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Fatigue-related reconfiguration of the functional network of the brain during cognitive load

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ABSTRACT

In this paper, we investigated the fatigue-related processes of reconfiguring the human brain functional network while solving the cognitive task. We analyzed the correlations between the psychophysiological state of the subject with the characteristics of neural activity. We found that the subject's fatigue positively correlates with the average degree of functional connectivities between neural ensembles in the beta and alpha frequency ranges. The obtained results indicate the increase in the integrative processes of a functional neural network. We revealed that the increasing fatigue during the experiment does not decrease the efficiency of the task completion: the speed and correctness of responses do not change. This suggests that functional integration may reflect the optimization of the brain's neural network during the experiment.

Keywords: Functional brain network, cognitive fatique, EEG, integrative processes, Sternberg paradigm, source localization

1. INTRODUCTION

At present, an actual problem in neuroscience is the development of brain-computer interfaces to control the human state in the process of solving cognitive tasks.[1–4] In particular, such technology seems to allow increasing the efficiency of learning new information by optimizing of the educational load, taking into account the individual psychophysiological characteristics of a subject, his/her cognitive state, and memory characteristics.[5–8] This direction is actively developing in world science.[9–13] A bulk of works aim to identify neurophysiological markers that characterize the efficiency of the human brain operation in the perception and assimilation of information and the efficiency of memory.[14–16] The properties of the time-frequency and space-time structure of the signals of brain activity neurovisualization were analyzed using artificial intelligence methods and statistical analysis in these works.[17–22] Nevertheless, the specific mechanisms of neural activity that determine the formation of the corresponding patterns are not considered in detail usually. As a consequence, the developed approaches are the subject-specific and there are instability of their operation due to the variability of the neural activity properties that are influenced by external and internal factors. Moreover, the relationship between a person's cognitive state (especially fatigue level) and the neural processes that determine memory efficiency in retaining new information remains poorly understood.

In this paper, we investigate the fatigue-related processes of reconfiguring the human brain functional network while solving the cognitive task using the Sternberg paradigm and analyze the correlations between the psychophysiological state of the subject with the characteristics of neural activity.

2. METHODS

The experimental design was based on the Sternberg paradigm. This test allows one to explore information-processing mechanisms in short-term memory.[23] The main part of the experiment begins and ends by recording the background activity for 60 s and consists of four blocks of tasks (see Fig. 1a). Each block in the main part consists of 72 trials. It was necessary to complete the task in the form of the Sternberg test within every trial. The experimental studies involved 17 student volunteers (11 males and 6 females, mean age – 20 years). All

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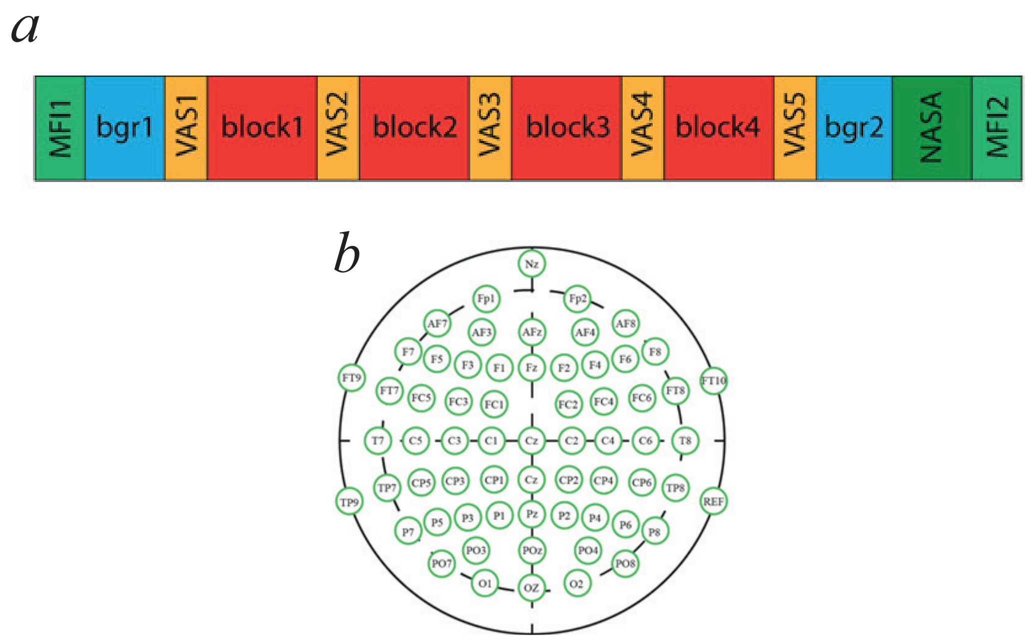

