Intermittent behavior in the brain neuronal network in the perception of ambiguous images

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ABSTRACT

Characteristics of intermittency during the perception of ambiguous images have been studied in the case the Necker cube image has been used as a bistable object for demonstration in the experiments, with EEG being simultaneously measured. Distributions of time interval lengths corresponding to the left-oriented and right-oriented Necker cube perception have been obtain. EEG data have been analyzed using continuous wavelet transform which was shown that the destruction of alpha rhythm with accompanying generation of high frequency oscillations can serve as a electroencephalographical marker of Necker cube recognition process in human brain.

Keywords: Intermittency, ambiguous images, Necker cube, electroencephalogram, continuous wavelet analysis, oscillatory patterns

1. INTRODUCTION

Nowadays the study of human brain arouse the great interest of investigators from different areas of science. An intensive progress in developing of methods of experimental investigation and mathematical approaches leads to increasing of interdisciplinary publications during last years[1–3] . It should be noted that initially the most part of human consciousness studies were connected with its psychological aspects, but at the present time it is mainly the field of interests of neuroscience which has combined tools of mathematics, physics and nonlinear dynamics with the neurophysiological and biological view on the processes in the brain neuronal structures and networks. Visual perception and attendant cognitive processes were often studied using ambiguous images (bistable objects).[1–5] The perception of bistable images is one of interesting tasks allowing to understand many different aspects of visual perception and objects recognition. The mechanism of bistable image recognition does not well understood yet, but it is known that the perception is the result of processes in distributed network of occipital, parietal and frontal areas of cortex.[6] There is a hypothesis that switchings in the perception of

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ambiguous object concern with the inner noise being inherent for neural cells[7–10] and arising due to the neuronal spikes. Thus, noise plays crucial role both in the process of ambiguous images perception and in other cases of making decision. An intermittency implies the presence of two or more types of behaviour in the system dynamics which alternates with each other and is observed not only in physical and chemical systems[4,11–17] but in neuronal networks of the brain.[18–20] Thus, one can consider bistable visual perception as a process of recognition of intermittent patterns, being the projections of ambiguous image. Present paper is devoted to the study of intermittency during the perception of Necker cube image being a good example of an ambiguous object, with simultaneous measurement of EEG and subsequent analysis of experimental data.

2. DESIGN OF EXPERIMENT

Unsymmetrical Necker cube was used as ambiguous image in our experiments. The contrast of the three middle lines centered in the left middle corner was used as one of the control parameter I taking the values from the range $[0; 1]$. If I is equal to 1 observer will see the right-oriented cube, whereas zero value of the control parameter corresponds to the left-oriented cube. The intensity of the three middle lines centered in the right corner was set to $(1 - I)$, and the intensity of the six visible outer cube edges was fixed to 1. For another values of control parameter there will be spontaneous alternations between these two projections of Necker cube in the process of its visual perception. Left- and right-oriented projections of Necker cube and several cubes from those having been used in experiments with I that differs from 0 and 1 are shown in Fig. 1.

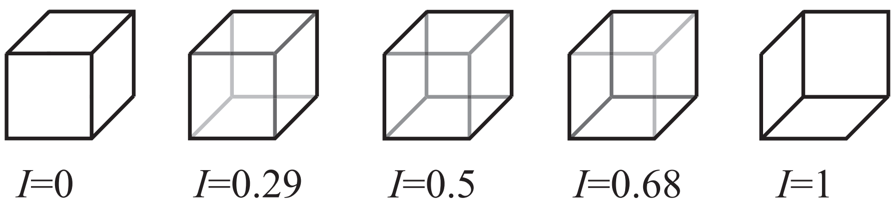

Figure 1. Unsymmetrical Necker cubes. Necker cubes with limit and intermediate values of I are shown.

Necker cube image was placed in the middle of the computer screen on the wight background. The bistable visual perception of the Necker cube image was explained to and really seen by all participants. Subjects were instructed to press left or right keys on the control panel each time their perception of the cube changed. The experiment consists of several runs of 10 min each. The runs were interrupted by breaks of a lengths freely chosen by the subjects, thus minimizing tiring effects.[21,22] The duration of each period at constant perception was computed from the time interval between two successive keystrokes. Total time of experiment was about 50 minutes for each cube.

To organize visual stimulation and data registration an equipment of Medicom MTD "ENCEPHALAN EEGR–19/26" with corresponding software program was used. Sampling frequency of EEG was equal to 250 Hz, frequency range of data was from 0.016 Hz to 70 Hz with a notch filter at 50 Hz. For EEG registration monopolar method of registration and the standard international system "10-20" for placing electrodes were used.[23] It should be noted that due to features of noninvasive registration of EEG data one can confirm that data are sufficiently correct if the frequency range is less than 50 Hz. After the registration data were analyzed using preprocessing operations. Data were split according to channels, export to text in ANSCII. Technical and biological artifacts were extracted with the standard methods of EEG processing software of Medicom MTD. For further analysis of EEG data set continuous wavelet transform has been used[1] which is optimal mathematical tool for time-frequency analysis of biological signals.[24–29]

