Demonstration of brain noise on human EEG signals in perception of bistable images

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ABSTRACT

In this report we studied human brain activity in the case of bistable visual perception. We proposed a new approach for quantitative characterization of this activity based on analysis of EEG oscillatory patterns and evoked potentials. Accordingly to theoretical background, obtained experimental EEG data and results of its analysis we studied a characteristics of brain activity during decision-making. Also we have shown that decision-making process has the special patterns on the EEG data.

Keywords: Electroencephalogram, continuous wavelet analysis, oscillatory patterns, ambiguous images

1. INTRODUCTION

The problem of studying nonlinear processes in brain neural network at perception of "ambiguous" (also known as bi- and multistable) images is characterized by a number of aspects for understanding visual recognition of objects and decision-making processes. It should be noted that the studies of ambiguous images perception are carrying out very active nowadays. In some sense, such objects are good models either for visual perception of surrounding world in general or decision making. Images of this type have been research objects for psychologists for a long time.[1,2] Recently, ambiguous images awoke interest of physicists and mathematicians.[3] Despite high attention of researchers, the main mechanism of image interpretation are not completely understood. Nowadays, it is well known that perception is a result of nonlinear processes which take place in distributed neural network of occipital, periental and frontal regions of brain cortex.[2,4] For a long enough observation of an ambiguous object the subject demonstrates individual effect of perception switching, e.g., the Rubin's vase is percepted alternately as two faces or as a vase.[1] According to existing hypothesis the perception switching when observing ambiguous images is connected with intrinsic noise of neural cells (the background neural activity as a result of randomly generated discharges).[5–8] Therefore, the neural background activity ("internal noise" of a neural network) plays the key role for ambiguous images interpretation as well as for other cases of decision makings. From the viewpoint of such approach, perception of ambiguous object can be described and modelled in terms of simple stochastic processes like Weiner's dynamics.[9–13] It is clear that description and prediction of such decision making process open wide perspectives for understanding, prediction and possible correction of behavior of a complex dynamical system including stochastic component, e.g., human.

Mechanisms of ambiguous perception of bistable images are thoroughly investigated in the last decade, and among the most popular bistable images are Rubin vase, Mach bands, Rorschach test, Boring's old woman/young woman illusion, etc.[1] However, the Necker cube remains the classical ambiguous figure with reversible perspective[14] that represents a contour image corresponding to the parallel projection of nodes and edges of the cube onto the plane, disregarding the rules of perspective, named after the Swiss mathematician and physicist Louis

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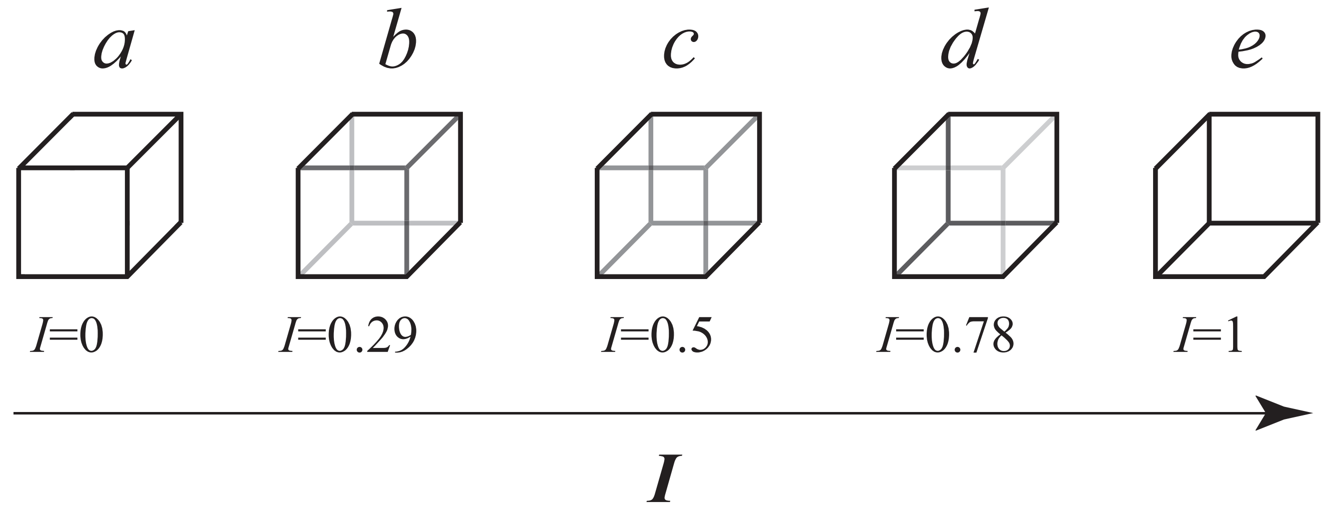

Figure 1. Examples of distinct Necker cube images with different wireframe contrasts characterized by control parameter I.