Figure 1. (a) The general scheme of the experimental study: the main part, consisting of four blocks of tasks (block1–4 or time intervals T1–T4); background activity at the beginning and the end of the main part (bgr1 and bgr2); NASA TLX test (NASA); two MFI tests (MFI1 and MFI2); subjective visual assessment of fatigue (VAS 1-5). (b) Scheme of EEG electrodes arrangement on the subject's head based on "10-1" scheme; Nz – grounding, REF – referent.

volunteers were asked to adhere to a healthy lifestyle within 48 hours before the experiment: ensure at least 8 hours of sleep, eliminate alcohol consumption, eliminate or limit consumption of caffeine-containing foods, and avoid excessive physical exertion. The volunteers were familiarized with the experimental procedure in advance and were aware of the possible inconveniences associated with participating in the experiment. Also, they had the opportunity to ask questions of interest and get satisfactory answers to them. Each volunteer completed and signed an informed consent form for participation in the experiment. All experimental works were carried out in accordance with the requirements of the Declaration of Helsinki and approved by the Ethics Commission of Innopolis University.

The subject sat in a specialized chair for carrying out neurophysiological experiments. There was a monitor on the table in front of him (distance from the screen to the eyes 90 cm; monitor resolution 1920 x 1080). A mouse and two one-button remote controls were used as input devices. The monitor was used to demonstrate tests and tasks, while input devices were used to record the subject's responses. The duration of each experiment was about 60-65 minutes. The electrical activity of the brain was recorded using actiCHamp electroencephalograph (Brain Products, Germany) during the experiment. EEG signals were recorded with 63 channels following the 10-10 scheme (see Fig. 1b). The ground (Nz) was located at the location of the Fpz electrode, and the reference electrode (REF) was placed behind the right ear. For EEG registration, active Ag/AgCl electrodes ActiCAP were used, which were located on the scalp surface in the sockets of a special EasyCAP cap. The scalp was pretreated with NuPrep abrasive gel to improve signal quality and provide better conductivity, and then the electrodes were positioned using SuperVisc conductive gel.

EEG signals were recorded with a sampling rate of 1 kHz and filtered using bandpass (1-70 Hz) and notch (49.5-50.5 Hz) filters. The bandpass filter limits the considered frequency range on the EEG signals and removes low-frequency and high-frequency activities not associated with the EEG. The notch filter removes 50 Hz interference from the power grid. Eyes blinking and heartbeat artifacts removal was performed by the Independent Component Analysis (ICA). Data was then inspected visually and corrected for remaining artifacts.

Functional connectivities in the cortical network of the brain were determined in the source space.[24,25] For

