PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Methods of assessing the degree of synchronization of multichannel EEG recordings

M. O. Zhuravlev, A. E. Runnova, A. E. Hramov

M. O. Zhuravlev, A. E. Runnova, A. E. Hramov, "Methods of assessing the degree of synchronization of multichannel EEG recordings," Proc. SPIE 11067, Saratov Fall Meeting 2018: Computations and Data Analysis: from Nanoscale Tools to Brain Functions, 1106705 (3 June 2019); doi: 10.1117/12.2527706

SPIE.

Event: International Symposium on Optics and Biophotonics VI: Saratov Fall Meeting 2018, 2018, Saratov, Russian Federation

Methods of assessing the degree of synchronization of multichannel EEG recordings

M.O. Zhuravlev[a,b], A.E. Runnova[a,c], A.E. Hramov[a]

[a]Innopolis University, Innopolis, Russia
[b]Saratov State University, Saratov, Russia
[c]Yuri Gagarin State Technical University of Saratov, Saratov, Russia

ABSTRACT

In the present paper we describe methods of assessing the degree of synchronization of multichannel EEG recordings of the human brain during the evaluation of mental tasks. We carry out the experiments involving the alternating trials of mental tasks evaluation with simultaneous registration of electroencephalographic (EEG) data.

Keywords: electroencephalogram, neurophysiological experiment, mental task, cognitive load, wavelet analysis

1. INTRODUCTION

The processes underlying cognitive functions are of a great interest of modern neuroscience.[1,2] The close attention of researchers to this topic is caused not only by urge to reveal the fundamental aspects of brain behaviour. Recent studies show strong possibility of early diagnosis of mental disorders[3] and mild cognitive impairments[4–6] using analysis of electrical brain activity during the evaluation of various mental tasks. At the same time, efficient classification and scoring of mental activity can be used in variety of brain-computer interface (BCI) applications with neurofeedback,[7–9] which present themselves promising technology for research in many related fields of cognitive science.[10]

The considerable progress in the investigation of cognitive activity has been made using electroencephalographic (EEG) frequency analysis. In particular, the importance of alpha (8–12 Hz), beta (20–35 Hz) and theta (4–8 Hz) bands is shown in several studies.[11–13]

In this work we describe methods to study the synchronization of multichannel EEG recordings in cognitive load for brain.

2. EXPERIMENTAL SETUP

During all experiment, the multi-channel EEG data has been acquired using the BE Plus LTM amplifier, manufactured by EB Neuro S.P.A., Florence, Italy (www.ebneuro.com). It was recorded at 8 kHz sampling rate using the standard bipolar method of registration with two reference and $N = 19$ electrodes (see Fig. 1 (a)). The adhesive Ag/AgCl electrodes based in special prewired head caps were used to obtain the EEG signals. Two reference electrodes A1 and A2 were located on mastoids, while the ground electrode N was located above the forehead. The EEG signals were filtered by a band pass filter with cut-off points at 1 Hz (HP) and 300 Hz (LP) and a 50-Hz Notch filter. To accurately split the recording into the active (Shulte table evaluation) and passive (rest) phases we used the video recording during all stages of experiment.

The experiments were carried out during the first half of the day at a specially equipped laboratory where the volunteer was sitting comfortably and effects of external stimuli, e.g. external noise and bright light, were minimized. The $S = 8$ subjects performed a series of attentional tests using the Schulte table. The Schulte table represents a square matrix with 5 columns and 5 rows, in which numbers from 1 to 25 are placed in random

Further author information: (Send correspondence to A. E. Runnova)
A. E. Runnova: E-mail: anefila@gmail.com, Telephone: +79631125902

Saratov Fall Meeting 2018: Computations and Data Analysis: from Nanoscale Tools to Brain Functions,
edited by Dmitry E. Postnov, Proc. of SPIE Vol. 11067, 1106705 · © 2019 SPIE
CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2527706

order (see Fig. 1 (b)). The participant's task is to point all numbers in the table in the reverse order (from 25 to 1). The experiment for each subject contained $M = 5$ active stages (one of the five Schulte table evaluation), which were alternating with the passive stages (rest).

Subjects participated in the experiment on a voluntary and gratuitous basis. All participants signed an informed medical consent to participate in the experimental work and received all necessary explanations about the process, including their agreement for further publication of the results. Acquired experimental data were processed with respect the confidentiality and anonymity of research respondents. 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.

