The study of evolution and depression of the alpha-rhythm in the human brain EEG by means of wavelet-based methods

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ABSTRACT

We study the appearance, development and depression of the alpha-rhythm 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, including the alpha rhythm, in the general dynamics of the electrical activity of the projections of various areas of the brain. The decision-making process by observe ambiguous images is characterized by specific oscillatory alfa-rhytm patterns in the multi-channel EEG data. We have shown the repeatability of detected principles of the alpha-rhythm evolution in a data of group of 12 healthy male volunteers.

Keywords: Electroencephalogram, ambiguous images, neurophysiological experiment, continuous wavelet analysis, energy distribution, oscillatory patterns, alpha-rhytm

1. INTRODUCTION

A study of nonlinear processes in the brain neural network during perception of "ambiguous" (also known as bi- and multistable) images is 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 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. The distribution of the intervals of dominance in each image has a stochastic nature with gamma probability distribution.[10–14] Bifurcation analysis and catastrophe theory show that the shift between two percepts of an ambiguous image is linked to the intensity of intrinsic individual "cognitive brain noise" caused by neuronal spontaneous activity.[3,4]

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 cognitive studies readily engages in the modeling of cognitive and neurophysiological processes using nonlinear dynamics tools.[15,15–19]

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2. 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,[20] 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.[21] Twelve healthy subjects from a group of unpaid male volunteers, between the ages of 18 and 25 with a normal visual acuity participated in the experiments. The purpose of this experiment is the study of 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 0.5 and 0.9 seconds, interrupted by a background abstract picture for 2.5 – 3.5 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.

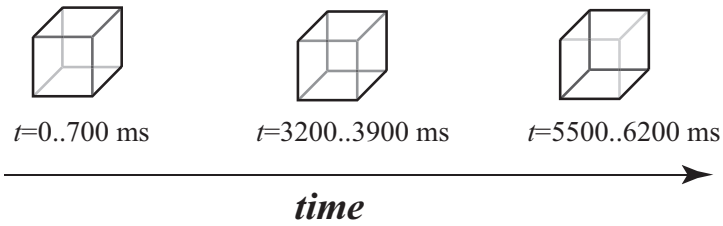

Figure 1. Examples of distinct Necker cube images with different wireframe contrasts characterized by control parameter I

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 2 shows an example of a typical EEG data set.

2.2 Wavelet-based method

In our work we used continuous wavelet transform (CWT)[18,22–24] 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:

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

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 $\omega_0 = 2\pi$:[25,26]

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

According to papers[27–31] the Morlet wavelet is one of the most effective in analysis of complex experimental signals of biological nature (including EEG) because of its optimal time-frequency resolution.

In present work intrinsic frequency dynamics was investigated using "skeletons" of wavelet surfaces.[31,32] The "skeletons" of wavelet surfaces are constructed to extract dominant EEG frequencies and determine the evolution of main rhythms in EEG data, in particular, alpha-rhytm. 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 our experimental studies we separated all Necker cube images on the "left" and "right" in accordance with the apparent position of the front face of the cube. Obviously, the intensity I of the ribs provided on the impact of the perception of the observer. In particular, an image with a small parameter I is usually interpreted as "left" one, respectively, with a large parameter I — as "right". All images that are close to symmetrical distribution of the intensity of the edges are perceived as left- or right-handle cube with a probability determined by the personal characteristics of the observer (e.g., the level of cognitive noise).[3,33,34]

