Neurophysiological mechanisms of visual sensory information processing in stimuli with high and low ambiguity

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***Abstract*—In this paper we studied neurophysiological mechanisms of brain information processing and following interpretation of visual stimuli with high and low levels of ambiguity. For visual stimuli we used images of the Necker cube which can be perceived in one of two ways — left- or right-oriented, and this interpretation is highly affected by the ambiguity of the stimulus. We demonstrated that visual sensory information processing of unambiguous and ambiguous visual stimuli follows different scenarios. For unambiguous visual information processing is accompanied by an increase of EEG spectral power in the delta frequency range in the occipital brain region. With increasing ambiguity of visual information, higher spectral power is observed in the delta and theta ranges in the frontal brain region.**

***Index Terms*—Necker cube, ambiguous visual stimuli, cognitive task, perceptual bias, EEG analysis, wavelet analysis**

I. Introduction

Perception of visual information and decision-making regarding such information requires the accumulation of sensory data [1]. However, in everyday life sensory information can often be ambiguous, so the brain must resolve this ambiguity in order to make a proper decision [2]. Thus, sensory information processing and decision-making are two subsequent stages of visual information perception.

When sensory information is ambiguous or contaminated with secondary information (noise), the brain switches attention to the most significant details [3]. Therefore, the observer should concentrate on getting more sensory information and rely on personal experience in order to reduce ambiguity of stimulus and interpret it [4]. These extra steps can explain, why the processing of unambiguous and ambiguous visual information follow different scenarios [5].

The study of neurophysiological mechanisms of sensory information perception is an important and urgent task from both fundamental [6] and practical points of view,for instance in the development of brain-computer interfaces [7] and human cognitive state monitoring systems [8].

In this paper we analyzed brain electrical activity of subjects performing the task of decision-making regarding the orientation of visual stimuli (Necker cube) with different levels of ambiguity. We performed time-frequency analysis of electrical activity and compared resulting topograms for stimuli of different ambiguities.

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II. Materials and methods

A. Experiment

We recruited a group of volunteers to participate in experimental studies. The group consisted of 20 subjects in the age of 18-26 years (mean = 19.8, standard deviation = 2.4) with normal or corrected-to-normal visual acuity. In this study we used experimental paradigm [9] based on the perception of visual stimuli in a form of Necker cube images with varying degrees of ambiguity [10]. The Necker cube is an image of 3D cube projected on 2D surface with transparent faces and visible edges. The ambiguity of the cube was controlled by balancing the brightness of it's inner edges: high contrast makes cube's orientation obvious while low contrast turns the image into ambiguous. We introduced control parameter $a \in [0, 1]$ (normalized brightness in the gray palette), and brightness was a for some edges and $1 - a$ for others. The limiting cases $a = 0$ and $a = 1$ corresponded to unambiguous left- and right-oriented cubes respectively, whereas $a = 0.5$ determined a completely ambiguous cube. The experiment used a set of images of a Necker cube with a = 0.15, 0.25, 0.4, 0.45, 0.55, 0.6, 0.75, 0.85. On the one hand, this set could be divided into subsets of left-oriented (a = 0.15, 0.25, 0.4, 0.45) and right-oriented cubes (a = 0.55, 0.6, 0.75, 0.85). On the other hand, this set could also be divided into images with low level of ambiguity (LA, a = 0.15, 0.25, 0.75, 0.85), which are easily interpreted by the observer and with a high level of ambiguity (LA, a = 0.4, 0.45, 0.55, 0.6), interpretation of which requires a lot of effort [11].

During the experiment we presented images to the subjects; each image was shown 50 times which results in 400 images shown in random order. The display of each image lasted from 1 to 1.5 seconds (time interval for each stimulus was chosen randomly). Between the images of Necker cubes the subjects observed an abstract image for 3-5 seconds (time interval for each case was also chosen randomly). The subjects were instructed to interpret each image and press left or right button on the joystick according to the orientation of the cube. During the experiment the electrical activity of the brain was recorded as electroencephalogram (EEG) using 32 sensors arranged in accordance with "10-10" scheme.

