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Studying of human's mental state during visual information processing with combined EEG and fNIRS

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ABSTRACT

We provided a combined analysis of electroencephalogram and functional near-infrared spectroscopy signals in order to investigate the process of prolonged visual perception. We investigated perception and decision-making processing during long-term and intense cognitive load. We found characteristic changes in electrical and hemodynamic activities during the neurophysiological experiment. The relationship was found between the EEG characteristics and the $\Delta O2Hb$ oscillation registered with the help of functional near-infrared spectroscopy.

Keywords: fNIRS, electroencephalogram, visual perception, intense cognitive load

1. INTRODUCTION

Currently, there is an active growth in research, both experimental and theoretical, aimed at understanding the processes occurring in the brain.[1–8] Here, one of the most important issue is to study the process of visual perception and information processing, as well as the level of attention associated with them, which is one of the most important characteristics of the cognitive processes of the brain.[9–16]

The most wide-spread method for investigation of brain activity is electroencephalogram (EEG).[17] EEG is commonly used to obtain information about electric activity in different parts of brain in its normal or pathological state. EEG methods suggests placing special electrodes on scalp (or into brain directly) and recording EEG signals as sum of electric currents generated by group of neurons.[18] EEG signal being a product of complex neuronal network is characterized by complex time-frequency structure with number of specific frequency ranges, oscillatory patterns, noise components (artifacts), etc.

Another popular method for estimation of brain activity is functional near-infrared spectroscopy (fNIRS) - a noninvasive, relatively low-cost, portable optical brain-imaging technique.[19] It uses near-infrared light to measure changes in oxygenated (HbO) and deoxygenated (HbR) hemoglobin levels due to the hemodynamic response, the rapid delivery of oxygenated blood to active cortical areas through neurovascular coupling.[20] Despite lower temporal resolution and time delay of the hemodynamic response compared to EEG signals, fNIRS represents another approach to obtain information about brain activity, which can be complementary to information provided by EEG analysis.

One of the most promising and complementary approaches to the study of brain activity is a combination of non-invasive methods of neuroimaging, such as EEG and fNIRS.[11, 21–25]

This work is devoted to the research of the process of perception and processing of visual information during long-term and intense cognitive load using combined EEG + NIRS. As a simple visual stimulus, a bistable image was chosen, namely the Necker cube.

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2. METHODS

The Necker cube is a 2D image which looks like a cube with transparent faces and visible edges (Figure 1). An observer without any perception abnormalities perceives the Necker cube as a bistable 3D object due to the specific position of the inner edges. The value $g \in [0,1]$ defining a contrast of the three middle edges is usually used as a control parameter. It is calculated as $g = y/255$, where y is the brightness of the middle lines according to the 8-bit gray scale palette. The values $g = 1$ and $g = 0$ correspond, respectively, to 0 (black) and 255 (white) pixels, luminance of the middle lines. Each Necker cube image drawn by black and gray lines was located at the center of the computer screen on a white background. A red dot drawn at the center of the Necker cube was used to attract the subject's attention and prevent possible perception shifts due to eye movements while observing the image. To demonstrate stimuli, we used LCD monitor with a spatial resolution of 1920 x 1080 pixels and a 60-Hz refresh rate. The subjects were located at a distance of 70–80 cm from the monitor with a visual angle of 0.25 rad. The Necker cube size on the monitor was 14.2 cm. The visual task was to classify consistently presented ambiguous Necker cubes with different g as left- or right-oriented.[26–28] In our experiment, we present to each subject a set of Necker cubes with $g \in [0.15; 0.4; 0.45; 0.55; 0.6; 0.85]$, the total number of views is 400. Figure 1*a* illustrates the experimental protocol.

For EEG recording we used electroencephalograph"actiCHamp" by Brain Products (Germany). EEG was recorded for 31 channels according to "10-10" system with ground electrode placed in the "Fpz" position on the forehead and one reference electrode on the right mastoid (see fig.1*b*). For EEG signal recording we used "ActiCap" — active Ag/AgCl electrodes (one for each EEG channel) placed on the scalp with the help of special cap. To increase the skin conductivity we treated scalp skin with abrasive "NuPrep" gel before the experiment and placed EEG electrodes on conductive "SuperVisc" gel. After the electrodes were placed, we monitored the impedance to get best possible quality of EEG recordings. Common impedance values were < 25 kΩ which is quite sufficient for active EEG electrodes. EEG signals were recorded with sampling rate of 1000 Hz and filtered by band-pass filter (cutoff frequencies at 0.016 Hz and 70 Hz), as well as 50-Hz notch filter.