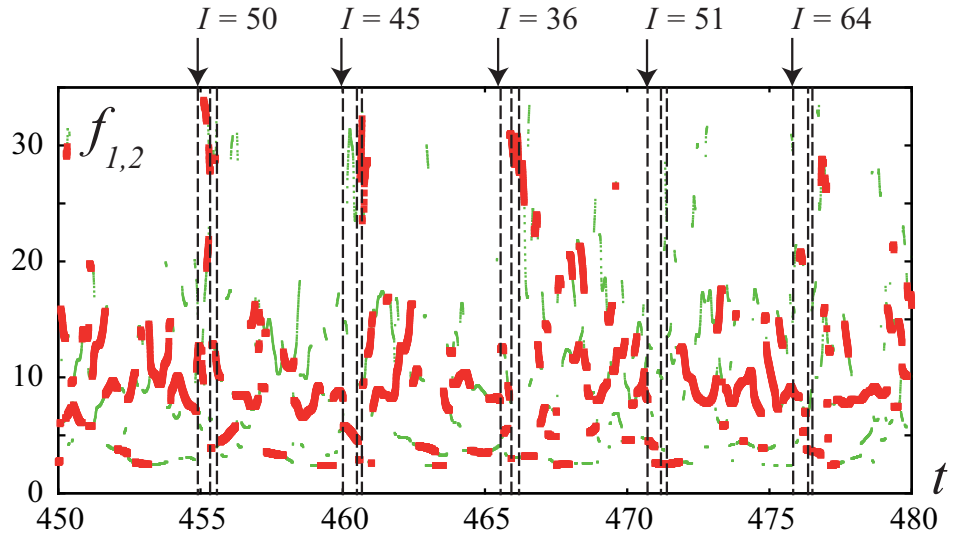

Figure 2. Fragments of time depending on the frequency spectrum of the wavelet, which account for maximum energy components hesitation. These curves are plotted according to the data in the channel register Pz volunteer number 4.

Figure 2 shows the temporal variation over the frequency bands, which account for the first two components of the maximum energy of the wavelet spectrum. In this case, we process the EEG data from only one channel Pz, which is located in the occipital region. This figure have a event marking — presentations of cubes with different intensity parameter. It is clearly seen that there are certain values of frequencies, for which the maximum of the

energy spectrum of the vibrational modes are observed regularly. In particular, most qualitatively similar energies allocated range of frequencies is 8 – 12 Hz, traditionally referred to as the alpha-rhythm. In the present work we will focus on the analysis of the alpha-rhythm evolution in the process of staged cognitive psychophysiological experiment. In this case, we are limiting our processing of multi-channel EEG data exceptionally occipital area of a brain electrical activity registration, in particular O1, O2, P3, Pz, P4, C4 and Cz channels of the classical ten-twenty electrode system. So, in rest period between the presentations of controversial facilities, most of our volunteers have demonstrated evolution alpha-rhythm, which sharply depresses and stops existence immediately upon presentation of the cube image.

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 9 to 12 Hz in this time. In other words, if the condition is satisfied for a particular channel of the occipital region, the alpha-criterion α is equivalent to the constant, and otherwise α is zero, then α – criterion:

$$\alpha_i = \begin{cases} 1 & \text{if } 8 < f_{1,2}^i < 12 \\ 0 & \text{in other cases} \end{cases}$$

In Figure 3 a shows the result of calculation of the proposed specifications at any given time for the channel Pz. However, with the continuous calculation of the characteristic is unstable, it is possible to compensate for the calculation of criteria in the time window. For further calculations of the value of the time window was chosen as universal for all 12 subjects and was 400 ms. The averaging is necessary in this case, as so structure of the alpha-rhythm is spindles, and due to possible failures relating to the imperfection of any equipment and methods.

Then, this presented calculation method for processing of EEG data can be extended to the entire occipital region. In this case the presence or depression of calculating the alpha-rhythm criterion for each channel, it can simple sum the "0" and "1":

$$\alpha_{6i} = \sum \begin{cases} 1 & \text{if } 8 < f_{1,2}^{O1} < 12 \quad \text{or} \quad 0 \quad \text{in other cases} \\ 1 & \text{if } 8 < f_{1,2}^{O2} < 12 \quad \text{or} \quad 0 \quad \dots \\ 1 & \text{if } 8 < f_{1,2}^{P3} < 12 \quad \text{or} \quad 0 \quad \dots \\ 1 & \text{if } 8 < f_{1,2}^{Pz} < 12 \quad \text{or} \quad 0 \quad \dots \\ 1 & \text{if } 8 < f_{1,2}^{P4} < 12 \quad \text{or} \quad 0 \quad \dots \\ 1 & \text{if } 8 < f_{1,2}^{Cz} < 12 \quad \text{or} \quad 0 \quad \dots \end{cases}$$

4. CONCLUSION

In this paper we have considered the technique for study alpha-rhythm evolution 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, not only the alpha-rhythm, in the general dynamics of the electrical activity of the projections of various areas of the brain. In addition, in further the use of approach can be directed objectively evaluate motivation and conscious involvement of volunteers in the experiment. Suffice it to appreciate that the alpha rhythm is associated with relaxation processes and apparently destroyed when cognitive performance associated with the perception of complex objects. At the same time, if the volunteer is interested in participation of the experiment and focuses on solving the problem, this phenomenon of periodic destruction and restoration of the alpha rhythm is not be observed. Furthermore, it becomes more clear that to detect EEG data complex processes "cognitive noise" we must bring it involved people volunteer for the relevant group.

