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# Research of dynamic relationships in induced signals of the human brain biomagnetic activity based on the Memory Functions Formalism

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In this paper, we have shown the capabilities of the original authorś method, namely, the Memory Functions Formalism, in the analysis of dynamic relationships between the signals of biomagnetic activity of the human brain exposed to combinations of red-blue, red-green, and blue-green light. We have analyzed the effects of synchronization and statistical memory in neuromagnetic responses of different cerebral cortex areas for a group of healthy subjects. By analyzing phase portraits and power spectra of memory functions, we identified the cerebral cortex areas with the most significant response. In addition, we carried out a quantitative assessment of the effects of statistical memory in simultaneously recorded signals.

**Keywords:** physics of complex systems, Memory Functions Formalism, magnetoencephalograms, flickering stimuli, synchronization.

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The human brain is a unique complex system that is of scientific interest to those studying the processes occurring in it. Among the methods for detecting neural activity of the cerebral cortex, electroencephalography (EEG) and magnetoencephalography (MEG) may be mentioned [1]. Instrumental methods allow studying the brain functioning under generation of sensory information coming from sense organs. For instance, in the case of exposing to sound stimuli it was found out that high individuality of brain signals becomes more pronounced when subjects focus on certain tasks (compared to the state of rest) [2]. Exposure to light can also make a significant impact on the rhythmic activity of human brain. As shown in [3], higher activity of the cerebral cortex in the $\alpha$-range does not manifest itself under the exposure to blue light. Periodicity of the visual stimulus affects primarily the activity of the occipital lobe of cerebral cortex and, to a lesser extent, other cerebral cortex areas of healthy subjects [4].

High spatiotemporal accuracy of the MEG technique allows creating new methods for recording signals, for example, those exploiting a magnetometer for revealing the rhythms [5]; in addition, there are being developed approaches for analyzing MEG data from healthy people, such as the $k$-average method and linear system analysis [6,7]. Among the methods enabling spectral analysis of signal dynamics and studying its fractal characteristics, one can mention the Fourier and wavelet transforms [8]. The emergence of new methods for studying the dynamics of MEG signals allows not only revealing specific features of functioning of healthy peopleś brain, but also identifying abnormalities in brain function during nervous system diseases, such as schizophrenia and photosensitive epilepsy, by analyzing phase characteristics and cerebral cortex rhythms [9] and studying resonant and high-frequency components of signals [10].

The goal of this work was to study the dynamic relationships in the signals of the human brain biomagnetic activity which are recorded by superconducting quantum interference sensors (SQUIDs) and are induced by various flickering light combinations: red-blue, red-green and blue-green. Experimental data on brain activity were obtained through international collaboration [11]. Nine healthy volunteers took part in the study: two women and seven men (of the age ranging from 22 to 27 years). During recording the magnetoencephalograms, each volunteer continued observing a two-color light combination generated by video projectors on a special screen. First a reference signal (free a stimulus) was recorded for a short time, after which the flickering light stimulus was applied. The number of volunteers was low because of the goal of the previous study for which the experimental data was recorded [11]. In that study, a diagnostic criteria for photosensitive epilepsy was searched for based on statistical analysis of MEG signals.

Here we analyze biomedical data (MEG signals) within the framework of the authorś approach that is the Memory Functions Formalism. The approach is based on a finite-difference analogue of the Zwanzig–Mori kinetic equations [12–16]. Within the framework of the autocorrelation approach, an experimentally recorded MEG signal is considered as a multidimensional state vector obeying the motion equation presented in the discrete form. Using the Zwantzig–Mori projection technique and Gram–Schmidt orthogonalization procedure, it is possible to restrict the description [14,15].

In this work we use a Memory Functions Formalism extension to the case of cross-correlations [12,13,16] when the normalized cross-correlation function is related to statistical