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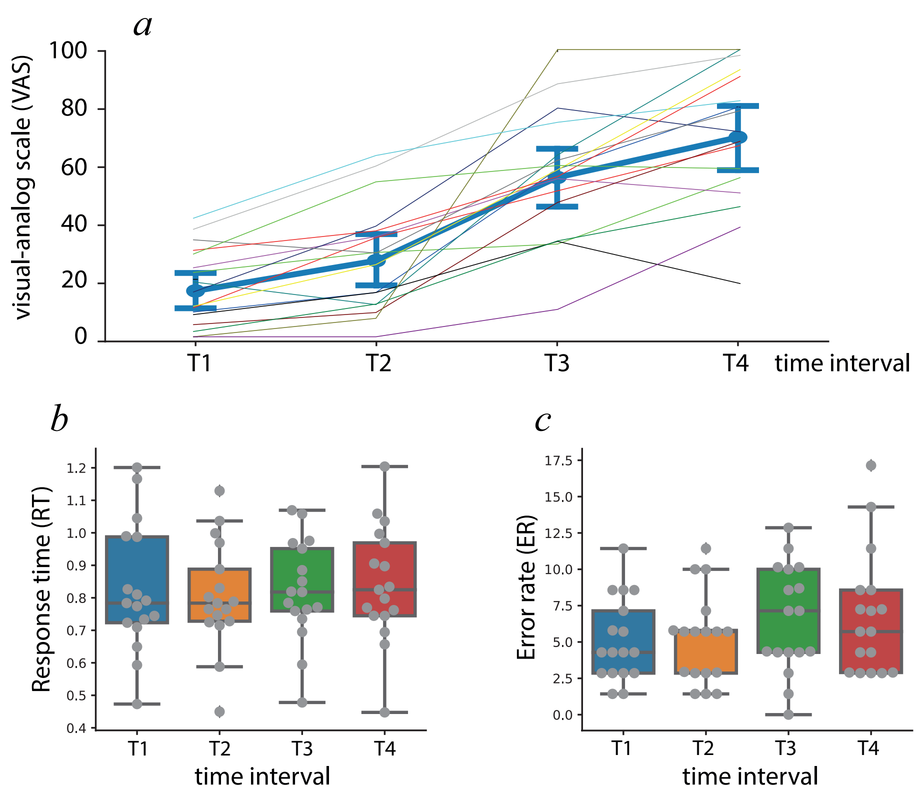

Figure 2. (*a*) Changes in the results of subjective fatigue assessment using the visual-analog scale (VAS) test during the experiment. Data are shown for each subject, as well as the group mean and the 95% confidence interval. (*b*) The change throughout the experiment (T1–T4) in the RT time taken by the subject to respond. (*c*) The change in the error rate (ER) of the subject throughout the experiment (T1–T4).

sources localization, the partial canonical coherence (PCC) method, which works in the frequency domain, was applied.[26] Solving such inverse problems is typical in many areas of physics.[27–31] We used FieldTrip software for sources localization.[32] Coherence was used as a measure to estimate the strength of the connectivity between sources,[33] which allows excluding the false connections caused by the field spread effect. Thus, the matrix of connectivities between all dipoles (voxels) in the brain volume was determined at the first stage. A parcellation procedure was then performed using the AAL brain atlas,[34] which calculated a 116x116 matrix containing measures of functional connections between 116 anatomical brain regions. We analyzed not the absolute values of the coherences but their change (difference) relative to the matrices of connectivities corresponding to the background recordings in the subject's resting state. A network modification of nonparametric cluster testing was used to identify significant functional connectivities (significantly changing between the conditions under consideration),[35] and also the approach based on false discovery rate,[36] which allows solving the problem of multiple comparisons on network-level effectively. The strength of connectivities was averaged over all connections belonging to the corresponding revealed cluster or over the group of subjects to analyze the direction of effect between conditions.

The result of psychological testing of fatigue (VAS) was considered subjective assessment of a person's psychophysiological state. The response time (RT) and error rate (ER) of subjects on test tasks were considered characteristics of information perception efficiency. Correlation analysis was performed using the method of repeated measures correlations.[37] The correlation coefficient, statistic value, and confidence interval limits were calculated for each case.

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3. RESULTS

Analysis of VAS results in the group of subjects showed that fatigue changes significantly during the experiment: $F(3, 48) = 49.298$, $p < 0.001^*$ (based on the results of ANOVA analysis of variance). The results are shown in Fig. 2a. Thus, the subjects reported an increase in fatigue by the end of the experiment. RT and ER of the subjects' answers remained unchanged during the experiment (Fig. 2b,c).