Albert Necker (1730-1804). During perception this figure spontaneously flips: one volumetric projection is replaced by another. In our work the advantage of the Necker cube is that its perception can be changed by varying several parameters, such as angle of displacement between planes, thickness of outlines, filling of sides with color or shade.[15] Figure 1 shows various examples of the Necker cube image with varying parameter I (the brightness of the cube faces converging in the right upper corner of the home, respectively, the brightness of the faces of the left inner corner of the cube is defined as $(1 - I)$).

From physical and mathematical point of view, visual perception of the Necker cube comprises two metastable states of perception each characterized by quasistability and last from seconds to tens of seconds. Intervals of stable perception with short duration are absent, and one of the perceived images usually dominates over relatively long period of time. The distribution of intervals of dominance in each image has a stochastic nature with gamma probability distribution.[1,5] Bifurcation analysis and catastrophe theory showed that the shift between two states of perception of ambiguous object linked with the intensity of intrinsic individually predetermined "cognitive noise" caused by spontaneous activity of neurons.[3] Nowadays the world neurophysiological and neurophysiological literature provides two opposing conceptions about the neural mechanisms of perception metastable images with the ascending ("bottom-up") and descending control ("top-down") of perception.[1,9] The first, ascending control (bottom-up influence) is passive process involving adaptive mechanisms of perception and antagonistic interactions in the visual system (reciprocal inhibition of visual neurons).[16] Long-term observation of metastable image causes a decrease of activity of neurons responsible for the perception of one of the possible configurations (due to acquired tolerance or adaptation to stimulus). When neuronal activity decreases below the critical level, neurons responsible for the perception of the second (competitor) configuration become active, resulting to inversion of image perception. The second, descending (top-down influence) control is active control resulting from cognitive processes, such as hypothesis testing, problem solving and voluntary attention. This view received strong experimental support[1] and the most powerful arguments supported significant effect of training and experience to control perception of metastable images.[9,16] It is known that the preliminary instruction of subjects about different interpretations of perceived image predetermines the outcomes of perception.[5]

It was found that the shift (inversion) of perception of ambiguous images was not spontaneously, but controlled by associative brain areas integrating sensory and non-sensory information and coordinating behavior. In practice, inversion of the perceived image may occur spontaneously or under the influence of subjective factors (division of attention, mood fluctuations).[3,17] It is known that the ability for alternative perception of bistable and multistable image can be changed with training, and it is lost after organic lesions in frontal cortex.[8] The perception of ambiguous images is influences by the objective factors (such as external stimuli - auditory, visual stimuli, changes of images' parameters), as well as subjective factors (such as the ability to focus attention, emotional state, etc.).

It is fundamentally important to create objective paradigm for data processing in cognitive research, because solely application of traditional neurophysiology methods, such as expert estimations and simple measures of signal's amplitude, may oversimplify our understanding of the process therefore fine and short-lasting process might be overlooked. Development and further application of standardized methods in neurophysiological experiments, including data acquisition, evaluation, analysis and processing of results, in already recorded data as well as in real time, have important practical application and it is still open field in research activity. International research practice in cognitive studies readily engages modeling of cognitive and neurophysiological processes with the aid of nonlinear dynamics and radiophysics methods.[18,18,19]

2. METHODS

2.1 Experiment

In present paper we studied brain noise intensity during decision-making in bistable visual perception. In our experiment as a stimulus we used a set of images based on a well-known bistable visual model – Necker cube. Necker cube is a simple image of a cube with transparent faces and visible ribs; the spectator with normal perception treats Necker cube as a 3d-object thanks to specific position of cube's ribs. Visual bistability consists in the fact that this 3d-object can be treated as oriented in two different ways, especially if different ribs of Necker cube are drawn with different intensity.

Demonstration of the Necker cube images with different wireframe contrast within 0.2-0.7 sec with background interruption within 2.5-3.5 sec. Participant will press left or right key to fix the projection being observed at each demonstration. In this experiment, unconscious decision on ambiguous image interpretation will be investigated. Between subsequent demonstrations of different Necker cube images other abstract pictures without any marks fixing eyesight from the set of sufficiently bright background images were exhibited (about 1000-1500 ms). Using of background images allows neutralizing possible effect of the previous Necker cube image. The whole experiment lasted about 40 min for each patient. During experiment we showed these pictures with Necker cube in random order (about 100 repeats foe each picture) and recorded EEG brain activity. As a tool for EEG recording we used electroencephalograph-recorder Encephalan-EEGR-19/26 with multiple EEG channels and two-button input device. To study EEGs the monopolar method of registration and the classic ten-twenty electrode system were used.