3. METHODS

We use the wavelet bicoherence to estimate the degree of synchronization between the brain regions. The wavelet bicoherence[?,14,15] has proved itself as very powerful instrument to quantify the interactions and correlations on various scales of biological systems,[16–18] including brain activity.[19–23] Below the detailed description of the calculation of wavelet bicoherence for the pairs of EEG signals is presented.

We calculate the complex-valued wavelet coefficients $W_n(f,t)$ for each EEG channel $x_i(t)$ as

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

where $i = 1, ..., N$ is the number of considered EEG channel, and $N = 19$ is the total number of EEG channels, "*" denotes the complex conjugation, and $\psi(f,t)$ is the mother wavelet function. We use the Morlet wavelet, which is often utilized for processing of biological signals[17]

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

where ω_0 is the wavelet scaling parameter. Previously we found that parameter $\omega_0 = 2\pi$ in the continious wavelet transform provides an optimal time-frequency resolution of EEG signal.[24,25]

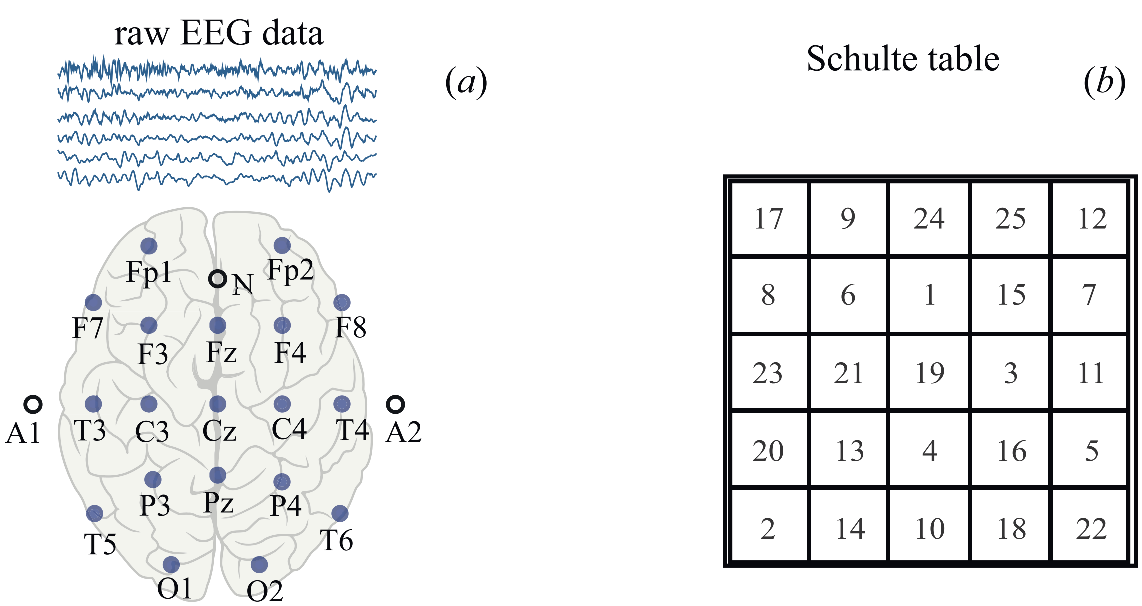

Figure 1. (a) The scheme "10 – 20" of EEG recording. (b) The depiction of an example of the Schulte table.

To measure the degree of coherence between two EEG signals $x_i(t)$ and $x_j(t)$, we use the corresponding complex-valued wavelet coefficients $W_i(f,t) = a_i + \mathrm{i}b_i$ and $W_j(f,t) = a_j + \mathrm{i}b_j$.

Wavelet bicoherence, $\sigma_{ij}(f,t)$, is estimated based on the mutual wavelet spectrum $W_{i,j}(f,t)$ of the signals $x_i(t)$ and $x_j(t)$. Similarly to[26] the coefficients $\mathrm{Re}\,[\sigma_{ij}(f,t)]$ and $\mathrm{Im}\,[\sigma_{ij}(f,t)]$ represented as real and imaginary parts of mutual wavelet spectrum can be calculated via Eqs. (3) and (4), respectively:

$$\begin{aligned}&\mathrm{Re}\,[\sigma_{ij}(f,t)] = \\ &= \frac{a_i(f,t)a_j(f,t) + b_i(f,t)b_j(f,t)}{\sqrt{a_i^2(f,t) + b_i^2(f,t)}\sqrt{a_j^2(f,t) + b_j^2(f,t)}}\end{aligned} \tag{3}$$

and

$$\begin{aligned}&\mathrm{Im}\,[\sigma_{ij}(f,t)] = \\ &= \frac{b_i(f,t)a_j(f,t) - a_i(f,t)b_j(f,t)}{\sqrt{a_i^2(f,t) + b_i^2(f,t)}\sqrt{a_j^2(f,t) + b_j^2(f,t)}}.\end{aligned} \tag{4}$$