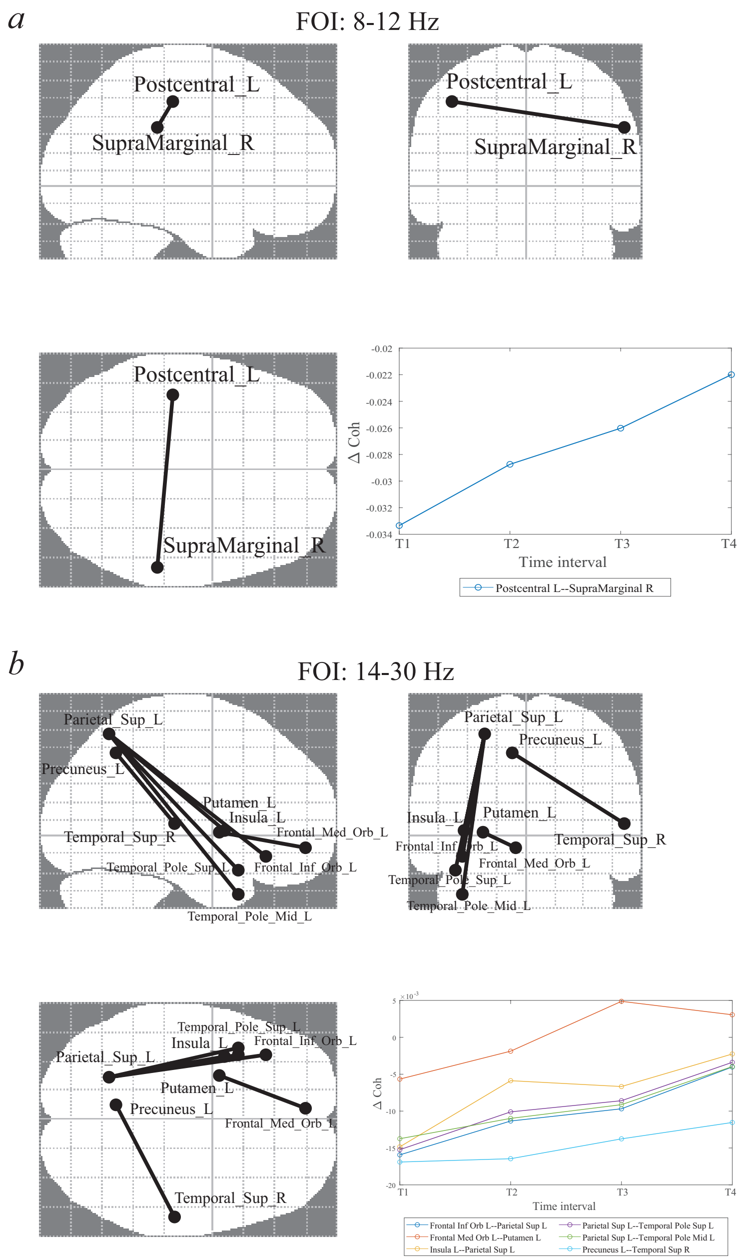

Figure 3. Illustration of functional connectivities in coronal, axial, and sagittal brain projections revealed by a statistical test in the alpha frequency range (8-12 Hz) (Fig. *a*) and beta frequency range (14-30 Hz) (Fig. *b*); connectivities change significantly between 4 time intervals T1-T4. The lower right corner shows the dependence of the change in the measure (coherence) of the detected connectivities between the corresponding time interval and the resting state.

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To reveal processes of reconfiguration of the brain's functional network, associated with the influence of internal factors, we analyzed the change of connectivities in the functional network on 4 intervals, preceding the presentation of the material. The statistical test revealed functional connectivity in the alpha range (8-12 Hz) that significantly changes between the 4 intervals: Postcentral L-SupraMarginal R (see Fig. 3a). The coherence of this connectivity increases with increasing interval number (Fig. 3a). In the beta range (14-30 Hz), the statistical test revealed the following functional connectivities, which change significantly between the T1-T4 time intervals: Precuneus L-Temporal Sup R, Parietal Sup L-Temporal Pole Mid L, Parietal Sup L-Temporal Pole Sup L, Insula L-Parietal Sup L, Frontal Med Orb L-Putamen L, Frontal Inf Orb L-Parietal Sup L (see Fig. 3b). The coherence of these connectivities significantly increases with increasing interval number (Fig. 3b).

Note that the sign of the coherence change (ΔCoh) is negative for all intervals for almost all connections. This corresponds to a decrease in the strength of the connectivities in the considered interval in relation to the background activity or, in other words, to the process of segregation between network elements. However, the absolute value of ΔCoh decreases with increasing interval number, which indicates the weakening of segregation over time. Moreover, ΔCoh for the Frontal Med Orb L-Putamen L connection in the beta range becomes positive starting from T3. This indicates the development of an integration process between the corresponding brain regions.

