Experimental Model of Study of Consciousness at the Awakening: FMRI, EEG and Behavioral Methods

Vladimir B. Dorokhov[1(✉)], Denis G. Malakhov[2], Vyacheslav A. Orlov[2], and Vadim L. Ushakov[2,3]

[1] Institute of Higher Nervous Activity and Neurophysiology of RAS, Moscow, Russia
vbdorokhov@mail.ru
[2] National Research Center "Kurchatov Institute", Moscow, Russia
[3] National Research Nuclear University "MEPhI", Moscow, Russia

Abstract. For the study of neuronal correlates of consciousness, a simple and effective model is the comparison of sleeping and waking states. Consciousness turns off during sleep and turns on at waking. The moment of awakening from sleep is a promising model for the study of neurophysiological correlates of consciousness. We developed a psychomotor test, the monotonous performance of which, causes within 60 min alternating episodes with the disappearance of consciousness when falling asleep (the "microsleep") and its restoration upon awakening (wakefulness). When performing this test, the subject with closed eyes counts from 1 to 10 and simultaneously presses sensitive buttons, alternately with the right and left hands. Spontaneous restoration of the test after the episode of "microsleep" requires the activation of consciousness, which is accompanied by consciously performing the test with counting and simultaneously pressing the buttons. EEG methods allow you to accurately assess the moments of the transition of sleep/wakefulness, the levels of wakefulness and the depth of sleep, and behavioral methods, by indicators of the correctness of the performance of the psychomotor test - to determine the levels of consciousness. We showed reproducibility of this test obtained both under normal conditions and in conditions of functional magnetic resonance imaging (fMRI) procedure. In 10 out of 14 subjects during a 60-min experiment performed in the MRI scanner, 3–48 episodes of "microsleep" were recorded with subsequent awakening. Preliminary results showed an increase in the activity of the visual regions (the region of the calcarine sulcus) of the cerebral cortex, left precuneus/cuneus, etc. during sleep and regions of the right thalamus, left cuneus, cerebellar zones, stem structures, etc. at the moment of awakening and resumption of conscious activity.

Keywords: Microsleep · Awakening · fMRI · Levels of consciousness

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1 Introduction

The study of consciousness is the most important and most complex problem of neuroscience, necessary for understanding the mechanisms of the functioning of the human mind [1, 2]. At the junction of cognitive and neurosciences, an approach to the study of consciousness has been formulated, as the search for neuronal correlates of consciousness. The basis of this approach is the postulate of the existence of a causal relationship between activity of consciousness and brain activity: for each event in the consciousness there is a corresponding event in the brain. Within the framework of the concept of "neural correlates of consciousness" [2, 3], the task is to find out which neurophysiological events correlate with certain states of the brain and the content of consciousness. Modern theories develop in the direction of the study of the neurological basis of consciousness [4]. The results of the study of neural correlates of consciousness are not only of fundamental importance, but are already applicable in the field of neurology and psychiatry [5].

According to modern ideas [6], studies within the framework of the paradigm of neural correlates of consciousness should look like this: during the experiment, the subject must several times be in two different states: the presence of consciousness (he experiences a certain state) and lack of consciousness (the subject does not experience this state). In all other respects, the experimental conditions must remain unchanged. At the same time, the functioning of the brain of the subject is simultaneously examined using fMRI, PET, EEG or MEG, which allow to evaluate various spatial and temporal characteristics of brain neuronal networks [7]. For the study of neuronal correlates of consciousness, a simple and effective model is a comparison of sleep and wakefulness states [6, 8, 9]. Consciousness turns off during sleep and turns on awakening, which proves its connection with different functional states of the brain [6, 9]. The moment of awakening from sleep is a promising model for the study of neurophysiological correlates of consciousness [10–13].

A necessary condition for the functioning of consciousness is the presence of the necessary level of depolarization of cortical neurons, which is characteristic for wakefulness. And lack of consciousness, in the slow-wave sleep stage, according to existing concepts, is determined by the bistable state of the cortical neurons, with intermittent hyperpolarization and depolarization of the neuronal membrane [7–9]. It is suggested that it is the bistability of the state of neurons in sleep that disturbs the synchronous interaction of the cortical areas of the brain, which is necessary for the functioning of consciousness, as shown by the method of transcranial stimulation of the brain during sleep [14].