Mathematical model for the theoretical analysis of experimental data was developed using the approach described in[3] where bistable potential has been applied to describe the situation of choice of ambiguous image projection. Taking into account an effect of cognitive noise on the visual perception, stochastic differential equation leading to the Fokker-Plank equation was be obtained.

In our research we conventionally called Necker cube's orientations as "left" and "right" according to the position of imaginable front face of cube. In experiment we used $8-16$ different images of Necker cube with distinctive intensity of several key ribs. Intensity of ribs was selected in some specific way to have an influence on bistable perception of the spectator. For example, some images had an intensity distribution that more likely would be interpreted as "left", other images were "right"–oriented; also one of the images had symmetrical intensity distribution.

After the experiment we analyzed obtained data. We had multi-channeled EEG recordings with different markers: "imgN" type – marker that shows the moment of presentation of an image, where N – code name of an image with particular intensity distribution; "LClick" or "RClick" type – marker that shows the moment when patient pressed one of the buttons on input device, L for left button and R for right. So for each image of Necker cube we had two cases: when it was interpreted as "left" and when interpreted as "right"; we analyzed each of the cases distinctively because we proposed some difference in EEG structure caused by different visual perception. We analyzed time-frequency structure of EEG recordings between presentation of an image ("imgN"–marker) and response ("LClick/RClick"–marker) and a brief time interval after it. Complete duration of analyzing interval is about 2–3 s). As an instrument for EEG analysis we chose continuous wavelet transform.

2.2 Wavelet-based methods

In our work we used continuous wavelet transform (CWT)[20, 21] for time-frequency analysis of oscillatory patterns in EEG. CWT is a convolution of investigated signal $x(t)$ (EEG signal in our case) and some 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, so-called mother wavelet, by following transform:

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

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 $\omega_0 = 2\pi$.

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

According to papers[22, 23] Morlet wavelet is one of the most effective in analysis of complex experimental signals of biological nature (including EEG) because of its high time-frequency resolution.

In present work intrinsic frequency dynamics was investigated using “skeletons” of wavelet surfaces, that were constructed based on the previously described procedure.[23] 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.

3. RESULTS

In signal analysis with CWT amplitude wavelet surfaces (or wavelet spectra) are usually used. Wavelet spectra are $3d$ - surfaces of continuous wavelet transform energy; they provide common information about time-frequency structure of the signal. In our work we constructed wavelet spectra for short parts of EEG signal between markers and analyzed EEG signal structure. Another important part of present research was investigation of intrinsic time-frequency dynamics in EEG patterns associated with bistable visual perception. This part or research was performed with help of more advanced technique based on CWT − construction of “skeletons”. “Skeletons” are lines of local maxima on wavelet surfaces. “Skeletons” were constructed by searching of local maxima of wavelet energy in fixed time moment t by changing frequency f. “Skeleton” shows only few most significant frequency components in each time moment. In our work we constructed “skeletons” of wavelet surfaces for short parts of EEG signal between markers and analyzed EEG signal structure. We averaged wavelet spectra and “skeletons” for each case of Necker cube image and button pressed (for example, only “image3” and only left button pressed). We analyzed these averaged distributions to find trends in bistable visual perception. The concept of these method was based on well-known method of evoked potentials.

Figures 2 and 3 show the results of the study data registered on the occipital $O1$ and $O2$ of the volunteers. The wavelet analysis demonstrated the patterns presence in the EEG recording, almost forming a spindle on time series, but well observed on the CWT amplitude wavelet surfaces. Note that at the time of the decision-making process there is a well-defined pattern oscillating at a frequency close to the alpha-rhythm (about 10 Hz). Then, after the decision doing, this oscillatory activity stops, replaced by expressed low-frequency component (around

