pressing factors and their interaction on the characteristics of the spectral power of individual EEG leads are shown in Fig. 2, *B* and Fig. 3, *B*.

The combination of the Psychomotor activity and Region factor was found to influence the power characteristics of the low-frequency α rhythm (F(1,16 = 14.1, $p = 0.002$), as was the combination of the Duration of pressing and Region factors ($F(1,16) = 7.6$, $p = 0.014$) and the combination of the Psychomotor activity, Duration of pressing, and Region factors ($F(1,16) = 6.7$, $p = 0.02$). The power of the high-frequency α rhythm was found to be influenced by combination of the Duration of pressing and Region factors ($F(1,16) = 35.3$, $p = 0.0001$). The δ rhythm was influenced by the combination of the Psychomotor activity and Region factors ($F(1,16) = 8.7$, $p = 0.01$).

We note that this analysis of variance design demonstrated that the power of the low-frequency and high-frequency α rhythms was significantly influenced by the Duration of pressing factor ($F(1,16) = 13.4$, $p = 0.002$ and $F(1,16) = 11.1$, $p = 0.004$).

Onset of performance of the psychomotor test occurred with a widespread cortical α rhythm, which declined during the activity. Data have been obtained indicating that the α rhythm appears in the encephalogram during brief episodes of waking after sleep onset (WASOs) and during waking from sleep [2, 3, 14, 15]. It can be suggested that the EEG α rhythm at a decreased level of consciousness is a necessary condition for motor interaction between the body and its environment.

Pairwise comparisons of EEG power characteristics for EEG leads in the periods before pressing the button are shown in Fig. 4. We felt that both significant results and trends should be presented in the figures for the following reasons. The EEG segments studied here were obtained in the transitional stage of the "sleep–waking" cycle, which is accompanied by a period of psychomotor activity and acti-

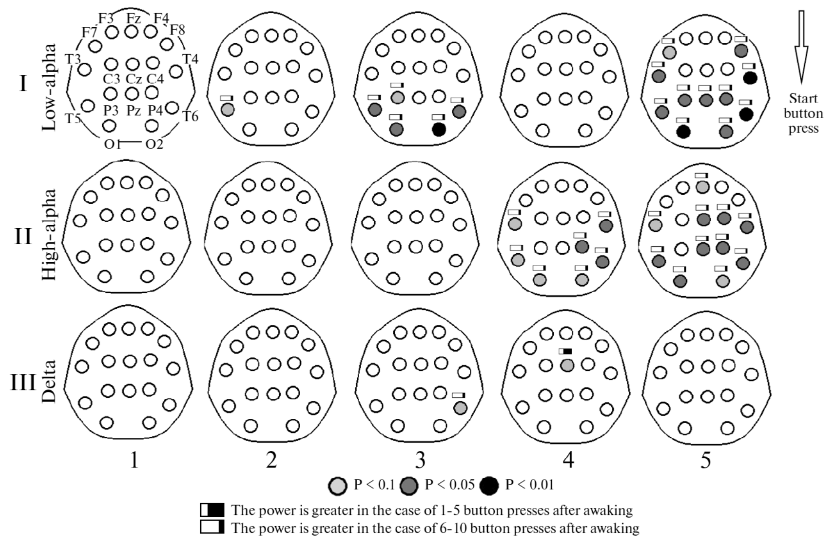

Fig. 4. Maps showing the results of pairwise comparison of EEG spectral characteristics preceding the start of pressing: comparison of situations in which waking was followed by a small (2–5) or large (6–10) number of presses. *I*, *II*, *III*) Low-frequency α, high-frequency α, and δ rhythm, respectively; 1–5) 2-sec time intervals; the arrow shows the moment at which pressing started; light gray, dark gray, and black leads: $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively; the rectangle with the larger dark part shows power greater in the case of 2–5 subsequent presses; the rectangle with the smaller dart part shows power greater for 6–10 subsequent presses.