Within the framework of the paradigm of two states - presence and absence of consciousness, we have developed a psychomotor test, monotonous execution of which during 50–60 min causes alternating episodes of "microsleep" and awakening [10]. When performing this test, the subject with the closed eyes counts from 1 to 10 and simultaneously presses sensitive analog buttons, alternately with the right and left hands. When performing this test in subjects with partial deprivation of night sleep, by the end of the 60 min experiment, several short-term episodes of "microsleep", with electroencephalographic activity corresponding to the third stage of sleep, with delta-waves of the EEG, could be observed. Spontaneous restoration of the test performed after the episode “microsleep” requires the activation of consciousness, which we believe is accompanied by the extraction of instructions from memory and the conscious execution of the test with counting and simultaneous pressing of the button. Thus, during one short experiment (1 h), several consecutive episodes can be analyzed, with the disappearance of consciousness during sleep (“microsleep”) and its recovery upon awakening (wakefulness). EEG methods allow you to accurately assess the moments of the transition sleep/wakefulness, wakefulness levels and the depth of sleep, and behavioral methods, by indicators of the correctness of the performance of the psychomotor test - to determine the levels of consciousness. A study of the feasibility of performing this test under conditions of a magnetic resonance imager (MRI) showed reproducibility of the results obtained under normal conditions.

2 Materials and Methods

MRI data were obtained from 14 healthy subjects, mean age 24 (range from 20 to 35 years). Permission to undertake this experiment has been granted by the Ethics Committee of the NRC “Kurchatov Institute”.

In 10 out of 14 subjects during a 60-min experiment performed in the MRI chamber, 3–48 episodes of “microsleep” were recorded with subsequent awakening. Simultaneous registration of EEG, fMRI and button presses was performed, which is a prerequisite for reconciling the spatial and temporal characteristics of the dynamics of brain neural networks with the nature of the test. It should be noted that this technique, when carrying out the experiment under ordinary conditions, allows preliminary selection of the subjects with the greatest number of episodes of “microsleep” having EEG patterns of deep delta sleep, for subsequent fMRI studies. Figure 1 shows the mechanogram of pressing the right and left button during sleep and wakefulness (the arrow marks the moment of “microsleep”, the red vertical lines indicate the moments of awakening according to the mechanogram).

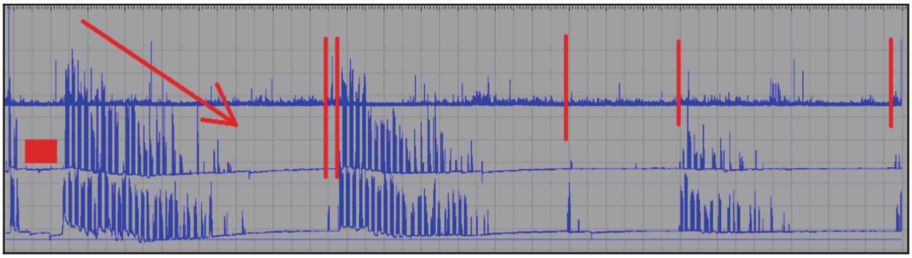

Fig. 1. Mechanogram of pressing the right and left button during sleep and wakefulness (the arrow marks the moment of “microsleep”, the red vertical lines indicate the moments of awakening according to the mechanogram).

Figure 2 shows an example of an EEG recorded synchronously with fMRI and the mechanogram. The time of awakening and the preceding slow-wave activity are shown. In this example, at the moment of awakening, the subject starts to press buttons with two hands simultaneously. Usually, after 1 cycle of several presses, subjects recall the instruction and start pressing buttons separately. Figure 3 shows an example of the alpha activity of the EEG in waking state.

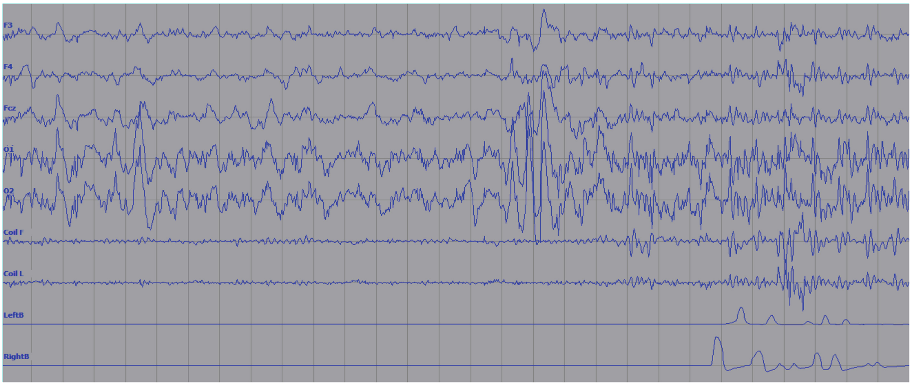

Fig. 2. An example of the EEG of the moment of awakening and the preceding slow-wave activity (after MRI gradient and cardioballistic artifact correction).

