Neuronal Correlates of Spontaneous Awakening and Recovery of Psychomotor Performance

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Abstract. The study of consciousness is crucial to understand how the human mind functions. Within the last twenty years new approaches to this question have been formulated and "establishing neural consciousness correlations" is one of the most promising. The sleep-wake paradigm is one of the most promising methodologies in this field, allowing the study of healthy subjects without medical interventions. We developed a monotonous psychomotor test that induces several episodes of losing consciousness because of falling asleep and its full or partial recovery while awakening within the 60 min. The following behavioral measures of consciousness level were noted: counting accuracy, time between presses, pressing force, so one could observe not only lapses, but also light sleep when subject starts to make mistakes. In our recent study, this method allowed us to assess 441 short episodes of falling asleep ("microsleep"), followed by spontaneous awakenings in 23 experimental sessions. Two different electroencephalographic patterns of awakening were observed. After deeper sleep stages the performance restoration was preceded by K-complexes. According to recent studies, it confirms that K-complex not only helps to maintain sleep, but also eases necessary awakenings. Our recent data suggest that not only external stimuli, but also the internal test instruction recall could start such awakening process. We believe that our experimental design could be used for wide range of consciousness studies because it gives researchers several continuous and objective indices of the subject's mind state.

Keywords: EEG · K-complex · Consciousness · Microsleep · Spontaneous awakening · Psychomotor test

1 Introduction

The study of consciousness is an essential task of cognitive science. It is critical for understanding the function of the human mind. In recent years, new approach to this question was formulated as a "search of neural consciousness correlations" (NCC) [1]. This approach is based on the axiom of existing causal links between brain activity and mind contents. There are two strategies within this approach, i.e. study of consciousness

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level or its contents [2]. Consciousness level is often defined as a byword of activation or an awakening level. Mind contents, on the other hand, is associated with comprehension or subjective experience [3]. Many authors emphasize the need for experimental tests uniting both aspects [4]. Studies on mind contents based on subject's reports have many limitations. Therefore, several new objective, "no-report" paradigms were recently developed [5].

Comparisons of sleep and wakefulness is very easy using the effective experimental model of NCC that allows researchers to assess various consciousness levels of healthy subjects without any medical interventions. Consciousness "extinguishes" during sleep and "switches on" while awakening. Depolarization of cortical neurons observed in wakefulness is the prerequisite for the conscious state. It is hypothesized that unconscious state during sleep is caused by cortical neurons' bi-stable state, i.e. synchronous periodical polarization and depolarization that make complex all-over-brain synchronization impossible [6].

2 Methods

Within the sleep-wake paradigm we developed an experimental model of consciousness activation during spontaneous awakening [7–10]. The design is described below.

28 healthy subjects (6 females) were recruited among university students. 5 subjects were excluded from further analysis because there were no short episodes of falling sleep during their experimental sessions. Each subject was informed in detail about the experimental procedures and gave his/her written consent. The study protocol was approved by the Ethics Committee of the Institute of Higher Nervous Activity and Neurophysiology (No. 046/19), and all experimental procedures were performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

Experiments were performed in daytime, started at 1–3 p.m. The subject lay on bed in a dark and quiet room, with eyes closed, counting from one to ten and pressing two pneumatic buttons holding on with thumbs and index fingers of each hand. To prevent buttons from falling, they were fixed with adhesive plaster to the subject's hand. The subject was instructed to press the buttons once a second in rotation (10 presses with the right hand, 10 presses with the left hand and so on). Thus, several behavioral measures of the subject's consciousness state were available during the experiment: counting accuracy, time between presses, pressing force. Electromyogram (EMG) from both thumb fingers (*musculus abductor pollicis brevis*) was recorded in addition to buttons mechanograms. Electroencephalogram (EEG) was also registered continuously, providing brain activity information. Standard 10–20 system with 19 channels was used to record EEG filtered in 0.1–70 Hz frequency range.

Each subject participated in two experimental sessions with 1–10 days in between. During the first training session periodical sound was used to instruct the subject to maintain 1-s intervals. This session was about 10–15 min long. Second (main) session lasted for 55–60 min.

This monotonous psychomotor test causes several short episodes of sleep and spontaneous awakening over the period of 1 h. EEG patterns of 2nd or even 3rd sleep stage could be observed during such short episodes of falling sleep ("microsleep") lasting from 10 s to several minutes (see Fig. 1).