5. ACKNOWLEDGMENTS

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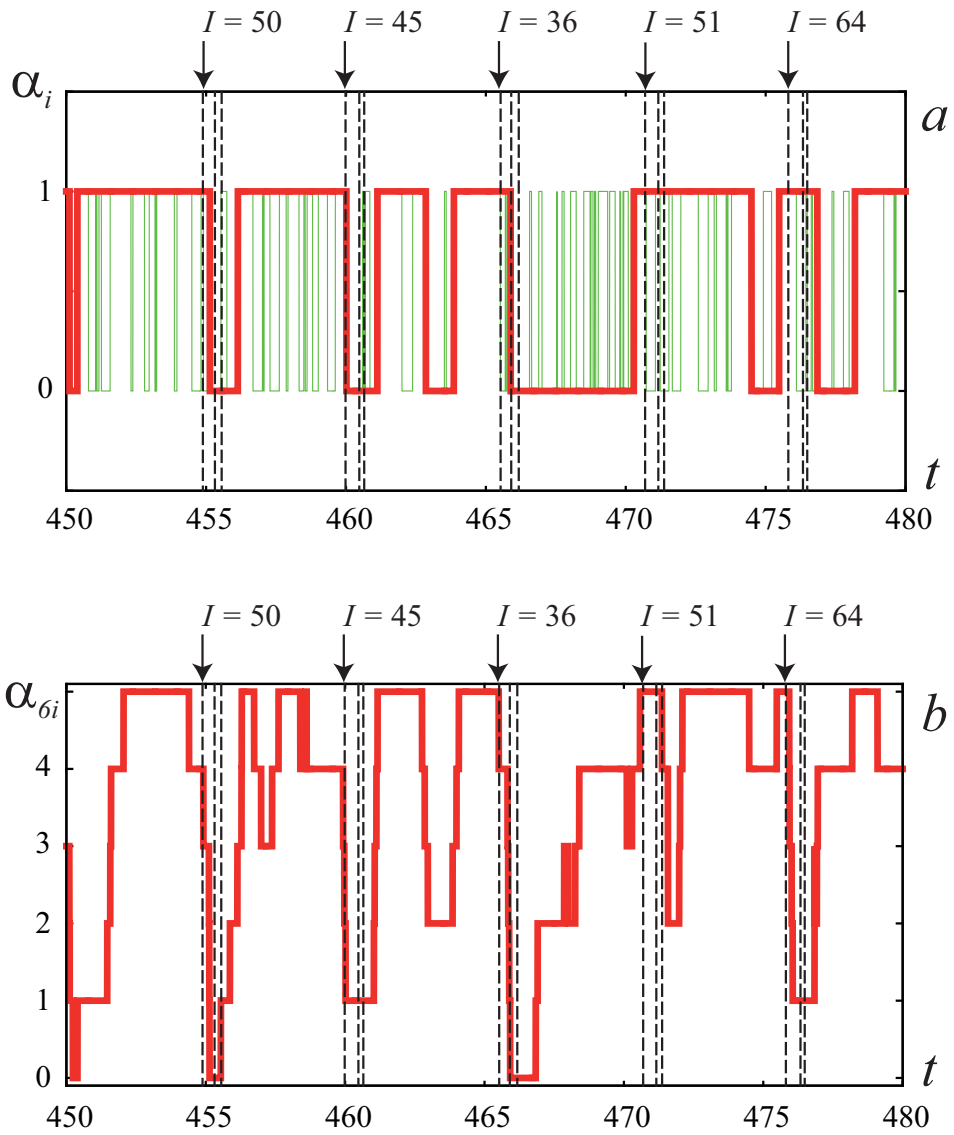

Figure 3. (a) The dependence of the alpha-criterion α over time for Pz channel. The green line demonstrates the result of calculation itself directly, the thick red line is the result of the characteristics averaging in time window about 400 mc. (b) The dependence of the alpha-criterion α_{6i} for brain occipital region.