The continuous wavelet transform is given by

$$W(s,t_0) = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} x(t)\Psi^*\left(\frac{t-t_0}{s}\right)\, dt, \qquad (1)$$

where $x(t)$ is time realization of the analyzed signal, s is the time scale determining the width of wavelet, $\Psi_{s,t_0}(t)$ is the mother wavelet, symbol "$*$" stands for complex conjugation. One of the channels of EEG signal was used as the signal $x(t)$, the Morlet wavelet has been taken as the "mother" wavelet

$$\Psi(\eta) = \frac{1}{\sqrt[4]{\pi}} \exp(j\Omega_0\eta) \exp(-\eta^2/2) \tag{2}$$

with $\Omega_0 = 2\pi$ which provides the best time-frequency resolution of physiological signal features.[18, 30]

3. RESULTS OF EXPERIMENTAL INVESTIGATIONS

Results of the analysis of experimental data are shown in figures below. In the Fig. 2 distributions of time intervals lengths corresponding to the left and right projections of Necker cube for the same subject and several cubes with different intensity of the cubes edges are shown. One can easily see the increase of difference Δt between the most probable values of time of perception for left and right Necker cube projections with the decreasing of parameter I. In addition, when the values of I is less than 0.5 the "left" projection dominates in the visual perception, at $I > 0.5$ the maximum of distribution for the "right" projection will account for the time interval value being greater than the maximum value for left-oriented cube distribution. Similar results were demonstrated by other subjects, however, the values of the most probable time of observation of each projection of bistable image differs because of individual characteristics of visual perception, and different levels of cognitive noise of the participants of the experiment.

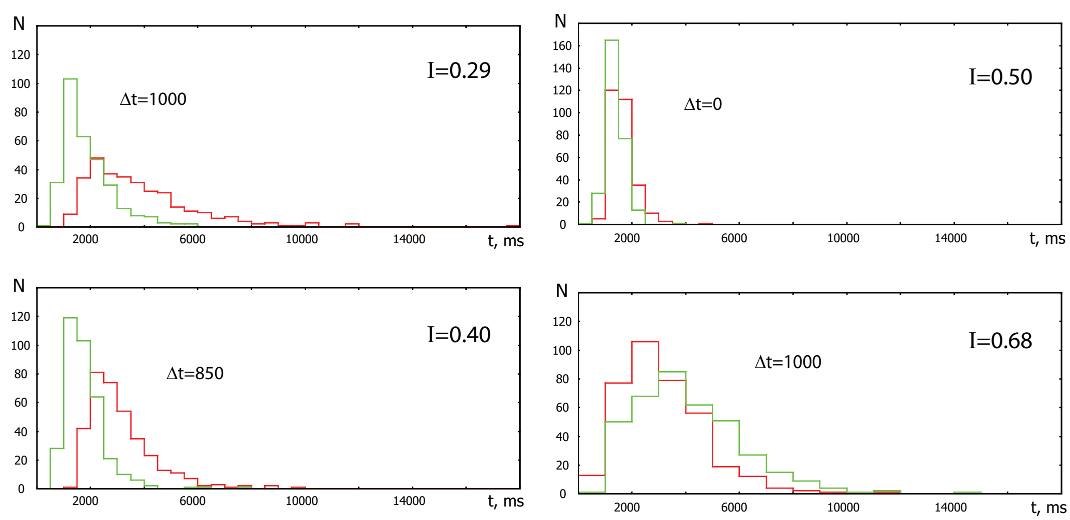

Figure 2. Distributions of time intervals lengths corresponding to the left and right projections of Necker cube for the same subject and several cubes with different intensity of the cubes edges. Δt is the difference between the most probable values of time of perception for left and right Necker cube projections.

Figure 3 shows the distributions of the time intervals of observation of the Necker cube left projection with the intensity of the edges $I = 0.29$ obtained for different subjects with different levels of cognitive noise. The y-axis is shown in logarithmical scale. It should be noted that in a large range of durations distribution of time intervals of observation one of the projections of the Necker cube obeys the exponential law, with the slope of the lines approximating the experimental data shown in the figure by points increasing with the increase of the cognitive noise level of subject being investigated in the experiment. The greater the intensity of cognitive noise is, the more frequently the changes of the bistable image projections occur in the perception of the subjects and, accordingly, the shorter the average time of observation of each projection is in the intermittent dynamics of ambiguous image perception.

