The study of cognitive processes in the brain EEG during the perception of bistable images using wavelet skeleton

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ABSTRACT

In the paper we study the appearance of the complex patterns in human EEG data during a psychophysiological experiment by stimulating cognitive activity with the perception of ambiguous object. A new method based on the calculation of the maximum energy component for the continuous wavelet transform (skeletons) is proposed. Skeleton analysis allows us to identify specific patterns in the EEG data set, appearing in the perception of ambiguous objects. Thus, it becomes possible to diagnose some cognitive processes associated with the concentration of attention and recognition of complex visual objects. The article presents the processing results of experimental data for 6 male volunteers.

Keywords: Electroencephalogram, ambiguous images, neurophysiological experiment, continuous wavelet analysis, wavelet skeletons, oscillatory patterns, cognitive processes

1. INTRODUCTION

Nowadays, the study of brain dynamics in cognitive activity attracted much attention of researchers. Such studies often used electroencephalography, because this method is non-invasive and does not require significant limitations volunteer mobility, nor for costs. This article is devoted to the study of the popular destinations in cognitive perception of ambiguous images. The investigations of nonlinear processes in the brain neural network during perception of ambiguous (the so-called *bi-* and *multistable*) images are very important for the understanding of both the visual recognition of objects and the decision-making process. Nowadays, the perception of ambiguous images attracts huge attention of many scientists. In a sense, such images are good objects for studying the visual perception in general as well as the decision-making mechanisms. Images of this type have been the object of research for psychologists for a long time.[1,2] Recently, ambiguous images awoke interest of physicists and mathematicians.[3,4] Despite of considerable efforts of many researchers, the main mechanisms underlying interpretation of a multistable image are not well understood. At present, perception is known to be a result of nonlinear processes which take place in the distributed neural network of occipital, parietal and frontal regions of the brain cortex.[2,5]

The perception of ambiguous (bistable) images was thoroughly investigated in the last decade. The most popular bistable images are Rubin vase, Mach bands, Rorschach test, Boring's old/young woman illusion, Necker cube, etc.[6–9] From a mathematical point of view, visual perception of bistable images comprises two metastable

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states, each with a duration that varies from seconds to tens of seconds. One of the perceived images usually dominates over the other for a relatively long period of time.

These fundamental results are important to create an objective paradigm for data processing in cognitive research, because the application of traditional neurophysiological methods solely, such as, expert estimations and simple measures of the signal amplitude, may simplify our understanding of the process. Therefore, the fine and short-lasting process might be overlooked. The development of standardized methods has an important practical application in neurophysiological experiments, including data acquisition, evaluation, analysis and processing of results in already recorded data, as well as in real time, and it is still an open field for research activity. International research in neurophysiological studies readily engages in the modeling of cognitive and pathological processes in the brain neuronal network using nonlinear dynamics tools.[15, 15–20]

2. STUDY METHODS

2.1 Experiment

In our physiological experiment with EEG activity registration we used a set of images based on a well-known bistable object, the Necker cube,[21] as a visual stimulus. This is a cube with transparent faces and visible ribs; an observer without any perception abnormalities treats the Necker cube as a 3D-object thanks to the specific position of the cube ribs. Bistability in perception consists in the interpretation of this 3D-object as to be oriented in two different ways, in particular, if the different ribs of the Necker cube are drawn with different intensity. In our experimental works we have used the Necker cube images with varying parameter I to be the brightness of the cube wires converging in the right upper inner corner (Fig. 1). The brightness of the wires converging in the left lower inner corner is defined as $(1 - I)$.

The experimental studies were performed in accordance with the ethical standards of the World Medical Association.[22] Six healthy subjects from a group of unpaid male volunteers, between the ages of 20 and 25 with a normal visual acuity participated in the experiments. The purpose of this experiment is the study of multi-channel EEG data registration in the unconscious decision on ambiguous image interpretation. We demonstrated the Necker cube images with different wireframe contrasts for a short time, each lasting between 1.0 and 1.5 seconds, interrupted by a background abstract picture for 5.0 – 5.5 seconds. The subject was instructed to press the left or right key depending on his/her interpretation of the projection being observed at each demonstration. The use of the background abstract images allows the neutralization of possible negative secondary effect of the previous Necker cube image. The whole experiment lasted about 40 min for each patient.

