Collective effects in human EEGs at cognitive activity

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Abstract. In this paper we use the Memory function formalism to study the collective phenomena in EEG signals from subjects with musical abilities (“musicians”) and from subjects with a low level of these abilities (“non-musicians”) at solving the three cognitive tasks. We have revealed the spectral features in the EEG collective dynamics of these groups, as well as sensor pairs, which have the different interaction of signals.

1. Introduction

The most important factor determining the evolution of complex systems is a presence of collective effects arising from the interaction or redistribution of certain relationships between parts of a composite object. In many cases, it is impossible to carry out the objective analysis of functioning of these systems, without taking into account group phenomena. There are different approaches to studying the collective phenomena of complex systems: frequency and phase synchronization [1, 2], stochastic synchronization [3], the “generalized synchronization” relationship [4], detrended cross correlation analysis [5]. All of them, one way or another, are connected with the research of unique features of composite objects: certain quantitative and qualitative relationships between the elements of the system, the consistency of the dynamics of components under external influences, specific phenomena of synchronization. One of the most amazing and complex objects in the functioning of which the effects of synchronization and synchronization of a large number of signals are most clearly manifested is the human brain.

In this paper we use the Memory function formalism (MFF) [6, 7] to study the collective phenomena in EEG signals from subjects with musical abilities (“musicians”) and from subjects with a low level of these abilities (“non-musicians”) at solving the three cognitive tasks.

2. Memory function formalism

Within the framework of MFF [6, 7], we consider studied time series as the sequences \( \{x_j\} \) and \( \{y_j\} \) of random values \( X \) and \( Y \):

\[
X = \{x(T), x(T + \tau), x(T + 2\tau), \ldots, x(T + (N - 1)\tau)\} = \{x_0, x_1, x_2, \ldots, x_{N-1}\},
\]

\[
Y = \{y(T), y(T + \tau), y(T + 2\tau), \ldots, y(T + (N - 1)\tau)\} = \{y_0, y_1, y_2, \ldots, y_{N-1}\}.
\]

\[
z_j = z(T + j\tau), \quad \langle Z \rangle = \frac{1}{N} \sum_{j=0}^{N-1} z_j, \quad \delta z_j = x_j - \langle Z \rangle, \quad \sigma_z^2 = \frac{1}{N} \sum_{j=0}^{N-1} \delta z_j^2.
\]
Here \( T \) is the initial time point, \( \tau \) is the time interval of signal discretisation, \( \langle X \rangle \) is the mean value of \( X \), \( \delta x_j \) is fluctuation, \( Z = X, Y \). To describe the probabilistic relations between the sequences of \( X \) and \( Y \) we use the normalized time-dependent cross correlation function (CCF):

\[
c(t = m\tau) = M_{0}^{XY}(m\tau) = \frac{1}{(N-m)\sigma_x\sigma_y} \sum_{j=0}^{N-m-1} \delta x_j \delta y_{j+m}, \tag{1}
\]

which is rewritten further as a scalar product of vectors of the initial state

\[
A_k^0 = A_k^0(0) = \{\delta x_0, \delta x_1, \ldots, \delta x_{k-1}\}, \quad B_k^0 = B_k^0(0) = \{\delta y_0, \delta y_1, \ldots, \delta y_{k-1}\}
\]

and of system state in time moment \( t \)

\[
A_{m+k}^m = A_{m+k}^m(t) = \{\delta x_m, \delta x_{m+1}, \ldots, \delta x_{m+k-1}\}
\]

\[
B_{m+k}^m = B_{m+k}^m(t) = \{\delta y_m, \delta y_{m+1}, \ldots, \delta y_{m+k-1}\}
\]

as follows:

\[
c(t) = \frac{\langle A_k^0(0)B_{m+k}^m(t) \rangle}{\langle A_k^0(0)B_k^0(0) \rangle}.
\]