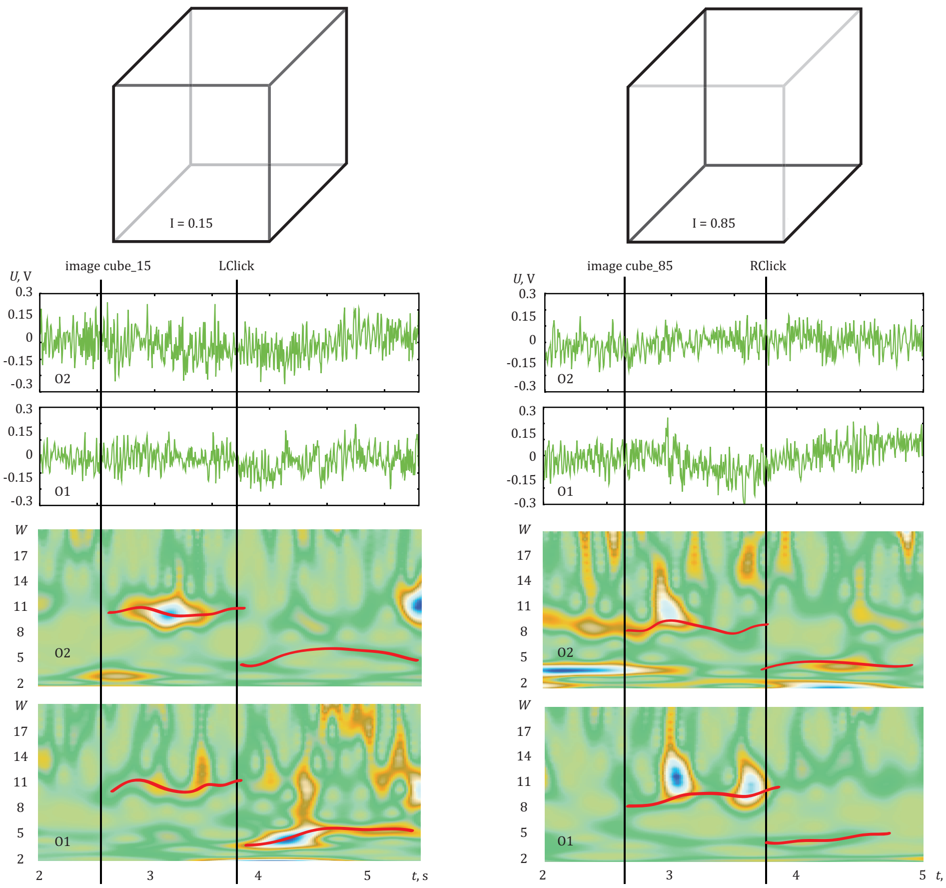

Figure 2. Examples of EEG recordings, wavelet spectra and “skeletons”(marked as red) during observation of Necker cubes with different intensities ($I = 0.15$ – “left” and $I = 0.85$ – ‘right”).

2.5 Hz), which may be perceived as relaxing. Figure 2 shows clearly that when choosing a definitely “left” cube the maximum activity is observed in EEG of the abduction $O1$, and to select the “right” of the cube — in EEG of the abduction of $O2$.

Figure 3 shows brain activity by observing a more complex object — the cube perceived essentially ambiguous. Note that in this case the choice of the volunteer realized the image as a “left” immediately, but in the beginning — erroneously pressed the “right” button. This case is more complex, high–amplitude characterized by activity and leads on both strong alpha–component and after the selection.

4. CONCLUSIONS

The present work is devoted to the research activity of the human brain on the EEG data during perception of ambiguous objects. A new approach based on the CWT to the study of EEG data occipital leads demonstrates characteristic patterns associated with the choice of one or another variant perception, as well as the subsequent decay of the activity of choice and may rest the brain. Further research will go towards greater formalization of the experimental conditions to eliminate the influence of, for example, leading the eye of man or the environment conditions. There will also be aimed at finding the correspondence between the cognitive noise used in mathematical models, and observed on EEG patterns.

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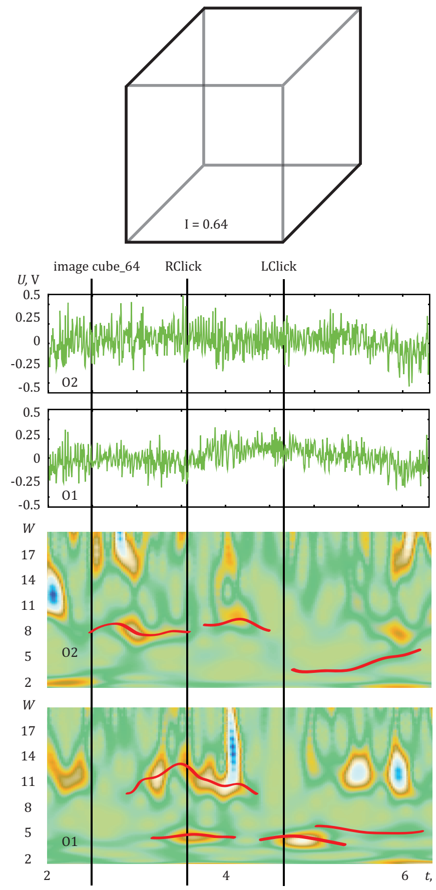

Figure 3. Example of EEG recordings, wavelet spectra and "skeletons"(marked as red) during observation of ambiguous Necker cube with different intensities ($I = 0.64$).

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