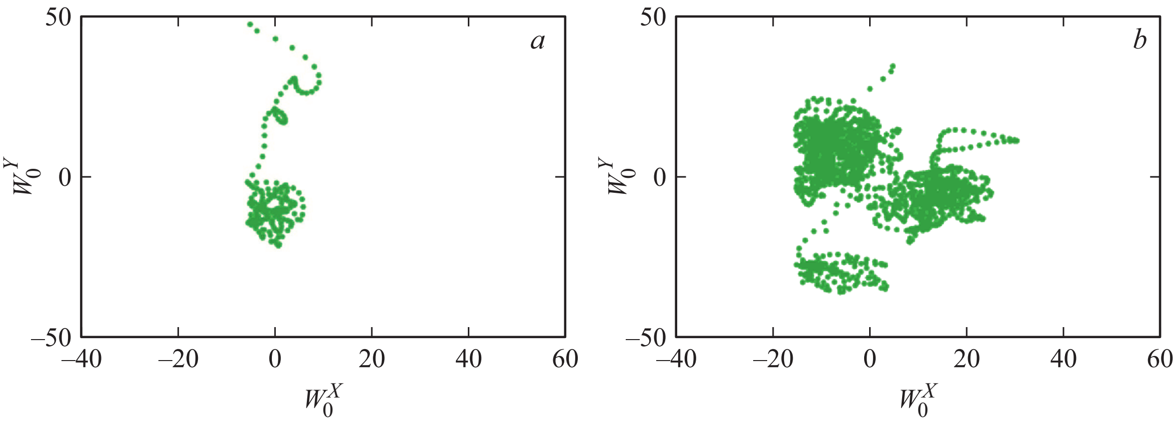


**Figure 1.** Phase portraits compiled by one of the combinations of orthogonal dynamic variables for brain signals from one of the healthy subjects before ($a$) and after ($b$) exposure to a blue-green stimulus.

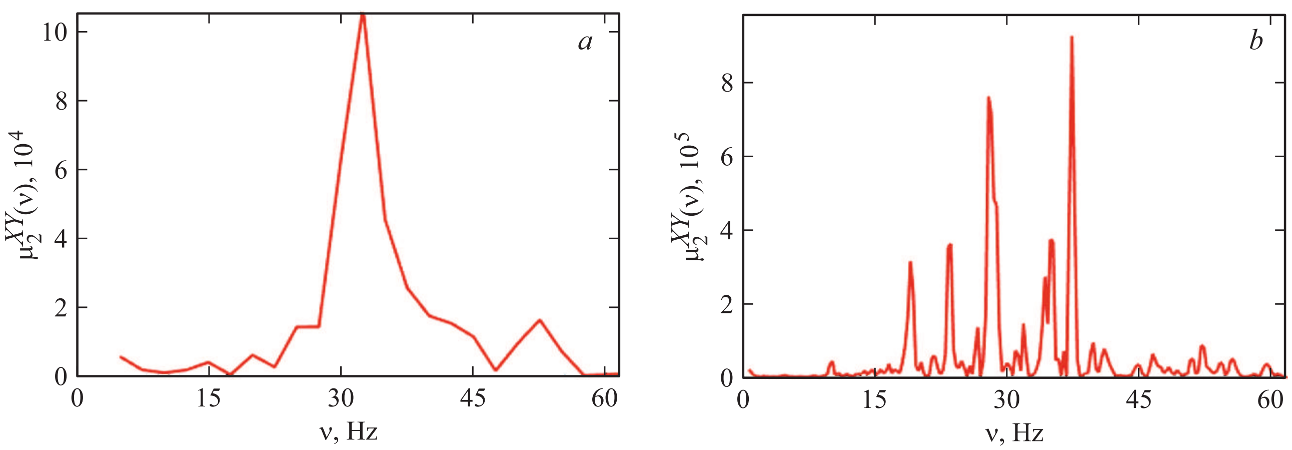


**Figure 2.** Representative power spectra of a second-order memory function. The plots are given in accordance with the conditions presented in the Fig. 1 caption.

memory functions. The calculated cross-correlation characteristics enable studying dynamic relationships between simultaneously recorded MEG signals from different areas of the human cerebral cortex exposed to flickering light stimuli.

Information on the spatiotemporal structure of the signals to be analyzed (as an example, a pair of sensors from the frontal and occipital lobes was chosen) was obtained based on phase portraits compiled by a combination of orthogonal dynamic variables [12]. Figs. 1, $a$ and $b$ show how the MEG spatiotemporal structure varies under the impact of a blue-green light stimulus. Notice an increase in spatial dimensions of the phase portrait, as well as its stratification into three unequal structures, after applying the stimulus (Fig. 1, $b$), which indicates variations in the magnetic field magnitude under external impacts. In the case of red-blue and red-green stimuli, specific features of the signal dynamics were also identified; those features led to an increase in the phase portrait spatial dimensions and stratification, typically into two structures, after applying the stimulus.