The MRI data was acquired using a 3 T SIEMENS Magnetom Verio MR scanner. The T1-weighted sagittal three-dimensional magnetization-prepared rapid gradient-echo sequence was acquired with the following imaging parameters: 176 slices, TR = 1900 ms, TE = 2.19 ms, slice thickness = 1 mm, flip angle = 9^0, inversion time = 900 ms, FOV = 250 mm × 218 mm^2. fMRI data was acquired with the following parameters: 42 slices, TR = 1000 ms, TE = 25 ms, slice thickness = 2 mm, flip angle = 90°, FOV = 192 × 192 mm^2, Mb = 8. The ultrafast fMRI protocol was obtained from the Minnesota Center for Magnetic Resonance Research university. The fMRI and structural MR data were pre-processed using SPM8 (available free at http://www.fil.ion.ucl.ac.uk/spm/software/spm8/). After Siemens DICOM files were converted into SPM NIFTI format, all images were manually centered at the anterior commissure. EPI images were corrected for magnetic field inhomogeneity using FieldMap toolbox for SPM8. Next, slice-timing correction for fMRI data was performed. Both anatomical and functional data were normalized into the ICBM stereotactic reference frame. T1 images were segmented into 3 tissue maps (gray/white matter and CSF). Functional data were smoothed using Gaussian filter with a kernel of 6 mm FWHM. Statistical analysis was performed using Student's T-statistics ($p < 0.05$, with correction for multiple comparisons (FWE)). The activity of the brain structures was compared at intervals of 8 s before the resumption of the button presses and 4 s after the start of the pressing. In the processing of data, the "microsleep" periods were taken if they were 8 s or more, and after which there were at least 2 button presses.

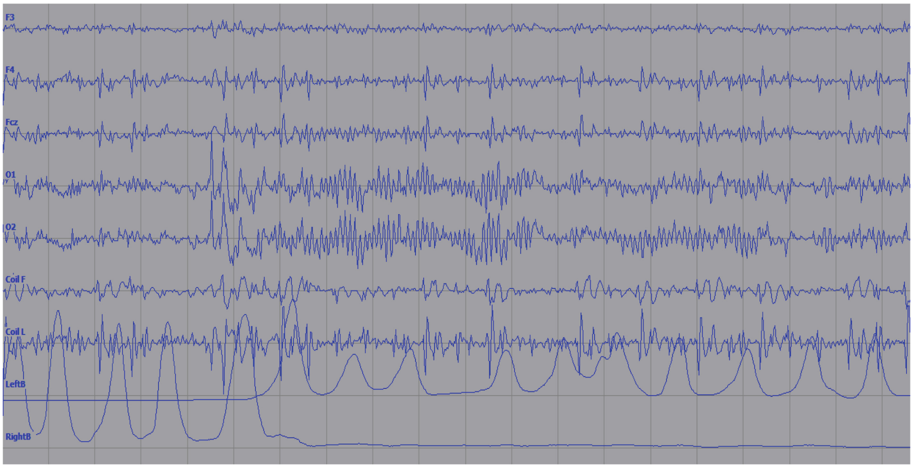

Fig. 3. Alpha-rhythm of EEG in waking state (after MRI gradient and cardioballistic artifact correction).

3 Results

Figure 4 shows the results of increasing the activity of the BOLD signal during sleep (left image) and at the moment of awakening and resumption of conscious activity (right picture).

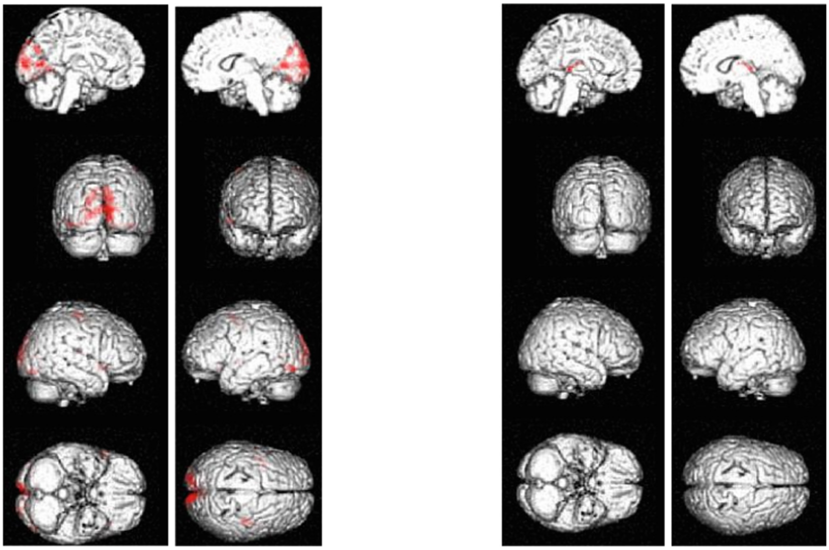

Fig. 4. Localization of neural network activity of the brain during sleep (left image) and at the moment of awakening and renewal of conscious activity (right figure) by fMRI data. ($p < 0.05$, FWE).

4 Conclusions

Preliminary results showed an increase in the activity of the visual regions (the region of the calcarine sulcus) of the cerebral cortex, left pre-cuneus/cuneus, etc. during sleep and regions of the right thalamus, left cuneus, cerebellar zones, stem structures, etc. at the moment of awakening and resumption of conscious activity.

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