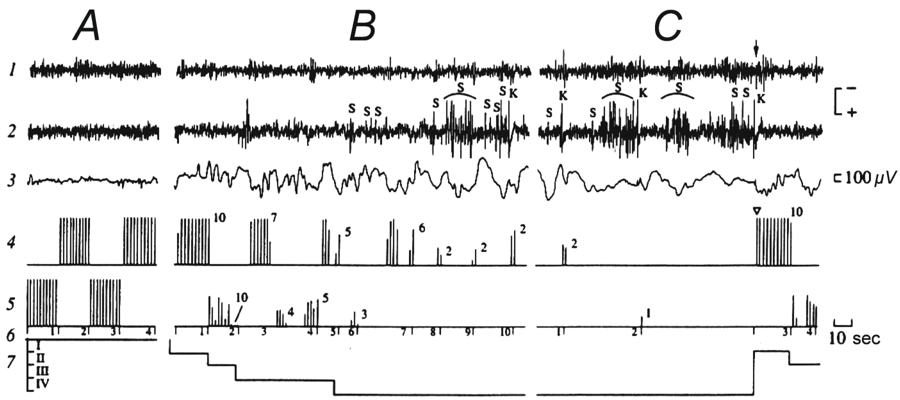

Fig. 1. EEG correlates of psychomotor test errors for various short episodes of falling sleep observed in single experiment. A — wakeful state, B — drowsiness and light sleep (1st stage), C — more deep sleep, (2nd stage — "microsleep"). 1,2 — O1 and C3 EEG electrodes, 3 — EOG (left eye), 4,5 — button presses for right and left hands, 6 — number of press in the batch, 7 — performance level. S — vertex sharp waves, K is for K-complexes. Arrow marks awakening sound. Performance levels are the following: I — correct task performance, II — lowered press power, II — lowered press power with errors, IV — "microsleep" episode.

3 Results

During the test, performance varied greatly, from totally correct 10–10 press batches to counting errors, short pauses, single presses and finally sleep episodes, providing good objective measures of subject's current consciousness level. Overall 441 "microsleep" episodes were found in 23 successful experiments of our recent experimental session (pause between presses equal to or more than, 10 s). In each successful experimental session 2–48 short episodes of falling sleep were observed. Lapses ("microsleep") duration varied from 20 s to several minutes, with median value about 52 s. Five subjects that didn't fall asleep at all were excluded from further analysis.

It was already shown in our studies that spontaneous renewal of psychomotor test performance goes hand in hand with two types of EEG patterns. The first one was mostly observed during awakening from 1st sleep stage, including alpha spindles with higher frequencies inclusions. 2nd pattern type followed awakenings after 2nd and 3rd sleep stages and includes not only alpha activity, but also slow-wave components or can even be preceded by K-complex (single high amplitude slow wave). Thus, our data confirms the well-known fact that phasic activation patterns in EEG depend on previous sleep depth [11]. Examples of such EEG patterns are presented in Fig. 2.

Figure 2 illustrates spontaneous awakenings followed by button presses after different sleep stages. Awakenings after episodes of light sleep (EEG markers of stage 1) usually demonstrate phasic activation patterns of 1st type (alpha waves). This patterns starts at the same time as the 1st button is pressed (see subplot A). 2nd type of pattern (subplot B) demonstrates isolated late component of K-complex immediately leading to presses renewal. At the subplot C one could observe classical high-amplitude