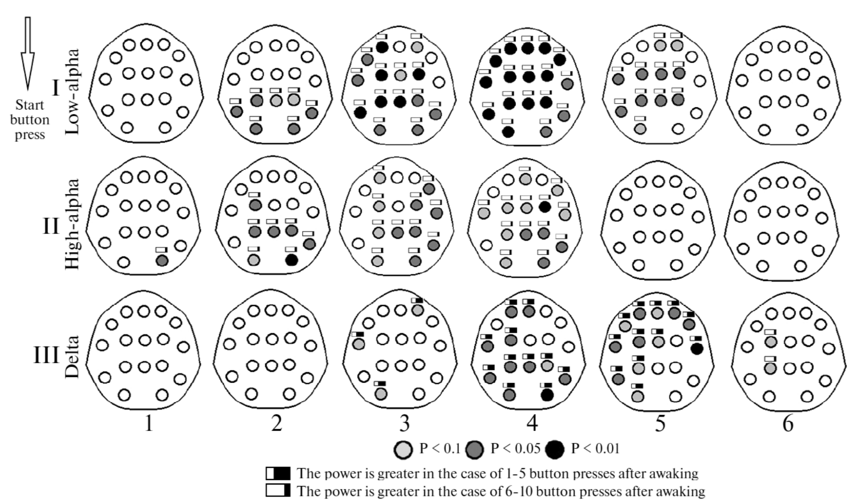

Fig. 5. Maps showing the results of pairwise comparison of EEG spectral characteristics between situations with small and large numbers of presses on recovery of psychomotor test performance after spontaneous waking. 1–6) 2-sec time intervals. For further details see caption to Fig. 4.

vation of consciousness. Our approach to evaluation of this phenomenon used a behavioral parameter – different numbers of presses in these transitional states. Cerebral support of waking/sleeping processes, psychomotor activity, and increases/decreases in consciousness occurring over short intervals of time were assessed in the present studies in terms of the power characteristics of oscillations in cortical electrical activity. We believe that detailed description of regional differences in the EEG in this parameterization of the set of phenomena observed should allow the reader to access more complete information. This does not seem to exclude a critical approach to the results obtained as tendencies.

We showed that before the onset of psychomotor activity, values for the α rhythm were greater when the subject subsequently spent longer pressing the button. These differences were seen in the low-frequency α rhythm 5–6 sec before pressing started with involvement of the caudal areas and immediately before pressing for 2 sec (Fig. 4, *I*). In the high-frequency α rhythm, this difference was seen later (3–4 sec before the start of pressing) in the caudal and anterotemporal areas, and propagated to areas Fz, Cz, and C4 immediately before the start of activity (Fig. 4, *II*). The anterotemporal cortex plays an important role in supporting working memory [16]. The lateral prefrontal cortex has a