The analysis of the effects of MEG-signal matching/mismatching was performed based on studying power spectra of the relevant cross-correlation functions and memory functions [12]. Fig. 2 demonstrates representative power spectra of the second-order memory function before (Fig. 2, $a$) and after (Fig. 2, $b$) applying the blue-green stimulus. This stimulus is characterized by a pronounced synchronization over a wide frequency band. There are observed amplitude peaks at the frequencies multiple of 4 Hz, in the $\beta$- and $\gamma$-activity region, as well as a self-similar signal structure in the $\alpha$-activity region. In the case of the red-blue and red-green stimuli, synchronization was detected in $\beta$-activity and higher-frequency $\gamma$-activity in the frequency range of 20–40 Hz. Within this range, the most intense peaks are observed at the frequencies multiple to 5 Hz; these peaks are accompanied by weak bursts. In the case of the red-blue stimulus, $\alpha$-activity was not detected in the spectrum, which evidences for the existence of peculiarities in the interaction of the analyzed combination of sensors under the specified stimulus.

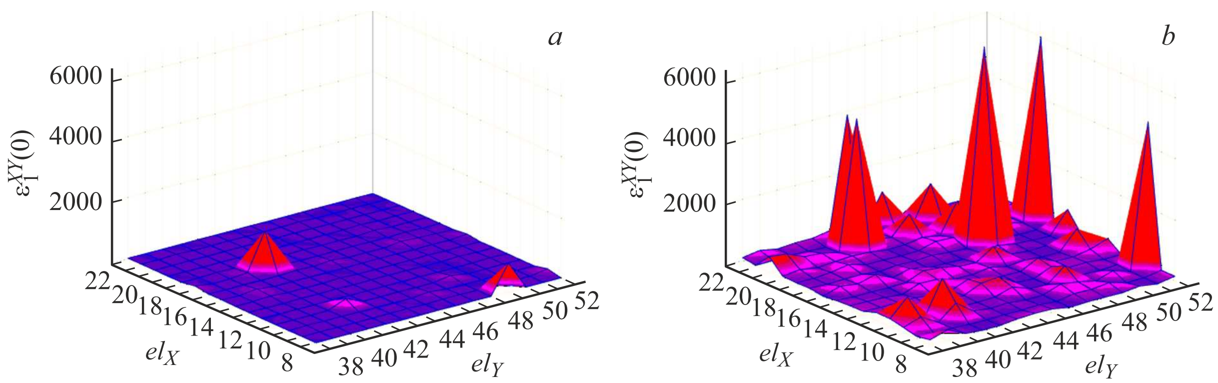


**Figure 3.** Average values of the first (zero-frequency) point of the non-Markovian parameter for combinations of sensors in the frontal and occipital lobes before ($a$) and after ($b$) applying the blue-green stimulus.

In most cases, applying a stimulus results in enhancement of the synchronization of signals recorded by different sensors. In some cases, synchronization gets weaker, which manifests itself in a decrease in intensities of the power-spectra peaks. Analysis of combinations of other sensors showed that the highest degree of synchronization takes place for signals recorded when a blue-green stimulus is applied (in 73% of cases).

Using the frequency dependence of the non-Markovian parameter, the effects of statistical memory may be quantified [12]. High values of this parameter at zero frequency evidence for short-term memory in the dynamics under study. Low values indicate the presence of non-Markovian effects with manifestation of strong (long-term) statistical memory. Fig. 3 presents average values of the first (zero-frequency) point of the non-Markovian parameter for individual combinations of sensors before (Fig. 3, $a$) and after (Fig. 3, $b$) applying the blue-green stimulus. 3D representation allows revealing what type of statistical memory manifests itself for a combination of sensors before and after applying a stimulus with a certain color combination. The blue-green stimulus initiates an increase in the number of cerebral cortex areas characterized by the Markovian dynamics. We attribute this to the fact that, against the background of resonant frequencies, a significant number of short-term overlapping dynamic low-intensity processes take place. Later on, comparing these values with those calculated for patients with pathological abnormalities in the cerebral cortex functioning will enable quantitative estimation of variations in the statistical memory effects in interactions between different areas under the impact of certain light stimuli.

In this study, we have analyzed the effects of synchronization and statistical memory in neuromagnetic responses of different cerebral cortex areas for a group of healthy subjects. The power spectra of statistical memory cross-correlation functions under various light combinations have been studied, and cerebral cortex areas with the most significant response have been identified. The structure of phase portraits, namely, spatial maps compiled for simultaneously recorded MEG signals, has been considered.