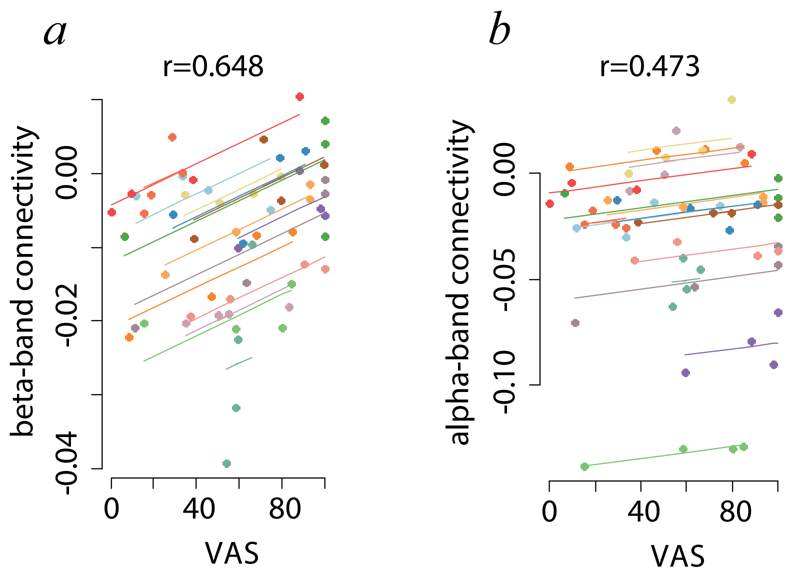

Figure 4. Results of analysis of correlations between psychophysiological state of the subject (level of fatigue according to VAS) and revealed characteristics of neuronal activity (measure of connectivity in alpha (a) and beta (b) frequency ranges).

An analysis of the correlations between the subject's psychophysiological state and the detected characteristics of neural activity resulted in the following. Subject fatigue positively correlates with the average degree of functional connectivity between neural ensembles in the beta range: $r(44) = 0.6483324$, $p = 1.105724e-06$, 95% confidence interval [0.4352224 0.7926464] (Fig. 4a). Subject fatigue positively correlates with the average degree of functional connectivity between neural ensembles in the alpha range: $r(44) = 0.4736535$, $p = 0.0008846606$, 95% confidence interval [0.2056981 0.6755404] (Fig. 4b). The results indicate an increase in the integrative properties of the functional neural network. The fact that increasing fatigue during the experiment does not lead to a decrease in task performance (speed and correctness of answers does not change) suggests that functional integration may reflect optimization of the brain's neural network during the experiment.

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4. CONCLUSION

We revealed that the subject's fatigue positively correlates with the average degree of functional connectivities between neural ensembles in the beta and alpha frequency ranges. The obtained results indicate the increase in the integrative processes of the functional neural network. We revealed that the increasing fatigue during the experiment does not decrease the efficiency of the task completion: the speed and correctness of responses do not change. This suggests that functional integration may reflect optimizing the brain's neural network during the experiment.

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REFERENCES

[1] Hramov, A. E., Maksimenko, V. A., and Pisarchik, A. N., "Physical principles of brain-computer interfaces and their applications for rehabilitation, robotics and control of human brain states," *Physics Reports* (2021).

[2] Frolov, N. S., Pitsik, E. N., Maksimenko, V. A., Grubov, V. V., Kiselev, A. R., Wang, Z., and Hramov, A. E., "Age-related slowing down in the motor initiation in elderly adults," *Plos one* **15**(9), e0233942 (2020).

[3] Maksimenko, V. A., Kuc, A., Frolov, N. S., Khramova, M. V., Pisarchik, A. N., and Hramov, A. E., "Dissociating cognitive processes during ambiguous information processing in perceptual decision-making," *Frontiers in Behavioral Neuroscience* **14**, 95 (2020).

[4] Pisarchik, A. N., Maksimenko, V. A., and Hramov, A. E., "From novel technology to novel applications: Comment on "an integrated brain-machine interface platform with thousands of channels" by elon musk and neuralink," *Journal of medical Internet research* **21**(10), e16356 (2019).

[5] Knyazev, G., Merkulova, E., Savostyanov, A., Bocharov, A., and Saprigyn, A., "Personality and eeg correlates of reactive social behavior," *Neuropsychologia* **124**, 98–107 (2019).