B. Protocol

During the experimental sessions, we formed a protocol. For each visual stimulus we evaluated the behavioural response by measuring the reaction time (RT), which corresponded to the time elapsed from the presentation of the stimulus to pressing the button. For each subject we calculated the error rate (ER) as the percentage of incorrect interpretations. The correctness of each response was assessed by comparing the actual orientation of the stimulus to the response of the subject.

C. Analysis of experimental data

The EEG recordings underwent a preprocessing procedure, which consisted of filtering using a bandpass filter with cutoff frequencies of 1 and 100 Hz and a 50 Hz notch filter. In addition, we have removed linear noise at frequencies of 50, 100, 150 Hz. Muscle and eye blinking artifacts were removed using the Independent Component Analysis (ICA) method. To analyze the neural activity of the brain we used method based on continuous wavelet transform. This method allows us to consider changes in EEG spectral power (SP) in various frequency ranges (delta, theta, alpha, beta, gamma). The advantage of wavelet analysis over Fourier analysis is the use of basis functions with better temporal localization.

To compare event-related (ER) SP at the sensory level we used a paired t-test in combination with nonparametric cluster correction for multiple comparisons and randomization using the Monte Carlo method. The cluster was considered significant when the p-value was below 0.05. The number of permutations was 2000.

III. Results

Results of wavelet analysis of EEG signals are illustrated by fig. 1. The analysis of EEG SP during the processing stimuli with high and low ambiguity revealed the following:

- Immediately after the stimulus is presented SP of the EEG increases in the low-frequency delta range ($1 - 3.5$ Hz) in the occipital region. At the same time, the processing of unambiguous stimuli demonstrates higher values of SP (see fig. 1A).
- Before decision-making ambiguous stimuli induces high SP in the delta and theta ranges ($1 - 9.5$ Hz) in the frontal region, while processing stimuli with low ambiguity is associated with an increase in SP in the occipital region (see fig. 1B).

IV. Conclusion

The results obtained indicate fundamentally different processing scenarios in the case of unambiguous and ambiguous stimuli. When visual information is unambiguous it is processed mainly in the visual (occipital) cortex, which is accompanied by an increase of EEG SP in occipital region in the delta frequency range. When visual information is ambiguous high EEG SP is observed in the delta and theta frequency ranges in the frontal region. An increase in the EEG SP in the theta range in the frontal region can indicate that the information accumulated in memory is used to process and interpret external information. This information reflects our knowledge about the stimulus, accumulated in the course of previous experience [12].

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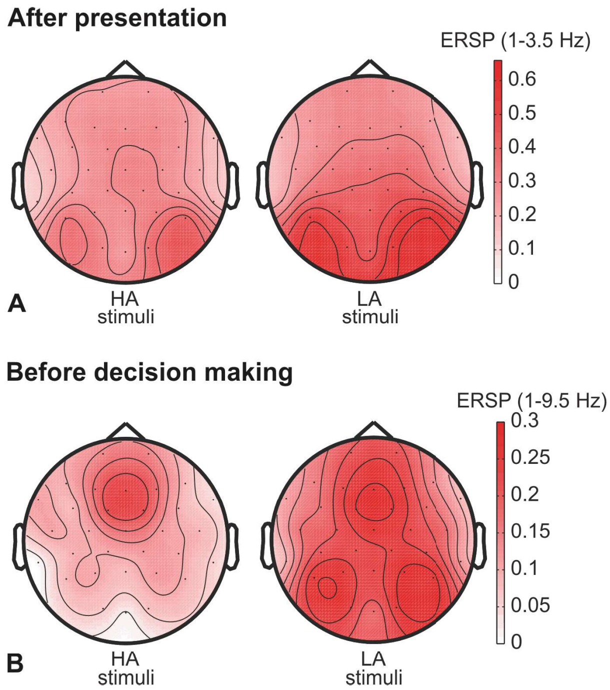

Fig. 1. Comparison of EEG SP in processing stimuli with high and low ambiguity immediately after the presentation of the stimulus (A) and before decision-making (B). Topograms reflect the values of EEG SP in relation to the values calculated before the presentation of the stimulus, i.e. a positive value indicates an increase in power and color saturation characterizes the magnitude of increase.

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