Figure 4 illustrates the skeletons of the wavelet transform (frequencies corresponding to the maxima of energy in the wavelet spectrum at the each moment of time) of EEG signals obtained from the different derivations from

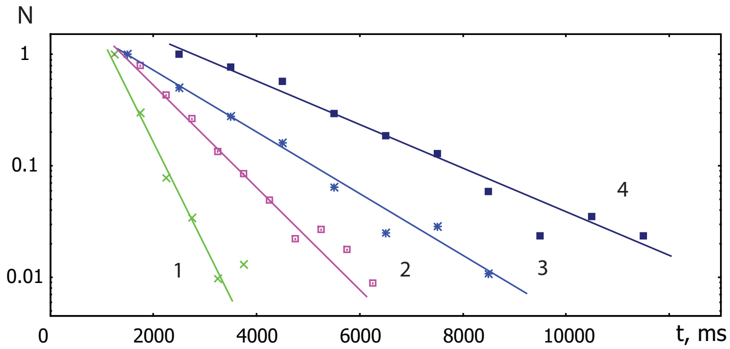

Figure 3. Distributions of time intervals lengths corresponding to the left projection of Necker cube for different subjects and the same cube with intensity of the cubes edges $I = 0.29$. The y-axis is shown in logarithmical scale. Experimental data are shown by points. Lines illustrate corresponding approximations.

occipital cortex (Cz, Pz, O1 and O2) for the same temporal fragment with the markers that shows the moments of the buttons pressings when selecting the "polarity" of Necker cube during the experiment.

Analysing EEG data from O1 and O2 channels in the occipital area being responsible for visual perception, one can see that high-frequency activity corresponding to the analysis of image and choice of the cubes projection is replaced by low-frequency one, and then the subject press the button according to the given choice. For the Pz derivation, intervals corresponding to the analysis of cubes projection and pressing the buttons represent a smooth transition from waves with a frequency of approximately 10 Hz (alpha rhythm) to the higher frequencies of 20-25 Hz.

4. CONCLUSION

Design of experiment allowing to measure characteristics of intermittency in the process of bistable visual perception was created. Distributions of time intervals lengths corresponding to the periods of left-oriented cube or right-oriented cube observation have been obtained. It was shown that for different values of I the difference between more probable duration of observation of the left projection and of the right one increases with the increasing or decreasing I with regard to $I = 0.5$. An EEG was also measured during the experiments and was analyzed using method based on consideration of skeletons of the continuous wavelet transform.

5. ACKNOWLEDGMENTS

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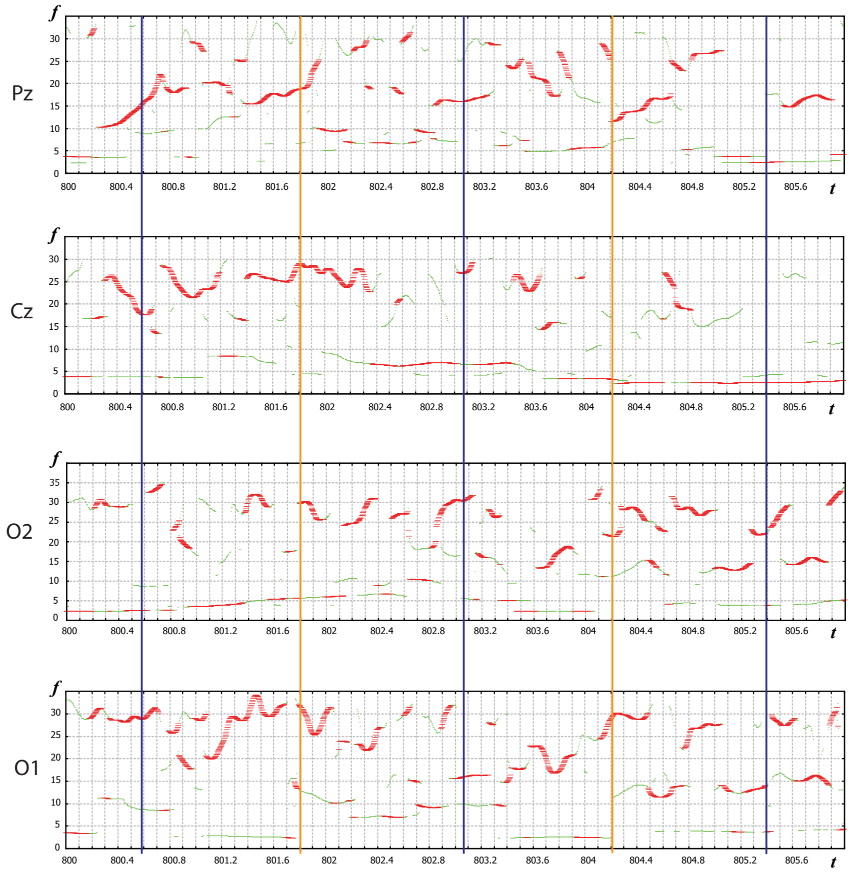

Figure 4. Skeletons of the wavelet transform (frequencies corresponding to the maximum of energy in the wavelet spectrum at the moment of time) of EEG signals obtained from the different derivations (Cz, Pz, O1 and O2) for the same temporal fragment with the markers that shows the moments of the buttons pressings when selecting the "polarity" of cube during the experiment. The blue straight line corresponds to the moment of time when the participant of experiment had pressed the left button, and the orange line corresponds to the right button click. The points of maxima of the first order in wavelet energy spectrum are shown by red colour, the green dots correspond to the maxima of the second order.

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