[6] Ko, L.-W., Komarov, O., Hairston, W. D., Jung, T.-P., and Lin, C.-T., "Sustained attention in real classroom settings: An eeg study," *Frontiers in human neuroscience* **11**, 388 (2017).

[7] Kuc, A., Grubov, V. V., Maksimenko, V. A., Shusharina, N., Pisarchik, A. N., and Hramov, A. E., "Sensor-level wavelet analysis reveals eeg biomarkers of perceptual decision-making," *Sensors* **21**(7), 2461 (2021).

[8] Frolov, N. S., Maksimenko, V. A., Khramova, M. V., Pisarchik, A. N., and Hramov, A. E., "Dynamics of functional connectivity in multilayer cortical brain network during sensory information processing," *The European Physical Journal Special Topics* **228**(11), 2381–2389 (2019).

[9] Maksimenko, V., Kuc, A., Frolov, N., Kurkin, S., and Hramov, A., "Effect of repetition on the behavioral and neuronal responses to ambiguous necker cube images," *Scientific Reports* **11**(1), 1–13 (2021).

[10] Ponomarenko, V., Kulminskiy, D., Andreev, A., and Prokhorov, M., "Assessment of an external periodic force amplitude using a small spike neuron network in a radiophysical experiment," *Technical Physics Letters* **47**(2), 162–165 (2021).

[11] Grigorev, N., Savosenkov, A., Lukoyanov, M., Udoratina, A., Shusharina, N., Kaplan, A., Hramov, A., Kazantsev, V., and Gordleeva, S., "A bci-based vibrotactile neurofeedback training improves motor cortical excitability during motor imagery," *bioRxiv* (2021).

[12] Wang, W., He, C., Wang, Z., Hramov, A., Fan, D., Yuan, M., Luo, X., and Kurths, J., "Dynamic analysis of synaptic loss and synaptic compensation in the process of associative memory ability decline in alzheimer's disease," *Applied Mathematics and Computation* **408**, 126372 (2021).

[13] Pavlov, A., Pitsik, E., Guyo, G., Frolov, N., Grubov, V., Pavlova, O., Wang, Z., and Hramov, A., "Effects of healthy aging on electrical activity of the brain during motor tasks characterized with wavelets," *The European Physical Journal Plus* **136**(4), 1–11 (2021).

[14] Aricò, P., Borghini, G., Di Flumeri, G., Sciaraffa, N., and Babiloni, F., "Passive bci beyond the lab: current trends and future directions," *Physiological measurement* **39**(8), 08TR02 (2018).

[15] Chholak, P., Maksimenko, V. A., Hramov, A. E., and Pisarchik, A. N., "Voluntary and involuntary attention in bistable visual perception: A meg study," *Frontiers in Human Neuroscience* **14**, 555 (2020).

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[16] Maksimenko, V. A., Frolov, N. S., Hramov, A. E., Runnova, A. E., Grubov, V. V., Kurths, J., and Pisarchik, A. N., "Neural interactions in a spatially-distributed cortical network during perceptual decision-making," *Frontiers in behavioral neuroscience* **13**, 220 (2019).

[17] Chholak, P., Pisarchik, A. N., Kurkin, S. A., Maksimenko, V. A., and Hramov, A. E., "Phase-amplitude coupling between mu-and gamma-waves to carry motor commands," in [*2019 3rd School on Dynamics of Complex Networks and their Application in Intellectual Robotics (DCNAIR)*], 39–45, IEEE (2019).

[18] Kurkin, S., Pitsik, E., and Frolov, N., "Artificial intelligence systems for classifying eeg responses to imaginary and real movements of operators," in [*Saratov Fall Meeting 2018: Computations and Data Analysis: from Nanoscale Tools to Brain Functions*], **11067**, 1106709, International Society for Optics and Photonics (2019).

[19] Andreev, A. V., Runnova, A. E., and Pisarchik, A. N., "Numerical simulation of coherent resonance in a model network of rulkov neurons," *Proc. SPIE* **10717**, 107172E (2018).

[20] Kuc, A., Korchagin, S., Maksimenko, V. A., Shusharina, N., and Hramov, A. E., "Combining statistical analysis and machine learning for eeg scalp topograms classification," *Frontiers in Systems Neuroscience* **15** (2021).