The results of studying dynamic relationships in the signals of human brain biomagnetic activity based on the Memory Functions Formalism will be of interest to researchers specializing in biophysics and physics of complex systems, neurophysiology, and cognitive psychology. Further it will be possible to relate them to the results of studying external impacts on other human brain functions, such as decision-making, coordination, emotions, attention, memory [14].

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## Compliance with ethical standards

All the works included in the research involving human participants were carried out in accordance to the ethical standards of the national Scientific Ethics Committee and the 1964 Declaration of Helsinki with its subsequent supplements, or to similar ethical standards. The Informed Voluntary Consent concerning the experiment purpose and possible risks was obtained from each participant of the study.

## Conflict of interests

The authors declare that they have no conflict of interests.

## References


[1] L.M. Andersen, K. Jerbi, S.S. Dalal, NeuroImage, **215** (3), 116817 (2020). DOI: 10.1016/j.neuroimage.2020.116817

[2] N. Colenbier, E. Sareen, T. del-Aguila Puntas, A. Griffa, G. Pellegrino, D. Mantini, D. Marinazzo, G. Arcara, E. Amico, NeuroImage, **271**, 120021 (2023). DOI: 10.1016/j.neuroimage.2023.120021

[3] Y. Okamoto, S. Nakagawa, Int. J. Psychophysiol., **104**, 10 (2016). DOI: 10.1016/j.ijpsycho.2016.03.008
[4] Y. Zhang, Z. Zhang, L. Lei, H. Tong, F. Chen, S.T. Hou, Front. Neurosci., **15**, 777183 (2021). DOI: 10.3389/fnins.2021.777183
[5] X. Zhang, C. Chen, M. Zhang, C. Ma, Y. Zhang, H. Wang, Q. Guo, T. Hu, Z. Liu, Y. Chang, K. Hu, X. Yang, J. Neurosci. Meth., **346**, 108948 (2020). DOI: 10.1016/j.jneumeth.2020.108948
[6] A. Capilla, L. Arana, M. Garcia-Huescar, M. Melcon, J. Gross, P. Campo, NeuroImage, **258**, 119373 (2022). DOI: 10.1016/j.neuroimage.2022.119373
[7] O. Hauk, M. Stenroos, M.S. Treder, NeuroImage, **255**, 119177 (2022). DOI: 10.1016/j.neuroimage.2022.119177
[8] P. Abry, H. Wendt, S. Jaffard, G. Didier, C.R. Phys., **20** (5), 489 (2019). DOI: 10.1016/j.crhy.2019.08.005
[9] D. Bai, W. Yao, S. Wang, W. Yan, J. Wang, Biomed. Signal Process. Control, **80** (1), 104310 (2023). DOI: 10.1016/j.bspc.2022.104310
[10] S.A. Demin, V.A. Yunusov, S.F. Timashev, Proc. SPIE, **12194**, 1219402 (2022). DOI: 10.1117/12.2623095
[11] J. Bhattacharya, K. Watanabe, S. Shimojo, Int. J. Bifurc. Chaos, **14** (8), 2701 (2004). DOI: 10.1142/S0218127404010850
[12] O.Yu. Panischev, S.A. Demin, J. Bhattacharya, PhysicA.A, **389** (2), 4958 (2010). DOI: 10.1016/j.physa.2010.06.026
[13] I.G. Isaeva, O.Yu. Panischev, S.A. Demin, A.R. Ildiryakova, J. Phys.: Conf. Ser., **1697** (1), 012052 (2020). DOI: 10.1088/1742-6596/1697/1/012052
[14] V. Yunusov. S. Demin, T. Panferova, in *2021 Int. Conf. on information technology and nanotechnology (ITNT)* (IEEE, 2021), p. 1. DOI: 10.1109/ITNT52450.2021.9649294
[15] S.A. Demin, R.M. Yulmetyev, O.Yu. Panischev, P. Hänggi, PhysicA.A, **387** (8-9), 2100 (2008). DOI: 10.1016/j.physa.2007.12.003
[16] S. Demin, O. Panischev, V. Yunusov, S. Timashev, in *Studies in systems, decision and control* (Springer, Cham, 2021), vol. 350, p. 27. DOI: 10.1007/978-3-030-67892-0_3

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