During the experiment we exhibited the pictures of the Necker cube randomly, each for about 100 times, and recorded brain activity with multi-channel EEG. As a tool for EEG recording we used the electroencephalograph–reorder Encephalan-EEGR-19/26 (Russia) with multiple EEG channels and the two-button input device. To study EEGs the monopolar registration method and the classical ten-twenty electrode system were used. Figure 1 shows an example of a typical EEG data set from EEG registration channels of occipital area. It seems occipital region associated with cognitive processes of perception of complex spatial objects, which include the Necker cube.

2.2 Wavelet-based method

In our work we used continuous wavelet transform (CWT)[18, 23–26] for time-frequency analysis of oscillatory patterns in EEG. CWT is a convolution of investigated signal $x(t)$ (EEG signal in our case) and a set of basic functions $\varphi_{s,\tau}$:

$$W(x,\tau) = \int_{-\infty}^{\infty} x(t)\varphi*_{s,\tau} dt \tag{1}$$

Each basic function from this set can be obtained from one function φ_0, the so-called mother wavelet, by following transform:

$$\varphi(s,\tau) = \frac{1}{\sqrt{s}}\varphi_0\left(\frac{t-\tau}{s}\right) \tag{2}$$

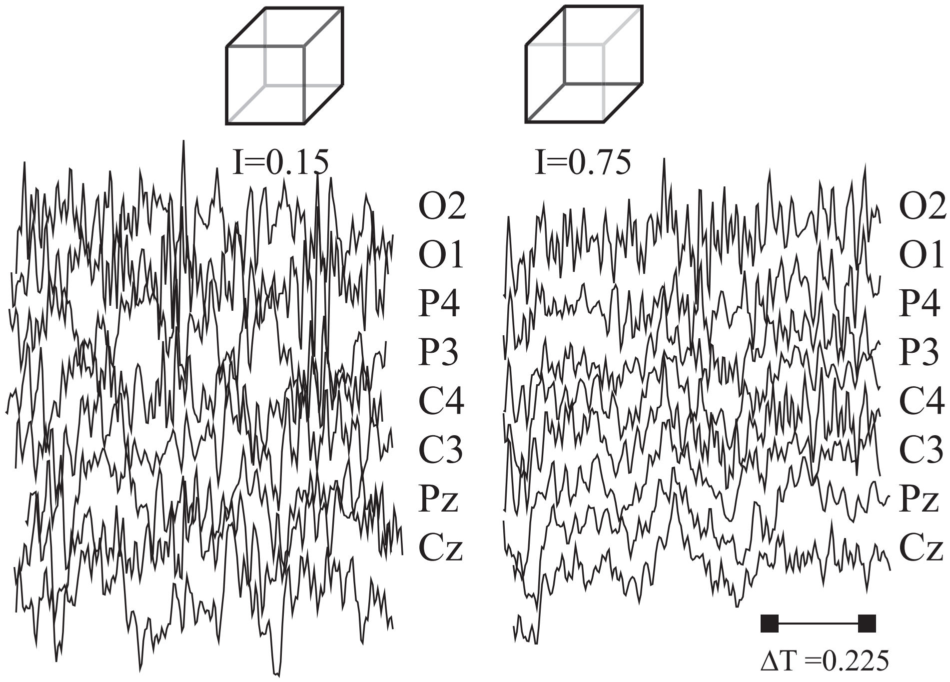

Figure 1. Examples of distinct Necker cube images with different wireframe contrasts characterized by control parameter I and fragments of EEG data. These curves are plotted according to the data in occipital area channels volunteer number 1.

In equation (2) φ_0 — mother wavelet, s — time scale, which determines extension or compression of initial mother function, τ — time shift of wavelet transform.

There are a lot of different mother wavelets that find a use according to the problems of the current study. In present work we used CWT with Morlet mother wavelet with parameter $\omega_0 = 2\pi$:[27, 28]

$$\varphi_0(\eta) = \pi^{-\frac{1}{4}} e^{j\omega_0\eta} e^{-\frac{\eta^2}{2}} \tag{3}$$

According to papers[29–33] the Morlet wavelet is one of the most effective in analysis of complex experimental signals of biological nature (including EEG data) because of its optimal time-frequency resolution.

In present work intrinsic frequency dynamics was investigated using "skeletons" of wavelet surfaces.[33–35] The "skeletons" of wavelet surfaces are constructed to extract dominant EEG frequencies and determine the evolution of oscillatory patterns in EEG data. In this paper, we focused on the processing of EEG data recorded in the occipital region (see Fig. 1). First, the momentary wavelet energy distribution $E_i(f_s, t_0)$ was constructed for some time moment t_0.

$$E_i(f_s, t_0) = |W(f_s, t_0)|^2 \tag{4}$$

Then the function $E_i(f_s, t_0)$ was examined for the presence of local maximum E_{max}. If several local maxima $E_{max,k}$ were detected in $E_i(f_s, t_0)$, then the highest maximum was selected and its frequency was considered as dominant frequency of oscillatory pattern at given time moment t_0. In order to construct full "skeleton" of wavelet surface the procedure described above was repeated consequently for all points in time series of given EEG signal. Figure 2 shows the wavelet surface fragments for EEG signals with selected first skeletons.

