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Study of the interactions in neural ensemble of the brain using wavelet analysis

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ABSTRACT

The focal riddle for physicists and neuroscientists consists in disclosing the way microscopic scale neural interactions pilot the formation of the different activities revealed (at a macroscopic scale) by EEG and MEG equipments. In the current paper we estimate the degree of the interactions between the remote regions of the brain, based on the wavelet analysis of EEG signals, recorded from these brain areas. With the help of the proposed approach we analyze the neural interactions, associated with cognitive processes, taken place in human's brain during the perception of visual stimuli. We show that neurons in the remote regions of brain interact with the different degree of intensity in the generation of different rhythms. In particular during the perception of visual stimuli strong interaction has been observed in β - frequency band while strong interaction in α - frequency band has been observed in resting state.

Keywords: Electroencephalogram, visual perception, neural interactions

1. INTRODUCTION

The current trends in neuroscience are connected with the analysis of the structure and dynamics of the neural networks of brain[1–4] which interact with each other to perform different types of cognitive tasks, as e.g. the formation of a memory trace,[5,6] the processing of a visual object,[7] or the development (on a clinical level) of pathological rhythms like epileptic seizures.[8] These interactions are often quantified by means of the degree of synchrony, which can be measured both locally (i.e. within the same brain structure), or over a more global scale (i.e. in between brain structures).[9] While neurophysiology aims at understanding the interplay of individual neurons,[10] the majority of available data (especially those acquired from human subjects) comes from non invasive tests. These tests are made, in daily practice, under the form of electro-encephalograms (EEG) or magneto-encephalograms (MEG), which actually measure the (electric or magnetic) group activity of large ensembles of cells. The focal riddle for physicists and neuro-scientists consists, therefore, in disclosing the way microscopic scale neural interactions pilot the formation of the different activities revealed (at a macroscopic scale) by EEG and MEG equipments.

In the current paper we consider the neural interactions associated with the perception of ambiguous visual stimuli. With the help of continuous wavelet analysis we estimate the degree of interactions between the neural ensembles and degree of their participation in generation of different types of brain rhythms.

2. METHODS

Healthy subjects males and females, between the ages of 20 and 43 with normal or corrected-to-normal visual acuity participated in the experiments. All of them provided informed written consent before participating in the experiment. The experimental studies were performed in accordance with the Declaration of Helsinki and approved by the local research ethics committee of the Yuri Gagarin State Technical University of Saratov.

The Necker cube[11] was used as the visual stimuli, Such ambiguous stimulus is a popular object of many psychological experiments[12–14] and theoretical models.[14–16] It represents itself a cube with transparent faces and visible ribs; an observer without any perception abnormalities sees the Necker cube as a 3D-object due to

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the specific position of the cube's ribs. Bistability in perception consists in the interpretation of this 3D-object as to be either left- or right-oriented depending on the contrast of different inner ribs of the cube. The contrast $I \in [0,1]$ of the three middle lines centered in the left middle corner was used as a control parameter like that which was considered in Ref.[17] The values $I = 1$ and $I = 0$ correspond, respectively, to 0 (black) and 255 (white) pixels' luminance of the middle lines. Therefore, we can define a contrast parameter as $I = y/255$, where y is the brightness level of the middle lines using the 8-bit grayscale palette.

All participants were instructed to press either the left or right key depending on their first impression of the cube orientation at each presentation. The whole experiment lasted around 10–15 min for each participant, including short recordings of the brain background activity before and after the stimuli presentation. During experimental sessions, the cubes with different I were randomly presented (each configuration for about 30 times) and the electrical brain activity was recorded using the electroencephalographic recorder Encephalan-EEGR-19/26 (Medicom MTD, Russia) which provided simultaneous registration of up to 20 EEG channels and a two-button input device. The monopolar registration method and the classical ten-twenty electrode system were used. The ground electrode N was located above the forehead and two reference electrodes $A_{1,2}$ were located on mastoids. The EEG signals were filtered by a band pass filter with cut-off points at 1 Hz (HP) and 100 Hz (LP) and a 50-Hz Notch filter. The electroencephalograph"Encephalan–EEGR–19/26" (Taganrog, Russian Federation) with multiple EEG channels was used for amplification and analog-to-digital conversion of the EEG signals.