REFERENCES

[1] Leopold, D. A. and Logothetis, N. K., "Multistable phenomena: changing views in perception," *Trends in Cognitive Sciences* **3**(7), 254–264 (1999).

[2] Sterzer, P., Kleinschmidt, A., and Rees, G., "The neural bases of multistable perception," *Trends in Cognitive Sciences* **13**(7), 310–318 (2009).

[3] Pisarchik, A. N., Jaimes-Reategui, R., Magallón-Garcia, C. D. A., and Castillo-Morales, C. O., "Critical slowing down and noise-induced intermittency in bistable perception: bifurcation analysis," *Biological Cybernetics* **108**(4), 397–404 (2014).

[4] Runnova, A. E., Hramov, A. E., Grubov, V. V., Koronovskii, A. A., Kurovskaya, M. K., and N., P. A., "Theoretical background and experimental measurements of human brain noise intensity in perception of ambiguous images," *Chaos, Solitons and Fractals* **93**, 201–206 (2016).

[5] Tong, F., Meng, M., and Blake, R., "Neural bases of binocular rivalry," *Trends in Cognitive Sciences* **10**(11), 502–511 (2006).

[6] Huguet, G., Rinzel, J., and Hupé, J.-M., "Noise and adaptation in multistable perception: Noise drives when to switch, adaptation determines percept choice," *Journal of Vision* **14**(3), 1–24 (2014).

[7] Gigante, G., Mattia, M., Braun, J., and Giudice, P. D., "Bistable perception modeled as competing stochastic integrations at two levels," *PLoS Computational Biology* **5**(7), e1000430 (2009).

[8] Moreno-Bote, R., Rinzel, J., and Rubin, N., "Noise-induced alternations in an attractor network model of perceptual bistability," *Journal of Neurophysiology* **98**, 1125–1139 (2007).

[9] Merk, I. and Schnakenberg, J., "A stochastic model of multistable visual perception," *Biological Cybernetics* **86**, 111–116 (2002).

[10] Aks, D. J. and Sprott, J. C., "The role of depth and $1/f$ dynamics in perceiving reversible figures," *Nonlinear Dynamics, Psychology, and Life Sciences* **7**(2), 161–180 (2003).

[11] Ratcliff, R. and Smith, P. L., "A comparison of sequential sampling models for two-choice reaction time," *Psychological Review* **111**(2), 333–367 (2004).

[12] Heekeren, H. R., Marrett, S., and Ungerleider, L. G., "The neural systems that mediate human perceptual decision making," *Nature Reviews Neuroscience* **9**, 467–479 (2008).

[13] Wang, X.-J., "Neural dynamics and circuit mechanisms of decision-making," *Current Opinion in Neurobiology* **22**(6), 1039–1046 (2012).

[14] Pearson, B., Raskevicius, J., Bays, P. M., Pertzov, Y., and Husain, M., "Working memory retrieval as a decision process," *Journal of Vision* **14**(2) (2014).

[15] Rabinovich, M. I., Varona, P., Selverston, A. I., and Abarbanel, H. D. I., "Dynamical principles in neuroscience," *Rev. Mod. Phys.* **78**, 1213–1265 (November 2006).

[16] Hramov, A. E., Koronovskii, A. A., Midzyanovskaya, I. S., Sitnikova, E., and Rijn, C. M., "On-off intermittency in time series of spontaneous paroxysmal activity in rats with genetic absence epilepsy," *Chaos* **16**, 043111 (2006).

[17] Sitnikova, E., Hramov, A. E., Grubov, V. V., Ovchinnkov, A. A., and Koronovsky, A. A., "On-off intermittency of thalamo-cortical oscillations in the electroencephalogram of rats with genetic predisposition to absence epilepsy," *Brain Research* **1436**, 147–156 (2012).

[18] Hramov, A. E., Koronovskii, A. A., Makarov, V. A., Pavlov, A. N., and Sitnikova, E., [*Wavelets in Neuroscience*], Springer Series in Synergetics, Springer, Heidelberg, New York, Dordrecht, London (2015).

[19] Luijtelaar van, G., Luttjohann, A., Makarov, V. V., Maksimenko, V. A., Koronovskii, A. A., and Hramov, A. E., "Methods of automated absence seizure detection, interference by stimulation, and possibilities for prediction in genetic absence models," *Journal of Neuroscience Methods* **260**, 144–158 (2016).