Next, we evaluate the degree of coherence between the different EEG signals, recorded during each EEG trial of rest or evaluation of cognitive task for each subject p. The values were averaged over time intervals, involved in each trial of experiment. As the result, coefficients $\mathrm{Re}\,[\sigma_{ij}(f,t)]_{T_{mp},m,p}$ and $\mathrm{Im}\,[\sigma_{ij}(f,t)]_{T_{mp},m,p}$ were obtained as

$$\mathrm{Re}\,[\sigma_{ij}(f)]_{T_{mp},m,p} = \frac{1}{MS}\sum_{p=1}^{S}\sum_{m=1}^{M}\frac{1}{T_{mp}}\int\limits_{T_{mp}} \mathrm{Re}\,[\sigma_{ij}(f,t)]\,dt \tag{5}$$

and

$$\mathrm{Im}\,[\sigma_{ij}(f)]_{T_{mp},m,p} = \frac{1}{MS}\sum_{p=1}^{S}\sum_{m=1}^{M}\frac{1}{T_{mp}}\int\limits_{T_{mp}} \mathrm{Im}\,[\sigma_{ij}(f,t)]\,dt, \tag{6}$$

where $M = 5$ is the number of stages of cognitive task evaluation or rest, S is the number of subjects, T_{mp} is the duration of m–th stage of task evaluation by p–th subject determined by recorded video analysis or the duration of rest interval which was fixed $T_{mp} = 10\,\mathrm{s}$. Based on coefficients (5) and (6) the degree of coherence, $\sigma(f)$, between the EEG signals was estimated as the amplitude of mutual wavelet spectrum

$$\sigma_{ij}(f) = \sqrt{(\mathrm{Re}\,[\sigma_{ij}(f)]_{T_{mp},m,p})^2 + (\mathrm{Im}\,[\sigma_{ij}(f)]_{T_{mp},m,p})^2}. \tag{7}$$

The $\sigma_{ij}(f)$ function takes the values from 0 to 1, containing the information about the degree of phase coherence of the two signals $x_i(t)$ and $x_j(t)$ for the particular frequency. There $\sigma_{ij}(f) = 0$ implies that there is no phase coherence at the current frequency, while for $\sigma_{ij}(f) > 0$ coherence takes place.

Obtained values (7) were then averaged over EEG frequency bands. As the result, coefficients $\sigma_{ij}(s)$, defined the coherence between EEG signals in six typical EEG frequency bands ($\Delta f = \delta, \theta, \alpha, \beta_1, \beta_2, \gamma$):

$$\sigma_{ij}(\Delta f) = \int\limits_{\Delta f} \sigma(f)\,df. \tag{8}$$

4. RESULTS

Using the wavelet bicoherence technique, the degree of synchronization between different EEG channels is evaluated for two different stages of the experiment: the active phase and the rest phase between the tests. Fig. 2 illustrates the most typical connections between channels for two stages of an experiment for all six frequency bands ($\Delta f = \delta, \theta, \alpha, \beta_1, \beta_2, \gamma$). For the active phase of the experiment, the most typical situation is the presence of the greatest synchronization between the channels in the right hemisphere of the subject's brain in three frequency ranges: β_1, β_2, γ. For the passive phase, on the contrary, the most typical is synchronization between the channels of the left hemisphere of the brain, and this synchronization is manifested in the following frequency ranges: $\alpha, \beta_1, \beta_2, \gamma$.