Using the technique of projection operators we introduce relations for the kinetic and relaxation parameters:

\[
\lambda_n^{XY} = \frac{\langle W_{n-1}^Xn\hat{L}W_{n-1}^Y \rangle}{\langle W_{n-1}^XW_{n-1}^Y \rangle}, \quad \Lambda_n^{XY} = i\frac{\langle W_{n-1}^XW_{n-1}^Y \rangle}{\langle W_{n-1}^XW_{n-1}^Y \rangle},
\]

the dynamic orthogonal variables:

\[
W_0^X = A_0^0(0), \quad W_1^X = (i\hat{L} - \lambda_1^{XY})W_0^X, \quad W_2^X = (i\hat{L} - \lambda_2^{XY})W_1^X, \\
W_0^Y = B_0^0(0), \quad W_1^Y = (i\hat{L} - \lambda_1^{XY})W_0^Y, \quad W_2^Y = (i\hat{L} - \lambda_2^{XY})W_1^Y
\]

the memory functions of the \( n \) order:

\[
M_{n}^{XY}(t = m\tau) = \frac{\langle W_n^X \{1 + i\tau\hat{L}_{22}\}^mW_n^Y \rangle}{\langle W_n^XW_n^Y \rangle},
\]

and their power spectra:

\[
\mu_n^{XY}(\nu) = \left| \tau \sum_{j=0}^{N-1} M_{n}^{XY}(j\tau) \cos 2\pi\nu j\tau \right|^2.
\]

3. Experimental data

Eight subjects \[8\] were considered and grouped in two different sets, musicians (number of subjects = four with mean age 28.5 years, each with at least 5 years of musical training) and non-musicians (number of subjects = four with mean age 28 years with no musical training). All subjects were instructed to listen attentively for several minutes via earphones to music (two sonatas for violin and piano by Brahms and Beethoven, respectively, and French Suite No. 5 by Bach). A piece of computer music by Martin and a text of neutral content (a short story, “Versuendigung gegen die Nachwelt” by H. Weigel, read by Christiane Hoerbiger) were also presented. In addition, the subjects were asked to perform a spatial imagination task, which involves mental rotation of figures. The EEGs were recorded for 90 s with a sampling rate of 128 Hz from 19 gold-cup electrodes equally distributed over the scalp according to the so-called 10-20 system as displayed in Figure 1 with respect to the averaged signals from both ear-lobes. Moreover, periods of EEG at rest were recorded before, during and after each task. Their durations were the same as those of the musical pieces. Eyes were closed during listening to music and text. See \[8\] for detail.
4. Discussion
Analyzing the types of power spectra (Figure 2 of the initial CCF demonstrates the dominance of low-frequency dynamics during the performance of mental rotation in both groups of subjects, which indicates the absence of differences in the interaction of the cerebral cortex areas in the performance of this task. However, when listening to classical music and listening to the text, differences in the EEG are found among musicians and non-musicians for certain pairs of electrodes. These pairs are electrodes numbered 1 and 19, 1 and 12, 8 and 17 for text; 2 and 18, 7 and 19, 7 and 13 for listening to music. For the remaining pairs of electrodes, there are no significant differences in the interaction of parts of the cerebral cortex.

Figure 1. Position of the 19 electrodes and their designations according to the international 10-20 electrode placements systems

Figure 2. Types of power spectra of the initial CCF: low-frequency peak, very low frequency peak, high frequency peak, two peaks

5. Conclusion
We have studied the EEG signals of two groups of subjects: people having (“musicians”) and not having (“non-musical”) musical abilities when solving several cognitive tasks. We have revealed the spectral features in the EEG collective dynamics of these groups, as well as sensor pairs, which have the a different interaction of signals. The presented results will be of interest for biophysics, cognitive psychology, neurophysiology and other fields related to the study of amazing features of the bioelectric activity of the human brain.

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References
[1] Rosenblum M, Pikovsky A and Kurths J 1996 Phys. Rev. Lett. 76 1804
[2] Quiroga R Q, Kraskov A, Kreuz T and Grassberger P 2002 Phys. Rev. E 65 041903
[3] Afraimovich V S, Verichev N N and Rabinovich M I Izv. Vyssh. Uchebn. Zaved. Radiofiz 1986 29 1050
[4] Rulkov N F, Sushchik M M, Tsimring L S and Abarbanel H D I 1995 Phys. Rev. E 51 980
[5] Podobnik B and Stanley H E 2008 Phys. Rev. Lett. 100 084102
[6] Panischev O Yu, Demin S A and Bhattacharya J 2010 Phys. A 389 4958
[7] Demin S A, Panischev O Yu and Demina N Yu 2016 J Phys. Conf. Ser. 741 012073
[8] Bhattacharya J and Petsche H 2005 Sig. Proc. 85 2161