For hemodynamic recording we used "NIRScout" with sampling rate of 7.8125 Hz by NIRx Medical Technologies (USA, Germany). The signal of fNIRS was filtering in the range of 0.012 to 0.4 Hz using 5th order Butterworth filter to reduce the physiological noise of low and high frequency such as respiration and cardiac-related fluctuations. The fNIRS signals were then converted to changes in the concentration of oxyHb, deoxy Hb and total Hb using the modified Beer-Lambert law. Furthermore, these changes oxyHb, deoxy Hb, and total Hb concentration were further processed by the moving average. Note that since the responses were more pronounced in oxyHb, we limited our analysis only to oxyHb signals.

The optode placement scheme is shown in Figure 1. This scheme was chosen to cover the occipital, prefrontal and parietal lobes because these areas are closely related to the perceptual decision-making task.

We have analyzed the EEG signals using the continuous wavelet transform which is now widely used in neuroscience and neurophysiology.[29] The instant wavelet energy spectrum $E^n(f,t) = \sqrt{W_n(f,t)^2}$ was calculated for each EEG channel $X_n(t)$ in the frequency range $f \in [1, 40]$ Hz. Here, $W_n(f,t)$ is the complex-valued wavelet coefficients calculated as[30]

$$W_n(f,t) = \sqrt{f} \int\limits_{-\infty}^{+\infty} X_n(t)\psi^*(f,t)dt, \quad (1)$$

where $n = 1, ..., N$ is the EEG channel number ($N = 31$ being the total number of channels used for the analysis) and "*" defines the complex conjugation. The mother wavelet function $\psi(f,t)$ is the Morlet wavelet often used for the analysis of neurophysiological data, defined as[29,30]

$$\psi(f,t) = \sqrt{f}\pi^{1/4} \mathrm{e}^{j\omega_0 f(t-t_0)} \mathrm{e}^{f(t-t_0)^2/2}, \quad (2)$$

where $\omega_0 = 2\pi$ is the central frequency of the mother Morlet wavelet.

We calculate separately the average energy in the alpha(8–13 Hz) and beta(13–34 Hz) bands one second before the presentation of the visual stimulus and in the first second of perceiving the stimulus as:

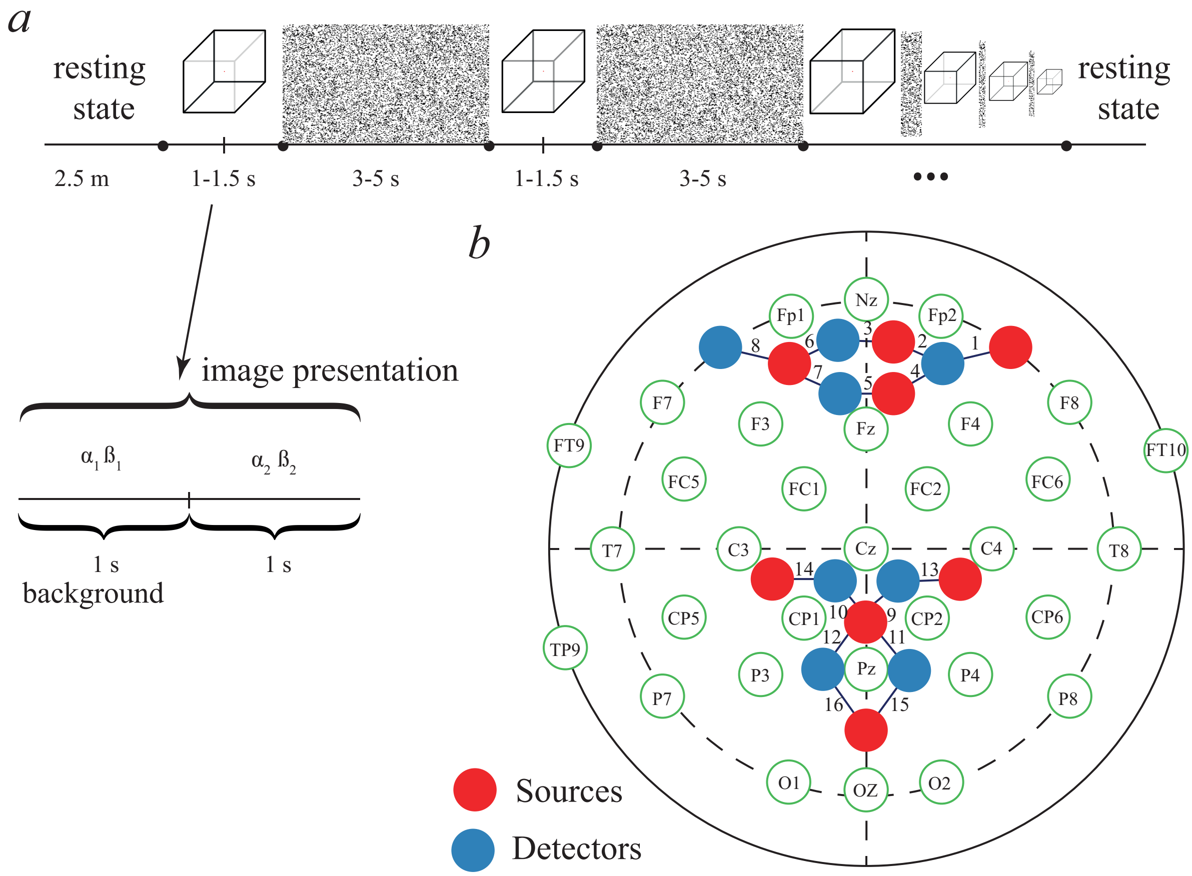

Figure 1. (a) Schematic representation of the experimental protocol.(b) The used layout of EEG electrodes and fNIRS optodes. The red and blue circles correspond to infrared sources and detectors, respectively. The solid lines between the source-detector pairs are the fNIRS channels.

$$E^{n}_{\alpha,\beta,\Delta t_1,\Delta t_2} = \frac{1}{\Delta f \Delta t} \int_{t\in\Delta t_1,\Delta t_2} \int_{f\in\alpha,\beta} E^n(f,t)df. \tag{3}$$

For each presentation of the cube, we calculate the following characteristic D(t), which demonstrates the change in energy in the alpha and beta bands during the perception of the visual stimulus:

$$D(t_k) = \frac{E^n_{\alpha 1} E^n_{\beta 2}}{E^n_{\alpha 2} E^n_{\beta 1}} \tag{4}$$

here t_k is the moment of presentation of the cube, E^n_{alpha1}, E^n_{beta1} and E^n_{alpha2}, E^n_{beta2} - energy in the alpha and beta ranges before the stimulus and during the perception of the stimulus, respectively.

For the analysis of hemodynamics, we calculated the characteristic correction time in the window of t_w= 300 sec for each of the fNIRS channels and different stage of the experiment:

$$\tau_c(t) = \int_{t-t_w/2}^{t+t_w/2} \Psi^2(\tau,t)d\tau; \tag{5}$$

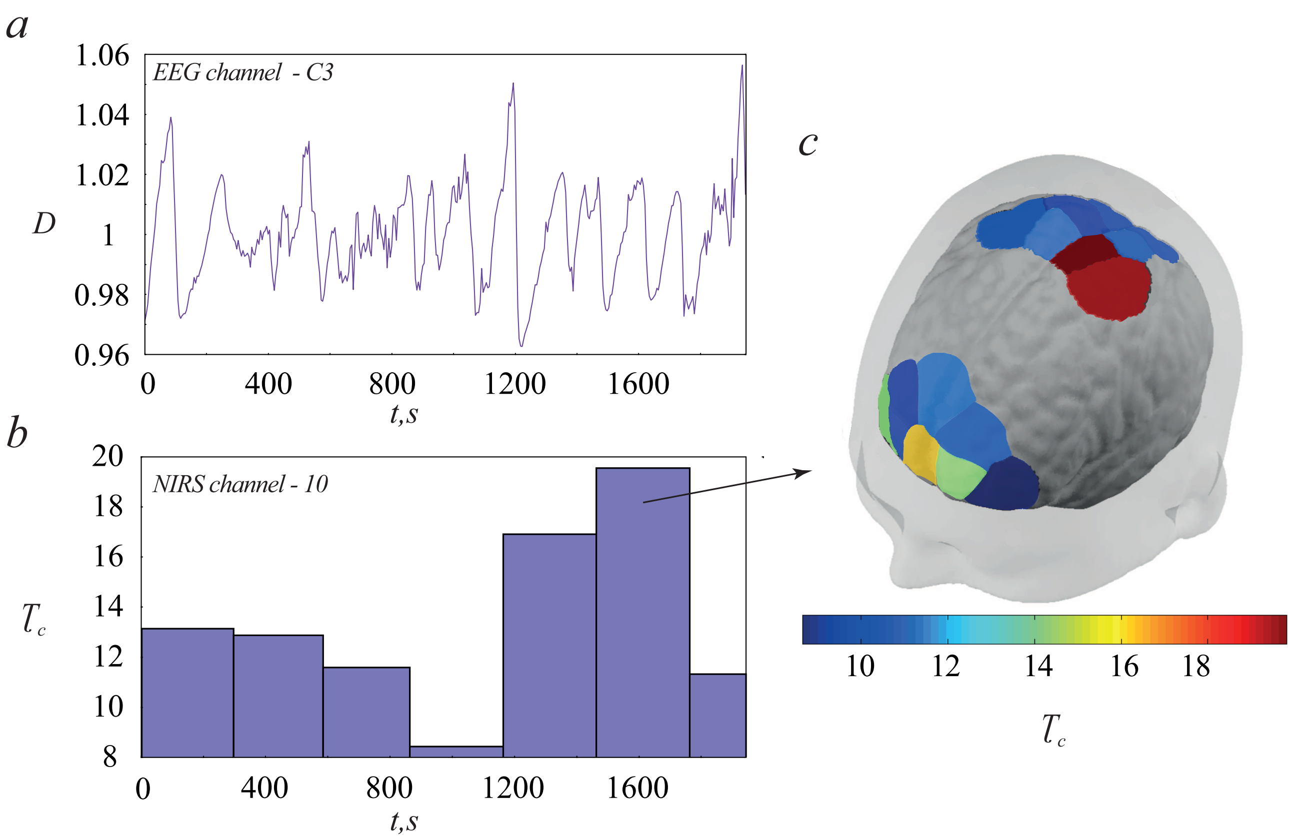

Figure 2. (a) The time dependence of characteristic $D(t_k)$ during the perception of the visual stimulus for the channel C3. (b) The characteristic correlation time for the NIRS channel 10 (near C3 EEG channel). (c) Distribution of the characteristic correlation time for $\Delta O2Hb$ in the final part of the experiment on the cortex.

$$\Psi(\tau, t) = \int_{t-t_w/2}^{t+t_w/2} \Delta O2Hb(t)\Delta O2Hb(t-\tau)dt \tag{6}$$

3. RESULTS

It is known that visual attention is associated with interaction in the alpha and beta bands in the occipital and parietal regions.[28] In particular, changes in alpha band activity are associated with visual perception[31] , while changes in beta band activity are associated with stimulus processing[32] and switching the brain to a state of attention.[33,34] The role of alpha and beta activity in the process of perception is also emphasized in work[35] in the context of information transition to visual cortex. In this regard, in the course of the research, for each EEG channel, the dependence $D(t_k)$ (4) was obtained, which characterizes the process of perception of a bistable image.

We analyzed the dynamics of these dependencies for each channel during the experiment. It was found that the dynamics of $D(t_k)$ has a fluctuating character. At the same time, a pronounced feature is observed in the parietal cortex – the closer to the end of the experiment, the closer the dynamics of $D(t_k)$ to periodic (see Fig. 2(a))). Such dynamics indicate the establishment of a characteristic mode in the brain corresponding to routine cognitive task. At the same time, the type of the dependence indicates strong fluctuations in attention level during the perception of the stimulus.

Also, we performed an analysis of hemodynamic activity together with the EEG analysis. For this, the dependence of the characteristic correlation time for each of the NIRS channels at different stages of the experiment was calculated. It was found that after about half of the experiment ($\sim$ 15 minutes), the characteristic correlation time in the parietal and prefrontal cortex sharply increases, as shown in figure 2 b. At the same time, it should be noted that the parietal cortex, namely channels 10 and 14 (see fig.2c), is more correlated and more active, in terms of the magnitude of the $\Delta O2Hb$ oscillations.

It should be noted that the functional brain regime established in the second part of the experiment is clearly visible when analyzing both EEG and hemodynamic activity (see Fig.2). In aggregate, this allows us to suggest that, with the continuous implementation of monotonous cognitive tasks for a long time (more than 15 minutes), the brain adapts to this type of load by controlling the process of attention and redistributing energy resources in the brain.

4. CONCLUSION

In this paper, we have investigated the process of perception and processing of information during the long-term solution of a monotonous cognitive task. The dynamics of the electrical and hemodynamic activity of the brain is studied. A relationship was found between the EEG characteristics and the $\Delta O2H$ oscillation. The obtained results suggest that in the process of long-term implementation of the considered cognitive task, the brain optimizes its work by redistributing energy resources through controlling the process of attention and hemodynamic activity.

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