In order to assess the degree of synchronization between different channels in a certain area, the simplest and most obvious way is to determine the average value of the coupling coefficient between the channels in a given area. Figure 3 shows the average value of the coupling coefficient in the frequency range β_2 in different areas of the brain: the frontal part, the occipital part, the right hemisphere, the left hemisphere. This figure illustrates well that during the active phase of the experiment, the right hemisphere channels demonstrate an increase in the degree of synchronization between themselves, while during the passive phase the degree of synchronization in this hemisphere falls, which suggests that this hemisphere during the solution task plays a decisive role. At the same time, the left hemisphere of the subject's brain demonstrates the opposite dynamics, that is, during the passive phase, an increase in the degree of synchronization between the channels of this area is observed, and during the active phase, the degree of synchronization decreases, this behavior indicates that this area of ??the brain is responsible for the restoration individual in front of the next task. In addition, a slight increase in the degree of synchronization between the channels of the occipital region is observed during the active phase of the experiment, this effect is due to the fact that the subject actively perceives visual information (Schulte tables) (see Fig. 3).

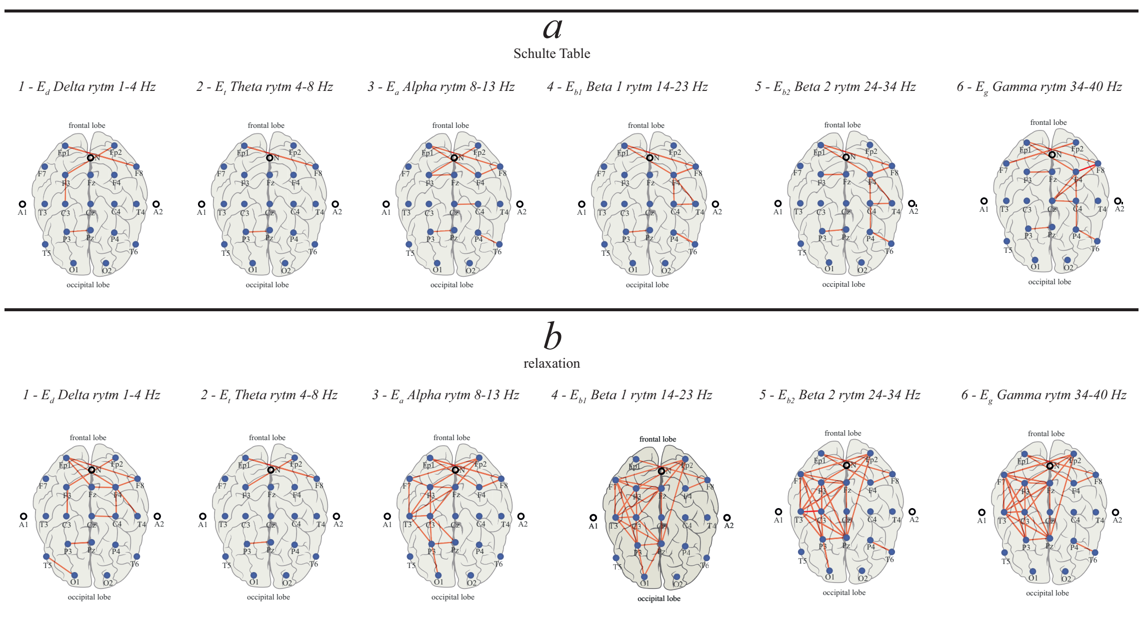

Figure 2. The results of the evaluation of the connection between the channels in different frequency ranges (alpha, beta-1, beta-2, theta, gamma, delta ranges) with the degree of synchronization $\sigma \in [0.9; 1]$. (a) - active the phase of the experiment, the subject performs the test with Schulte's tables, (b) - the rest phase

5. CONCLUSION

In this work, we describe method for estimation of the degree of synchronization between the EEG channel based on wavelet bicoherence during the subjects passing of the attention function evaluation (Schulte table). During work we found that the active phase of the experiment with Schulte tables most typical is the synchronization between channels in the right hemisphere of three frequency bands $(\beta_1, \beta_2, \gamma)$ and for the rest phase is typical synchronization between the channels of the left hemisphere in other frequency ranges $(\alpha, \beta_1, \beta_2, \gamma)$. In addition, in this work suggested to carry out the averaging coefficient synchronization between channels of EEG brain areas. It is shown that such averaging allows you to quite simply and clearly identify areas of the brain in which the degree of synchronization between the channel for each phase of the experiment increases or decreases.