The gray-scale images were demonstrated on the 24" BenQ LCD monitor with a resolution of 1920 × 1080 pixels and a refresh rate of 60 Hz. The subject was located at a distance of 70–80 cm from the monitor with a visual angle of approximately 0.25 rad.

3. CALCULATIONS AND RESULTS

The EEG signals recorded by five electrodes (O_1, O_2, P_3, P_4, P_z) were analyzed. Electrodes were placed according to the the ten-twenty international system.[18]

The wavelet energy spectrum $E^n(f,t) = \sqrt{W_n(f,t)^2}$ was calculated for each EEG channel $X_n(t)$ in the frequency range $f \in [1,30]$ Hz. Here, $W_n(f,t)$ is the complex-valued wavelet coefficients calculated as

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

where $n = 1,...,N$ is the EEG channel number ($N = 5$ being the total number of channels used for the analysis) and "*" defines the complex conjugation. The mother wavelet function $\psi(f,t)$ is the Morlet wavelet often used for analysis of neurophysiological data is defined as

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

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

The wavelet energy spectrum was analyzed in three frequency bands: $\Delta f_\delta = [1-4]$ Hz (δ-rhythm), $\Delta f_\alpha = [8-12]$ Hz (α-rhythm), and $\Delta f_\beta = [20-30]$ Hz (β-rhythm), corresponding to typical patterns of the human cognitive activity.

For these frequency bands the corresponding wavelet energy values $E_{\alpha,\beta,\delta}(t)$ were calculated by averaging the spectral energy $E^n(f,t)$ over the corresponding bands α, β, δ as

$$E^n_{\alpha,\beta,\delta}(t) = \frac{1}{E^n_*(t)} \int\limits_{\Delta f_{\alpha,\beta,\delta}} E^n(f',t)df', \tag{3}$$

where $E^n_*(t)$ is the energy value $E^n(f,t)$ averaged over the whole considered spectrum of the EEG signal.

$$E^n_*(t) = \int\limits_{1\mathrm{Hz}}^{30\mathrm{Hz}} E^n(f',t)df' \tag{4}$$

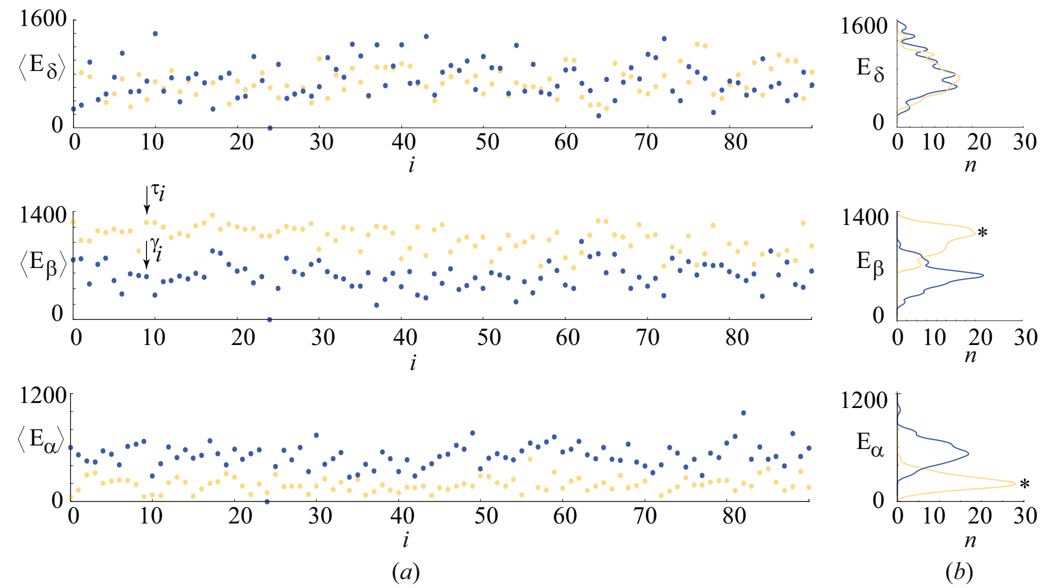

Figure 1. (a) The values of wavelet energy, calculated for time intervals τ_i and γ_i, associated with i-th presentation in three frequency bands - α, β, δ. Different color of the dot defines the time segment (τ_i or γ_i). (b) values $\langle E_{\alpha,\beta,\delta}\rangle_{\tau_i,\gamma_i}$ are shown in the form of statistical distributions. Line color again defines the time segment. "*" indicates significant change in wavelet energy between segments τ_i and γ_i.