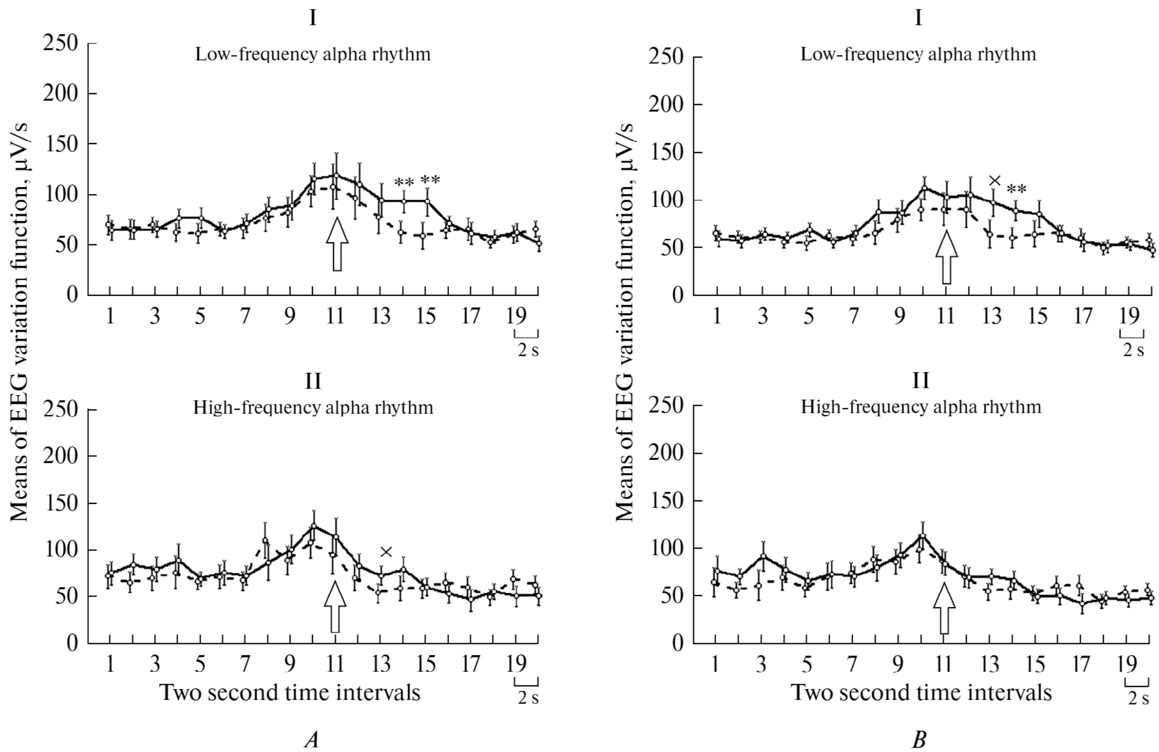

Fig. 6. Spectral characteristics of the low-frequency and high-frequency α rhythms in the EEG leads in the frontal areas after spontaneous waking. *A*) F3; *B*) F4. For further details see Fig. 2.

role in organizing the directed attention system and top-down cognitive control [17–19]. In our study, activation anticipating the onset of activity in the anterotemporal prefrontal cortex could reflect processes linked with extraction of the instructions from working memory and used as the basis for planning further actions.

Differences in the power of α oscillations in the central area of the right hemisphere reflect preparation for longer-lasting motor activity which in time approaches the complete cycle of pressing in the psychomotor test. EEG changes associated with realization of limb movements were most marked in the hemisphere contralateral to the limb (in particular the arm) carrying out the movement [20, 21]. It can be suggested that preparation to initiate the motor reaction also occurs in the contralateral hemisphere.

There were essentially no differences in the δ rhythm before pressing patterns of different durations (Fig. 4, *III*).

Pairwise comparisons of EEG power characteristics for EEG leads in the period before pressing the button are shown in Fig. 5. The characteristic of the α rhythm may also serve as indicator of the duration of waking in the arousal periods studied. Relatively long periods of pressing were accompanied by generally higher α-rhythm amplitudes than shorter periods (Fig. 5, *I* and *II*). The end of pressing in both cases returned α-rhythm power indicators to those seen before waking.

Less pronounced differences between situations with different durations of behavioral activity were seen in the δ rhythm. Realization of activity during relatively long periods of pressing was associated with some decline in power levels, while there was virtually no change during short periods (Fig. 5, *III*). We note that even small decreases in power in the δ rhythm in the situation in which subjects approached complete reproduction of the pressing cycle in the psychomotor test led to the appearance of significant differences, most marked at 7–10 sec from the onset of pressing. Retention of low-frequency activity typical of the state of sleep after waking, i.e., sleep inertia, has been described in the literature [4–7].

We note that the term "sleep inertia" is used in studies of impairments to activity after prolonged daytime and nocturnal sleep, including the stage of deep sleep (third stage). The subject's activity was not studied immediately after waking, but after some period of time. In the conditions of our study, the sleep periods preceding spontaneous waking were relatively short, and sleep itself only reached the second stage. Studies have been reported showing that brain activation rather than sleepiness occurred after short periods of sleep lacking the third stage [22]. Considering all these points, use of this term to explain changes in the EEG during the phenomenon observed here is not entirely correct. However, it does not seem justified to categorically deny that the consequences of sleep influence short-term waking, psychomotor activity carried out during this period, and subsequent rapid falling asleep.

Thus, δ-rhythm power can also to some extent be regarded as a characteristic of the duration of short-term wakings.

The absence of differences in the α rhythm in any areas at the initial stage of psychomotor activity of different durations (transient for longer periods, i.e., approaching performance of the complete cycle of pressing) is evidence that these areas are involved to the same extents regardless of the number of presses (Fig. 6).

This result may support the view that the psychomotor activity seen here may not be automatic and unconscious, but is accompanied by decreased and fragmentary consciousness [23, 24]. We suggest that the number of presses on performance of the psychomotor test during the transitional processes from sleep to activity and from activity back to sleep is evidence of the level of consciousness apparent at these stages. We hope our study will provide food for thought and impetus for the search for new experimental paradigms in studies of consciousness and its neuronal correlates.

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