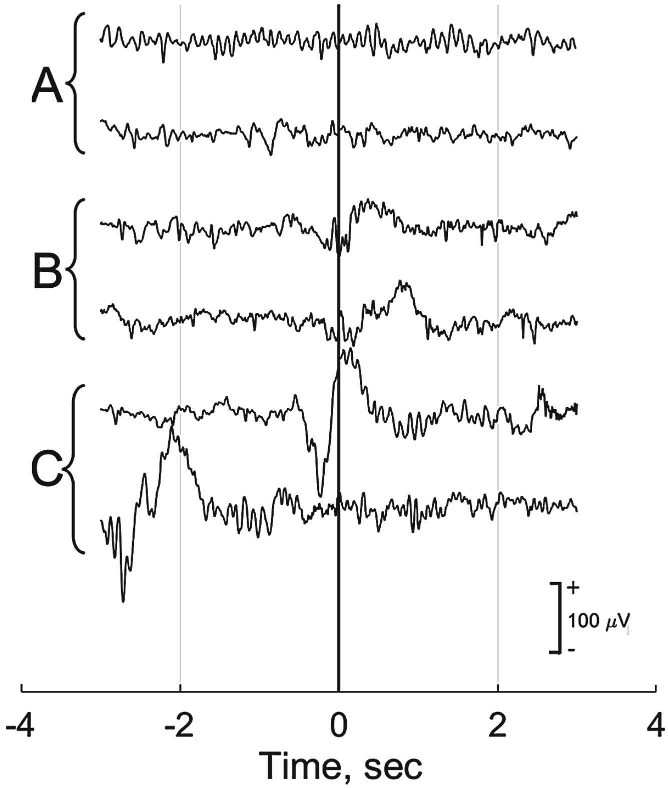

Fig. 2. EEG patterns (derivation Fp1) of spontaneous awakening and performance renewal after sleep episodes. A — light sleep (1 stage), pattern type 1 (alpha waves), alpha activity increases along with performance renewal, B — more deep sleep, 2 stage (late component of K-complex accompanies performance renewal), C — high-amplitude K-complex precedes alpha activity. Vertical line marks first button press after sleep episode.

(up to 300 μV) K-complex after sleep episode of stage 2 accompanied by alpha range oscillations.

We suggest that spontaneous performance renewal after falling sleep is initiated by test instruction "to press button and count" retrieval during sleep. The very moment of such retrieval can be determined precisely using EEG predictors, particularly K-complex. First button pressing doesn't occur immediately after EEG activation and instead takes some time [10]. According to recent scientific knowledge about awakening this time lapse is necessary to re-connect neuronal ensembles in different brain regions. This so-called "binding process" [12] is a crucial pre-condition of the consciousness state.

An experimental session within fMRI was also performed. Although co-registration of EEG and fMRI data is very difficult, button presses are still available for detailed analysis. Even with the high noise level of fMRI device, 2–48 episodes of "microsleep" were registered from 10 subjects during 1-h experiments. An increase in the activity of the visual regions (the region of the calcarine sulcus) of the cerebral cortex, left precuneus/cuneus during sleep and regions of the right thalamus, left cuneus, cerebellar zones, stem structures at the moment of awakening and resumption of conscious activity were observed [9].

4 Discussion

The scientific meaning of sleep state has changed in recent decades. The view now is that the sleeping subject has some limited access to environmental signals and is able to awake immediately if something changes drastically [13]. Instead of being totally isolated from environmental events, the sleepy brain combines sensory isolation with oversight elements and chooses between sleep and awakening continuously.

In recent research [14] the split "personality" of K-complex is discussed in detail. Different phases of this EEG phenomenon are balanced between suppression and facilitation of outer stimuli. Starting with some initial activation, the K-complex then includes a short downstate period followed by an upstate component (900 ms from the start, or P900). This upcoming front opens a potential "window of wakefulness" for stimuli processing [15], and it has already been demonstrated that at such moments the information could be processed or even learned [16]. There is also evidence that speech processing during non-REM sleep is suppressed, but significantly improves just after it [17]. Therefore, the K-complex correlates with suppression of isolated environmental signals and improved reaction to repeating events at the meantime, i.e. is involved in creation of 'windows of wakefulness' within sleep during which relevant environmental or inner inputs can be processed [14].

5 Conclusion

As Andrillon and Kouider [14] assume, the sleeping subjects maintain a certain amount of minimal vigilance, a stand-by mode allowing the quick reversal to wakefulness, if necessary. It is well-known that K-complex can be caused not only by environmental, but also by internal stimuli [18]. Hypothetical instruction "to press button and count" could act as such internal stimuli, given it is retained in the short-time memory and gains access to brain executive structures when the "windows of wakefulness" opens [15]. Hence, its emergence just before spontaneous awakenings in our experiment could signify the test instruction retrieval followed by further cortex activation and neuronal activity integration.

We therefore suggest that "spontaneous" awakenings occur when hypothetical instruction "to press button and count" successfully gains access to brain executive structures. Thus, high-amplitude K-complex could play its role in urgent activation and further synchronization of these executive neural networks.

We assume that subject's performance after "microsleep" episode could be used as an objective, "no-report" measure of consciousness level. We also believe that EEG phasic patterns during spontaneous awakening represent a binding process between neurons of various brain regions, that in turn builds a foundation to gradual consciousness activation.

It was also shown in our studies that the psychomotor test could be successfully combined with functional magnetic resonance imaging. Preliminary results about the activity of the brain structures during spontaneous awakening, were obtained using such experiments [9].

One could expect that the performance resuming is preceded by cognitive processes of remembering the instruction "to press button and count" followed by activation of neural networks involved in mental counting and finally launching the effector process of actually pressing the button. This sequence of processes meets all requirements to the neural correlate of consciousness in the frame of our experimental model of consciousness in the sleep-wake paradigm [9, 10]. We suggest that further research of EEG features during successful and partial awakening episodes will allow us to localize and interpret electrophysiological correlates of the consciousness level increase during awakening.

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