3. RESULTS

In our experimental studies we recorded EEG data during the sufficiently regular ambiguous perception of complex objects. Between the two moments of the perception of ambiguous object associated with a spatial imagination Necker cube, a pause is enough to restore the background activity is not associated with the cognitive process of spatial modeling. At the moment, we are not interested in causes, for example, the phenomenon of

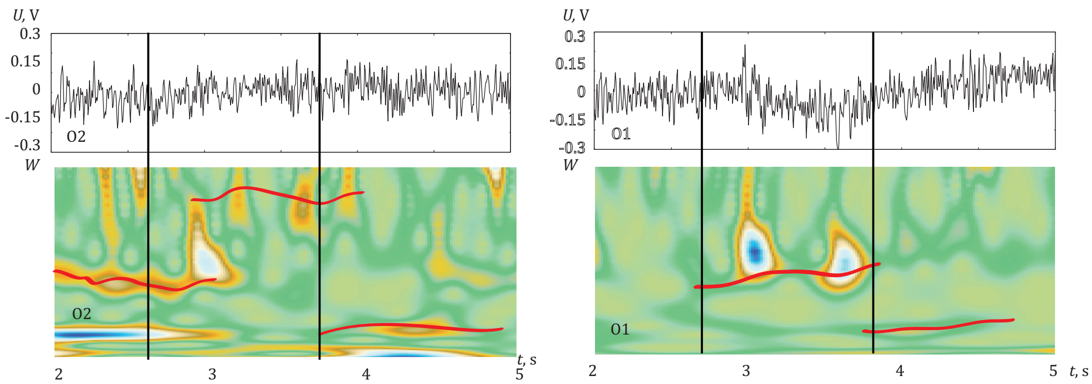

Figure 2. The fragments of the wavelet surfaces with selected two first skeletons, calculated for O1 and O2 channels. These surface and skeleton–curves are plotted according to the data in the channel register O1 and O2 volunteer number 2. The left vertical line shows the time of presentation of the cube, and the right vertical line corresponds to the moment of the volunteer clicking on the button.

cognitive noise, forcing Necker cube with intensity I perceived as the "left" and "right".[3, 4, 36] However, we directly focused on the processes that occur in the perception and the internal filling volume of a two-dimensional object Necker ambiguous image.

The result of the first three wavelet skeletons calculation and corresponding time dependencies for the three occipital channels are shown in Figure 3. Figure 3 a corresponds to a situation Necker cubes recognition as a "right"−"left". Figure 3 b shows a test situation when the same volunteers did not show any incentives for cognitive activity, however, at random times, he clicks on the remote. It is clearly seen that the situations are different even visually. For the figure 3 a characterized by the predominance of high frequencies (beta–rhythms), and for the test (background) of the situation in Figure 3 b such a pronounced high–frequency activity is observed.

It is clear that visual analysis is not enough, and we propose a method for an estimation of level and nature of beta–activity for occipital region in the human brain. For this we consider the main characteristic of the frequency range of 30–40 Hz, well traced throughout the duration of the processes associated with the recognition of ambiguous images for the majority of volunteers. Note that one volunteer with displacement of the pattern frequency to 25–32 Hz was found in the processing data. However, it is clear that this fact is easily detected and can be corrected adaptation algorithm.

Now we are limiting our processing of multi-channel EEG data exceptionally occipital area of a brain electrical activity registration, in particular O1, O2, P3, P4, Pz, C3, C4 and Cz channels of the classical ten-twenty electrode system. We introduce a numerical criterion for the presence of alpha-rhythm in every time moment: the values of first two skeletons are in the range of 30 to 40 Hz in this time. In other words, if the condition is satisfied for a particular channel of the occipital region, the alpha-criterion β is equivalent to the constant, and otherwise β is zero, then β − criterion:

$$beta_i = \begin{cases} 1 & \text{if } 30 < f^i_{1,2} < 40 \\ 0 & \text{in other cases} \end{cases}$$