The values of the wavelet energy (3) were calculated for all experimental session. Obtained values were then partitioned into two subsequent segments, related to the perception of i-th visual stimuli. Segment τ_i defines time interval for which i-th stimuli is presented to the subject, segment γ_i defines time intervals preceded i-th image presentation.

For i-th presentation the obtained coefficients $E^n_{\alpha,\beta,\delta}(t)$ were averaged over time intervals of the corresponding segment and over all EEG channels used for the analysis, as follows

$$\langle E_{\alpha,\beta,\delta}\rangle_{\tau_i,\gamma_i} = \frac{1}{N}\sum_{n=1}^{N}\int_{\tau_i,\gamma_i} E^n_{\alpha,\beta,\delta}(t')dt'. \qquad (5)$$

Obtained values $\langle E_{\alpha,\beta,\delta}\rangle_{\tau_i,\gamma_i}$ are shown in Fig. 1, *a* for each of $i = 1\dots 90$ image presentations by dots. Different color of the dot defines the time segment (τ_i or γ_i). in Fig. 1, *b* $\langle E_{\alpha,\beta,\delta}\rangle_{\tau_i,\gamma_i}$ are shown in the form of statistical distributions.Here the line color again defines the time segment (τ_i or γ_i). One can see that the processing of the visual stimuli is associated with the decrease of the energy of α–activity and increase of the energy of β–rhythm. Change in low-frequency δ–activity is shown to not be associated with the image processing.

According to the recent research,[3] the obtained values of $E^n_{\alpha,\beta,\delta}(t)$ calculated by Eq. (3) for all channels can be considered as the measure of the degree of participation of neural ensembles (associated with different EEG channels) in generation of the corresponding rhythm, because it determines the energy contribution of the corresponding spectral band. Therefore, the EEG channels were analyzed together to find the values of $\Delta E^n_{\alpha,\beta,\delta}(t)$ which represent the average deviations of $E^n_{\alpha,\beta,\delta}(t)$ over all channels, i.e.

$$\Delta E^n_{\alpha,\beta,\delta}(t) = E^n_{\alpha,\beta,\delta}(t) - \frac{1}{N}\sum_{n=1}^{N} E^n_{\alpha,\beta,\delta}(t). \qquad (6)$$

For each image presentation the values $\Delta E^n_{\alpha,\beta,\delta}(t)$ were averaged over the time intervals τ_i and γ_i. For the