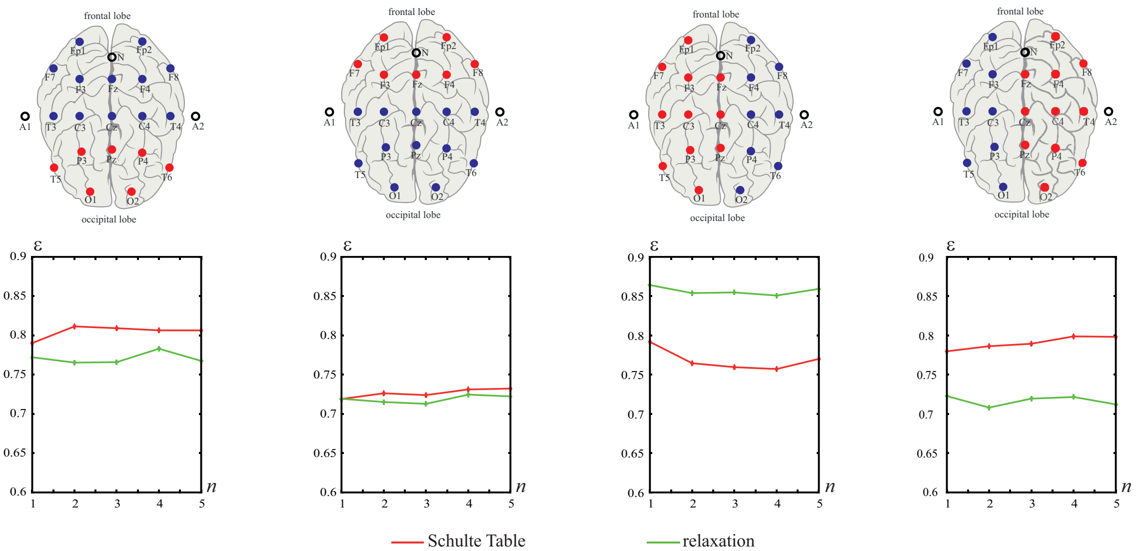

Figure 3. The dependence of the coefficient ϵ degree of synchronization between channels in different areas of the brain of the test during the passage of the test with the Schulte tables and during the rest phase between tests

6. ACKNOWLEDGMENTS

This work has been supported by the grant of the President of Russian Federation for the Leading Scientific Schools of Russia (NSh-2737.2018.2) the part of experimental studies. Study of the neurophysiological processes in human brain has been supported the Russian Foundation for Basic Research (Grant No. 19-32-80036).

REFERENCES

[1] D'esposito, M. and Postle, B. R., "The cognitive neuroscience of working memory," *Annual review of psychology* **66** (2015).

[2] Poldrack, R. A. and Yarkoni, T., "From brain maps to cognitive ontologies: informatics and the search for mental structure," *Annual review of psychology* **67**, 587–612 (2016).

[3] Li, Y., Cao, D., Wei, L., Tang, Y., and Wang, J., "Abnormal functional connectivity of eeg gamma band in patients with depression during emotional face processing," *Clinical neurophysiology* **126**(11), 2078–2089 (2015).

[4] Waninger, S., Berka, C., Meghdadi, A., Karic, M. S., Stevens, K., Aguero, C., Sitnikova, T., Salat, D. H., and Verma, A., "Event-related potentials during sustained attention and memory tasks: Utility as biomarkers for mild cognitive impairment," *Alzheimer's & Dementia: Diagnosis, Assessment & Disease Monitoring* (2018).

[5] Chiang, H.-S., Mudar, R. A., Pudhiyidath, A., Spence, J. S., Womack, K. B., Cullum, C. M., Tanner, J. A., Eroh, J., Kraut, M. A., and Hart Jr, J., "Altered neural activity during semantic object memory retrieval in amnestic mild cognitive impairment as measured by event-related potentials," *Journal of Alzheimer's Disease* **46**(3), 703–717 (2015).

[6] Maksimenko, V. A., Runnova, A. E., Zhuravlev, M. O., Protasov, P., Kulanin, R., Khramova, M. V., Pisarchik, A. N., and Hramov, A. E., "Human personality reflects spatio-temporal and time-frequency eeg structure," *PloS one* **13**(9), e0197642 (2018).

[7] Hong, K.-S., Naseer, N., and Kim, Y.-H., "Classification of prefrontal and motor cortex signals for three-class fnirs–bci," *Neuroscience letters* **587**, 87–92 (2015).

[8] Maksimenko, V. A., Runnova, A. E., Zhuravlev, M. O., Makarov, V. V., Nedayvozov, V., Grubov, V. V., Pchelintceva, S. V., Hramov, A. E., and Pisarchik, A. N., "Visual perception affected by motivation and alertness controlled by a noninvasive brain-computer interface," *PloS one* **12**(12), e0188700 (2017).