In Figure 4 a shows the result of calculation of the proposed specifications at any given time for the channel Pz. This EEG-signal registration is corresponding to the electricity activity of the interhemispheric slot in human brain. However, consideration of the signal for each EEG channel is not convenient and leads to the accumulation of errors. We have tried to average characteristics of excitable beta–activity for the whole occipital region. Note that in this case we consider the spatial and temporal dynamics of occurring beta–pattern correlated with the cognitive process of recognition of a complex ambiguous object. In this case the presence of the beta–rhythm criterion for each channel, it can simple sum the "0" and "1":

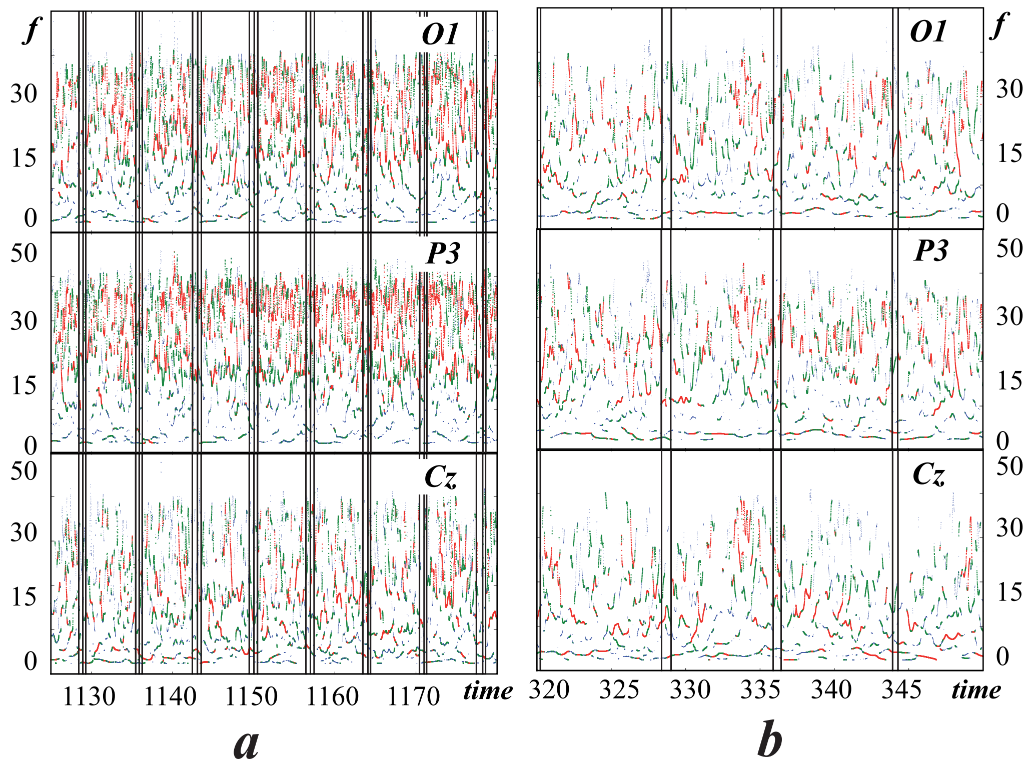

Figure 3. The dependencies of the first three wavelet–skeletons over time for O1, P3, Cz channels. *a* These features are calculated for the above case neurophysiological experiment with the presentation of the subject of ambiguous images. Vertical lines form groups of three lines and meet the time of submission of the cube, and the filter pressing the remote button. Figure *b* shows the processing of test records, when volunteer arbitrarily pressed on the remote control without cognitive stimulus. These curves are plotted according to the data of volunteer number 4.

$$\beta_{8i} = \sum \begin{cases} 1 & \text{if } 30 < f_{1,2}^{O1} < 40 \quad \text{or} \quad 0 \quad \text{in other cases} \\ 1 & \text{if } 30 < f_{1,2}^{O2} < 40 \quad \text{or} \quad 0 \quad \ldots \\ 1 & \text{if } 30 < f_{1,2}^{P3} < 40 \quad \text{or} \quad 0 \quad \ldots \\ 1 & \text{if } 30 < f_{1,2}^{Pz} < 40 \quad \text{or} \quad 0 \quad \ldots \\ 1 & \text{if } 30 < f_{1,2}^{P4} < 40 \quad \text{or} \quad 0 \quad \ldots \\ 1 & \text{if } 30 < f_{1,2}^{C3} < 40 \quad \text{or} \quad 0 \quad \ldots \\ 1 & \text{if } 30 < f_{1,2}^{Cz} < 40 \quad \text{or} \quad 0 \quad \ldots \\ 1 & \text{if } 30 < f_{1,2}^{C4} < 40 \quad \text{or} \quad 0 \quad \ldots \end{cases}$$