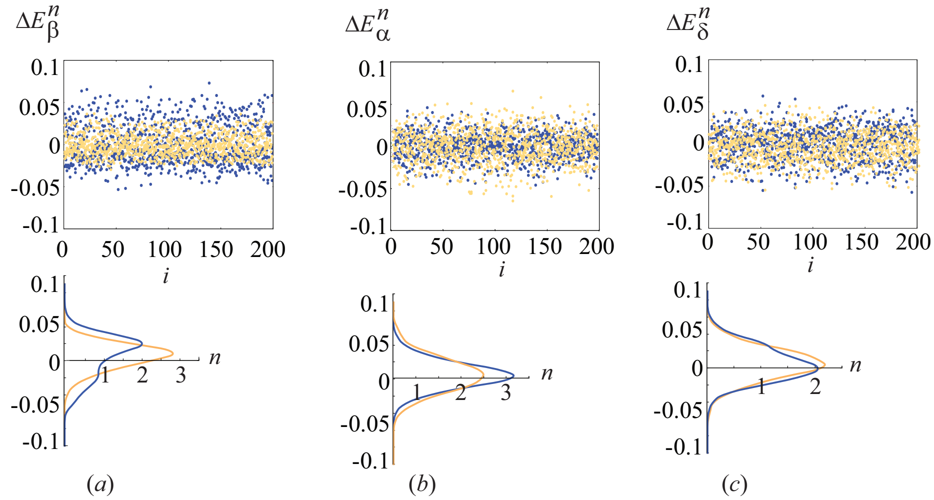

Figure 2. the values of $\Delta E^n_{\alpha,\beta,\delta}(i)$ are shown by dots for all channels, for i-th image presentation. Different color of the dot defines the time segment (τ_i or γ_i). (b) values $\Delta E^n_{\alpha,\beta,\delta}(i)$ are shown in the form of statistical distributions. Line color again defines the time segment.

i-th presentation the corresponded values $\Delta E^n_{\alpha,\beta,\delta}(i)$ were calculated as

$$\Delta E^n_{\alpha,\beta,\delta}(i)_{\tau_i,\gamma_i} = \int\limits_{t\in\tau_i,\gamma_i} \Delta E^n_{\alpha,\beta,\delta}(t')dt'. \quad (7)$$

By comparison the values of $\Delta E^n_{\alpha,\beta,\delta}(i)$ for all channels, one can decide about the similarity in the behavior of different brain areas. Since the signal from each EEG channel characterizes the electrical activity of a large group of neurons, an increase in the spectral energy in a particular frequency band indicates the increasing involvement of these neurons in generation of this rhythm, as well as their synchronization. The values of $E^n_{\alpha,\beta,\delta}(t)$ calculated by Eq. (3) represent the fraction of the spectral energy in the corresponding frequency band $(\Delta f_\alpha, \Delta f_\beta, \Delta f_\delta)$ with respect to the whole spectral energy, that, in fact, determines the contribution of a group of neurons participated in generation of α, β, and δ rhythms.

Obtained values $\Delta E^n_{\alpha,\beta,\delta}(i)_{\tau_i,\gamma_i}$ are shown in Fig. 2 for each i-th image presentation by dots of different color. Color of the dot corresponds to the time interval (τ_i or γ_i). One can see, that for time interval τ_i, corresponded to the image observation (yellow dots) the β-rhythm exhibited smaller dispersion than for time interval γ_i, preceded the image observation. At the same time α-rhythm exhibited smaller dispersion for the interval γ_i, preceded i-th image presentation. Dispersion in the δ-rhythm remains practically unchanged during the transition from interval γ_i to τ_i.

If the spectral energy averaged over a particular frequency band normalized to the whole spectral energy describes the contribution of the corresponding brain area to generation of this brain wave, a simultaneous increase (or decrease) of this contribution calculated for different channels and for different frequency bands can reveal similarity (or difference) in the behavior of associated groups of neurons. According to this, we can assume that neural ensembles located in the remote regions of the occipital lobe start to interact more intensively in β frequency band when the perception of the visual stimuli takes place. At the same time neural interaction in α band becomes less intensive.

4. CONCLUSION

We have demonstrated the possibility to determine the degree of interaction between the interconnected regions of the brain based on the analysis of time-frequency structure of EEG signals, recorded in these brain areas.

Specifically, depending on the type of brain activity, we have found that the neurons in remote regions of brain interact in the different frequency bands with different degrees of intensity.

Having applied the proposed approach we have analyzed the neural interactions, associated with cognitive processes, taken place in human's brain during the perception of visual stimuli. We have shown that neurons in the remote regions of brain interact with the different degree of intensity in the generation of different rhythms. In particular during the perception of visual stimuli strong interaction has been observed in β - frequency band while strong interaction in α - frequency band has been observed in resting state.

Our approach constitutes a practical technique for the investigation of brain neuronal network interactions, with the potential of getting a glance at interactions at a microscopic level by the analysis of the macroscopic signals commonly acquired in neuroscience studies. In particular, our study may be applied in a wide range of neurophysiological studies,which investigate functional brain network conductivities by means of EEG and MEG data during different forms of cognitive and behavioral tasks as well as for the study of pathophysiological brain processes.

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