[20] Necker, L. A., "Observations on some remarkable phenomena seen in switzerland; and an optical phenomenon which occurs on viewing of a crystal or geometrical solid," *Philos. Mag.* **3**, 329–343 (1832).

[21] "World medical association (2000) declaration of helsinki: ethical principles for medical research involving human subjects," *The Journal of the American Medical Association* **284**(23), 3043–3045 (2000).

[22] Hramov, A. E., Koronovskii, A. A., Ponomarenko, V. I., and Prokhorov, M. D., "Detecting synchronization under varying frequency of driving signal using continuous wavelet transform in application to medical data," in [*Proceedings of Int. Symposium "Topical Problems of Nonlinear Wave Physics". Part 1. Nonlinear Dynamics: Theory and Applications (St. Peterburg – N. Novgorod, Russia, 2–9 August, 2005).*], Nekorkin, V. I., ed., 33, Nizhnij Novgorod, 2005 (2005).

[23] Hramov, A. E., Koronovskii, A. A., Ponomarenko, V. I., and Prokhorov, M. D., "Detection of synchronization from univariate data using wavelet transform," *Phys. Rev. E* **75**(5), 056207 (2007).

[24] Pavlov, A. N., Hramov, A. E., Koronovskii, A. A., Sitnikova, Y. E., Makarov, V. A., and Ovchinnikov, A. A., "Wavelet analysis in neurodynamics," *Physics-Uspekhi* **55**(9), 845–875 (2012).

[25] Ovchinnikov, A. A., Luttjohann, A., Hramov, A. E., and Luijtelaar van, G., "An algorithm for real-time detection of spike-wave discharges in rodents," *Journal of Neuroscience Methods* **194**, 172–178 (2010).

[26] Ovchinnikov, A. A., Hramov, A. E., Luttjohann, A., Koronovskii, A. A., and Van Luijtelaar, E. L., "Method for diagnostics of characteristic patterns of observable time series and its real-time experimental implementation for neurophysiological signals," *Technical Physics* **56**(1), 1–7 (2011).

[27] Hramov, A. E. and Koronovskii, A. A., "An approach to chaotic synchronization," *Chaos* **14**(3), 603–610 (2004).

[28] Hramov, A. E., Koronovskii, A. A., Ponomarenko, V. I., and Prokhorov, M. D., "Detecting synchronization of self-sustained oscillators by external driving with varying frequency," *Phys. Rev. E* **73**(2), 026208 (2006).

[29] Sitnikova, E., Hramov, A. E., Koronovskii, A. A., and Luijtelaar, E. L., "Sleep spindles and spikewave discharges in EEG: Their generic features, similarities and distinctions disclosed with fourier transform and continuous wavelet analysis," *Journal of Neuroscience Methods* **180**, 304–316 (2009).

[30] van Luijtelaar, E. L. M., Hramov, A. E., Sitnikova, E., and Koronovskii, A. A., "Spikewave discharges in WAG/Rij rats are preceded by delta and theta precursor activity in cortex and thalamus," *Clinical Neurophysiology* **122**, 687–695 (2011).

[31] Sitnikova, E., Hramov, A. E., Grubov, V., and Koronovsky, A. A., "Time-frequency characteristics and dynamics of sleep spindles in WAG/Rij rats with absence epilepsy," *Brain Research* **1543**, 290–299 (2014).

[32] Sitnikova, E., Grubov, V. V., Hramov, A. E., and Koronovskii, A. A., "Structure of EEG sleep spindles in rats with genetic predisposition to absence epilepsy (WAG/Rij)," *Journal of higher nervous activity* **62**(6), 733–744 (2011).

[33] Pisarchik, A. N., Bashkirtseva, I. A.., and Ryashko, L. B.., "Controlling bistability in a stochastic perception model," *Eur. Phys. J. Special Topics* **224**(8), 1477–1484 (2015).

[34] Runnova, A.E., Hramov, A.E., Grubov, V.V., Koronovskii, A.A., Kurovskaa, M.K., Pisarchik, A.N.., "Theoretical background and experimental measurements of human brain noise intensity in perception of ambiguous images," *Chaos, Solitons Fractals* **93**, 201-206 (2016)