In Figure 4 b we show the calculation result of the characteristics of β–activity for the whole of the occipital region of the brain. However, we paid attention to the existence of certain regularities in the distribution of β–pattern in the occipital region, directly related to the nature of cognitive activity. At a time when the Necker cube selected "left" or "right", the maximum wave activity at frequencies of 30–40 Hz accounted for by appropriate "right" or "left" with respect to the channels of interhemispheric slot. In this case, we can consider the new forms of the criteria of having β–pattern:

$$\beta_{left} = \sum \begin{cases} 1 & \text{if } 30 < f_{1,2}^{O2} < 40 \quad \text{or} \quad 0 \quad \ldots \\ 1 & \text{if } 30 < f_{1,2}^{P4} < 40 \quad \text{or} \quad 0 \quad \ldots \\ 1 & \text{if } 30 < f_{1,2}^{C4} < 40 \quad \text{or} \quad 0 \quad \ldots \end{cases}$$

$$\beta_{right} = \sum \begin{cases} 1 & \text{if } 30 < f_{1,2}^{O1} < 40 \quad \text{or} \quad 0 \quad \dots \\ 1 & \text{if } 30 < f_{1,2}^{P3} < 40 \quad \text{or} \quad 0 \quad \dots \\ 1 & \text{if } 30 < f_{1,2}^{C3} < 40 \quad \text{or} \quad 0 \quad \dots \end{cases}$$

Figure 4 c show the results of calculation of these characteristics β_{left} and β_{right}.

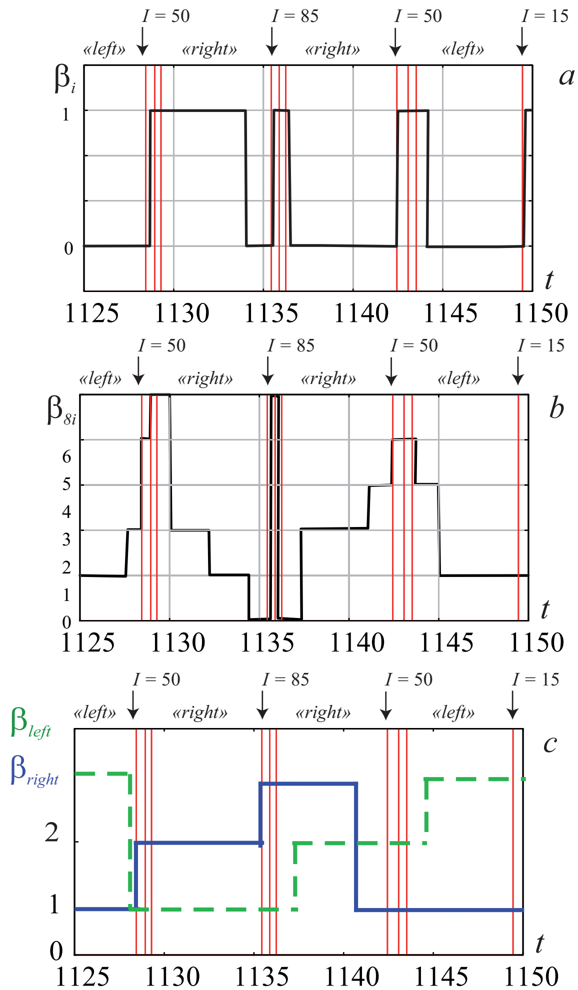

Figure 4. (a) The dependence of the beta–criterion β over time for Pz channel. (b) The dependence of the beta–criterion β_{8i} for brain occipital region. (c) The dependence of the beta–criterion β_{left} and β_{right} for "left" and "right" area of occipital region. The green dashed line is corresponded the beta–criterion β_{left} and blue solid line – to the beta–criterion β_{right}.

4. CONCLUSION

In this paper we have considered the technique for study evolution of the space-wave patterns in human EEG data during a psychophysiological experiment by stimulating cognitive activity with the perception of ambiguous object. The new method based on continuous wavelet transform allows to estimate the energy contribution of various components in the general and partial dynamics of the electrical activity for the projections of various areas of the brain.

The results of these studies appear promising for further study of the dynamics and the activity of the cerebral cortex in cognitive processes of various kinds. The technique is based on the calculation of the wavelet skeleton, it is universal for the study of various processes. Furthermore, this approach is highly customizable to individual features volunteers that allows the theoretical possibility of that using in the biofeedback systems.

5. ACKNOWLEDGMENTS

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