Influence of the sensory information ambiguity on the brain state during the decision-making task

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***Abstract*— The process of visual information classification includes different states of brain activity, such as sensory processing and decision-making. The stage of sensory processing is usually short and occurs in the occipital and parietal areas of the brain, while the decision-making stage is more pronounced over time and includes the parietal and frontal areas. In the current paper, we consider the brain activity during the classification task using ambiguous visual stimuli with varying degrees of ambiguity. We show that with increasing ambiguity of the visual stimulus, the brain engages neuronal populations in the distributed cortical regions in 15-30 Hz frequency band, including the frontal area at the early stages of information processing.**

Keywords*— *classification task, cortical network, wavelet analysis.

I. Introduction

The task of visual information classification includes two steps: sensory processing and decision-making [1]. The decision-making is associated with the choice of one option from a set of alternatives based on available sensory data. To make a decision, the received sensory information must be processed and interpreted.

The processes of sensory processing and decision-making are actively studied in rodents and monkeys using implanted microelectrodes [2]. In this paper, we analyze these processes in the human brain using noninvasive electrical activity recordings. The recent review [3] highlights the important role of large-scale cortical interactions in human perceptual decision-making. At the same time, according to a recent review [4], most studies have focused on a limited number of recording sites and therefore the current understanding of how different areas coordinate sensory processing decision-making in the brain is limited.

In the paper we consider the classification task implying classification of bistable visual stimuli with varying degrees of ambiguity. It is clear that increasing the ambiguity of the visual stimulus affects the complexity of the decision. However, it is unclear how the change of ambiguity affects the neural activity dynamics of the brain at the stage of sensory processing.

We focus on the beta (15-30 Hz) frequency bands, since, on the one hand, it is associated with the processing of visual information, and on another hand, the activity of the beta-band plays an important role in human decision-making.

II. Materials and Methods

A. Participants

Ten healthy volunteers, twelve males and eight females, between the ages of 20 and 43 with normal or corrected-tonormal visual acuity participated in the experiments. All of them provided informed written consent before participating. The experimental studies were performed in accordance with the Declaration of Helsinki and approved by the local Research Ethics Committee of the Innopolis University.

B. Visual task

Necker cube was used as bistable visual stimuli [5]. Visual task consisted in the classification of the sequentially presented ambiguous Necker cubes as left- or right-oriented. The Necker cube [6] is a 2D-image which looks like a cube with transparent faces and visible ribs.

An observer without any perception abnormalities perceives the Necker cube as a bistable 3D-object due to the specific position of the inner ribs. The value g defining a contrast of the three middle ribs is usually used as a control parameter. 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 attention of subjects and prevent possible perception shifts due to eye movements while observing the image.

C. Signal Analysis

To analyze time-frequency structure of EEG signals we used continuous wavelet analysis. Wavelet energy spectrum $E^n(f,t) = \sqrt{W_n(f,t)^2}$ was calculated for each EEG channel in the frequency range $f \in [1,30]$ Hz. Here, $W_n(f,t)$ is the complex-valued wavelet coefficients calculated as

$$W_n(f,t) = \sqrt{f} \int_{t-4/f}^{t+4/f} X_n(t)\psi^*(f,t)dt, \quad (1)$$

where $n = 1, \dots, N$ is the EEG channel number ($N = 31$ is the total number of channels used for analysis). The symbol "*" denotes complex conjugation.

The Morlet wavelet was chosen as the mother wavelet. This wavelet is often used to analyze neurophysiological data [7] is defined as

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

where $\omega_0 = 2\pi$ is the parameter of the mother wavelet function.

For beta-frequency band the wavelet amplitude $E_\beta^n(t)$ was calculated via the following equation

$$E_\beta^n(t) = \frac{1}{\Delta f_\beta} \int_{\Delta f_\beta} E^n(f', t) df', \quad (3)$$

where $\Delta f_\beta = 15 - 30$ Hz.

All demonstrations of Necker cubes were divided into two groups in the accordance with image ambiguity:

1. Low ambiguity stimuli, including the Necker cube images with $g \in \{15, 25, 75, 85\}$.
2. High ambiguity stimuli, including the Necker cube images with $g \in \{40, 45, 55, 60\}$.

For each value of *g* we selected *I* = 20 presentations of Necker cubes. As the result, for each set of cubes (low ambiguity and high ambiguity) the number of Necker cubes presentations was M = 80.

The values of the wavelet energy (3) calculated for the whole time of the experimental session were then averaged over all *M* presentations of Necker cubes separately for low ambiguity and high ambiguity images as

$$\langle E_\beta \rangle = \frac{1}{M} \sum_{n=1}^{M} \int_{\tau_i, \gamma_i} E_\beta^n(t') dt'. \quad (4)$$

This value was calculated for each EEG channel. After that, were allocated the time intervals τ and γ, where τ - 500 ms before the Necker cube demonstration, γ – 500 ms after the Necker cube demonstration. Using statistical analysis, we identified EEG channels with the most significant changes. Finally, the difference between the number of channels demonstrating increase and decrease of beta-band energy was calculated for the cubes of high and low ambiguity

III. Results

We have recorded 31 EEG signals via noninvasive electrodes, arranged according to 10-10 layout during human processing of visual information and solving the visual stimuli classification task.

The spectral energy of EEG was averaged for a set of simple Necker cubes (low ambiguity) and for complex ones (high ambiguity). EEG channels with the most significant changes during processing and classification of visual information were identified and the difference between the number of EEG channels exhibiting increase and decrease of the beta-band spectral power was calculated. This difference is shown in Fig 1 (a) for the cubes with low and high ambiguity. Statistical test (Wilcoxon signed rank test for the related samples) demonstrates the significant change of this difference with the increase of the image ambiguity.

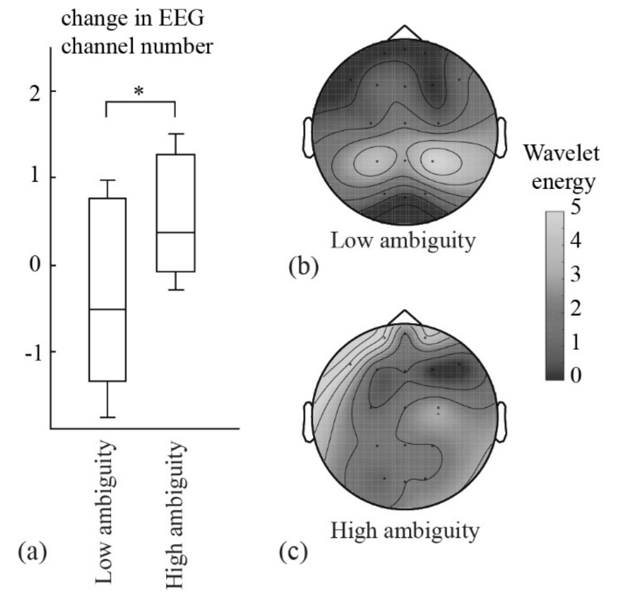

Fig.1. (a) Change of EEG channel number and (b,c) topographical plot of the distribution of EEG spectral power in the beta-band

In Fig. 1 (b, c) the topographical distributions of the beta-band spectral energy are shown for the cubes of low (b) and high (c) ambiguity.

It can be seen, that for the Necker cubes with low ambiguity the beta-band energy increases in the parietal area. For the Necker cubes stimuli with high ambiguity, the beta-band energy increases mostly in the frontal area.

Conclusion

We demonstrate that the spatio-temporal cortical activity in the beta-band during a sensory processing is affected by the ambiguity of visual information.

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