[9] Maksimenko, V., Badarin, A., Nedaivozov, V., Kirsanov, D., and Hramov, A., "Brain-computer interface on the basis of eeg system encephalan," in [*Saratov Fall Meeting 2017: Laser Physics and Photonics XVIII; and Computational Biophysics and Analysis of Biomedical Data IV*], **10717**, 107171R, International Society for Optics and Photonics (2018).

[10] Jeunet, C., N'Kaoua, B., Subramanian, S., Hachet, M., and Lotte, F., "Predicting mental imagery-based bci performance from personality, cognitive profile and neurophysiological patterns," *PloS one* **10**(12), e0143962 (2015).

[11] Klimesch, W., "Eeg alpha and theta oscillations reflect cognitive and memory performance: a review and analysis," *Brain research reviews* **29**(2-3), 169–195 (1999).

[12] Zoefel, B., Huster, R. J., and Herrmann, C. S., "Neurofeedback training of the upper alpha frequency band in eeg improves cognitive performance," *Neuroimage* **54**(2), 1427–1431 (2011).

[13] Makarov, V. V., Zhuravlev, M. O., Runnova, A. E., Protasov, P., Maksimenko, V. A., Frolov, N. S., Pisarchik, A. N., and Hramov, A. E., "Betweenness centrality in multiplex brain network during mental task evaluation," *Physical Review E* **98**(6), 062413 (2018).

[14] van Milligen, B. P., Sánchez, E., Estrada, T., Hidalgo, C., Brãnas, B., Carreras, B., and Garsia, L., "Wavelet bicoherence: A new turbulence analysis tool," *Physics of Plasmas* **2**(8), 3017–3032 (1995).

[15] Koronovskii, A. A. and Hramov, A. E., "Wavelet bicoherence analysis as a method for investigating coherent structures in an electron beam with an overcritical current," *Plasma Physics Reports* **28**(8), 666 (2002).

[16] Schiecke, K., Wacker, M., Benninger, F., Feucht, M., Leistritz, L., and Witte, H., "Matching pursuit-based time-variant bispectral analysis and its application to biomedical signals," *IEEE Transactions on Biomedical Engineering* **62**(8), 1937–1948 (2015).

[17] 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).

[18] Sheppard, L. W., Vuksanović, V., McClintock, P., and Stefanovska, A., "Oscillatory dynamics of vasoconstriction and vasodilation identified by time-localized phase coherence," *Physics in Medicine & Biology* **56**(12), 3583 (2011).

[19] Le Van Quyen, M., Foucher, J., Lachaux, J.-P., Rodriguez, E., Lutz, A., Martinerie, J., and Varela, F. J., "Comparison of hilbert transform and wavelet methods for the analysis of neuronal synchrony," *Journal of neuroscience methods* **111**(2), 83–98 (2001).

[20] Sakkalis, V., "Review of advanced techniques for the estimation of brain connectivity measured with eeg/meg," *Computers in biology and medicine* **41**(12), 1110–1117 (2011).

[21] Maksimenko, V. A., Lüttjohann, A., Makarov, V. V., Goremyko, M. V., Koronovskii, A. A., Nedaivozov, V., Runnova, A. E., van Luijtelaar, G., Hramov, A. E., and Boccaletti, S., "Macroscopic and microscopic spectral properties of brain networks during local and global synchronization," *Phys. Rev. E* **96**, 012316 (Jul 2017).

[22] Maksimenko, V. A., Runnova, A. E., Frolov, N. S., Makarov, V. V., Nedaivozov, V., Koronovskii, A. A., Pisarchik, A., and Hramov, A. E., "Multiscale neural connectivity during human sensory processing in the brain," *Phys. Rev. E* **97**, 052405 (May 2018).

[23] Maksimenko, V., Makarov, V., and Goremyko, M., "Study of the interactions in neural ensemble of the brain using wavelet analysis," in [*Dynamics and Fluctuations in Biomedical Photonics XV*], **10493**, 104931I, International Society for Optics and Photonics (2018).

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

[25] 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).

[26] Bandrivskyy, A., Bernjak, A., McClintock, P., and Stefanovska, A., "Wavelet phase coherence analysis: application to skin temperature and blood flow," *Cardiovascular engineering: an international journal* **4**(1), 89–93 (2004).