[21] Frolov, N., Kabir, M. S., Maksimenko, V., and Hramov, A., "Machine learning evaluates changes in functional connectivity under a prolonged cognitive load," *Chaos: An Interdisciplinary Journal of Nonlinear Science* **31**(10), 101106 (2021).

[22] Pitsik, E., Frolov, N., Hauke Kraemer, K., Grubov, V., Maksimenko, V., Kurths, J., and Hramov, A., "Motor execution reduces eeg signals complexity: Recurrence quantification analysis study," *Chaos: An Interdisciplinary Journal of Nonlinear Science* **30**(2), 023111 (2020).

[23] Pelosi, L., Hayward, M., and Blumhardt, L., "Is "memory-scanning" time in the sternberg paradigm reflected in the latency of event-related potentials?," *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section* **96**(1), 44–55 (1995).

[24] Schoffelen, J.-M. and Gross, J., "Source connectivity analysis with meg and eeg," *Human brain mapping* **30**(6), 1857–1865 (2009).

[25] Kurkin, S., Hramov, A., Chholak, P., and Pisarchik, A., "Localizing oscillatory sources in a brain by meg data during cognitive activity," in [*2020 4th International Conference on Computational Intelligence and Networks (CINE)*], 1–4, IEEE (2020).

[26] Grech, R., Cassar, T., Muscat, J., Camilleri, K. P., Fabri, S. G., Zervakis, M., Xanthopoulos, P., Sakkalis, V., and Vanrumste, B., "Review on solving the inverse problem in eeg source analysis," *Journal of neuroengineering and rehabilitation* **5**(1), 1–33 (2008).

[27] Frolov, N. S., Kurkin, S. A., Koronovskii, A. A., and Hramov, A. E., "Nonlinear dynamics and bifurcation mechanisms in intense electron beam with virtual cathode," *Physics Letters A* **381**(28), 2250–2255 (2017).

[28] Kurkin, S., Hramov, A., and Koronovskii, A., "Nonlinear dynamics and chaotization of virtual cathode oscillations in annular electron beam in uniform magnetic field," *Plasma Phys. Rep* **35**(8), 628–642 (2009).

[29] Kurkin, S., Koronovskii, A., and Hramov, A., "Formation and dynamics of a virtual cathode in a tubular electron beam placed in a magnetic field," *Technical Physics* **54**(10), 1520–1528 (2009).

[30] Dubinov, A. E., Petrik, A. G., Kurkin, S. A., Frolov, N. S., Koronovskii, A. A., and Hramov, A. E., "Virpertron: A novel approach for a virtual cathode oscillator design," *Physics of Plasmas* **24**(7), 073102 (2017).

[31] Kurkin, S., Koronovskii, A., and Hramov, A., "Output microwave radiation power of low-voltage vircator with external inhomogeneous magnetic field," *Technical Physics Letters* **37**(4), 356–359 (2011).

[32] Oostenveld, R., Fries, P., Maris, E., and Schoffelen, J.-M., "Fieldtrip: open source software for advanced analysis of meg, eeg, and invasive electrophysiological data," *Computational intelligence and neuroscience* **2011** (2011).

[33] Bastos, A. M. and Schoffelen, J.-M., "A tutorial review of functional connectivity analysis methods and their interpretational pitfalls," *Frontiers in systems neuroscience* **9**, 175 (2016).

[34] Tzourio-Mazoyer, N., Landeau, B., Papathanassiou, D., Crivello, F., Etard, O., Delcroix, N., Mazoyer, B., and Joliot, M., "Automated anatomical labeling of activations in spm using a macroscopic anatomical parcellation of the mni mri single-subject brain," *Neuroimage* **15**(1), 273–289 (2002).

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[35] Zalesky, A., Fornito, A., and Bullmore, E. T., "Network-based statistic: identifying differences in brain networks," *Neuroimage* **53**(4), 1197–1207 (2010).

[36] Genovese, C. R., Lazar, N. A., and Nichols, T., "Thresholding of statistical maps in functional neuroimaging using the false discovery rate," *Neuroimage* **15**(4), 870–878 (2002).

[37] Bakdash, J. Z. and Marusich, L. R., "Repeated measures correlation," *Frontiers in psychology* **8**, 456 (2017).

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