Frequency-phase synchronization in visually induced MEG signals of the human cerebral cortex

I G Isaeva¹, O Y Panischev, S A Demin and A R Ildiryakova
Kazan Federal University, Institute of Physics, Kazan, 420008 Russia

¹E-mail: nastyaadema@mail.ru

Abstract. In paper, using the Memory Functions Formalism, we carry out a comparative analyzing the induced neuromagnetic responses of the cerebral cortex of healthy people to the two visual flickering stimuli. At the first stage, based on the correlation coefficient, we determined the regions whose interaction (on average for the group) for different stimuli differs most strongly. Next, we analyze the phase portraits of dynamic orthogonal variables and the memory function power spectra. We have found the differences in dynamic, spectral and stochastic characteristics of the magnetoencephalogram signals of the cerebral cortex under the influence of the considered stimuli. The findings provide an opportunity for a deeper understanding of the processes of the spread of excitation in the cerebral cortex with visual stimuli.

1. Introduction

Using the analyzing methods of the frequency-phase synchronization in studying the cerebral cortex bioelectric activity allows to make the significant progress in understanding the physiological mechanisms of brain activity, and also, their abnormalities. This was also facilitated by the development of equipment, which made it possible to record increasingly weak signals. For example, using magnetoencephalography (MEG), where quantum interference devices are used, it is possible to record changes in the magnetic field up to $10^{-15}$ T/cm [1]. Such devices, as well as the modern analyzing methods for synchronization and coupling effects, provide an opportunity for a deeper understanding the processes that provide the higher nervous activity.

In paper, using the Memory Function Formalism (MFF) [2], we carry out a comparative analyzing the induced neuromagnetic responses from the cerebral cortex of healthy people to the two combinations of visual flickering stimuli. In our previous works [3, 4], the main attention was focused on studies of the photosensitive epilepsy (PSE) manifestations induced by visual stimulation. Now, the main task was to reveal the reaction mechanisms to different visual stimuli in healthy people. The Memory Function Formalism allows us to obtain dynamic, spectral, and stochastic characteristics of the studied signals, as well as to quantitatively evaluate the manifestations of statistical memory effects in them.

The evoked MEG signals induced by the color combination stimuli (Red-Blue, RB and Red-Green, RG) were recorded using the Neuromag–122 (Neuromag Ltd., Finland) using 61 SQUIDs (superconducting quantum interference device) with a sampling frequency of 500 Hz [1]. Light stimuli were generated on a special screen 80 times for 2 seconds with an interval of 3 seconds. The results of all attempts were averaged. The experiment involved 9 healthy subjects (age 22–27 years) who did not have a hereditary predisposition to epilepsy.
2. Basic relations of the Memory Function Formalism

Following [2, 4] we consider stochastic dynamics of the magnetic induction gradient, registered in two spaced brain areas as the sequences \{x_j\}, \{y_j\} of random values \(X, Y\):

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

\[
Y = \{y(T), y(T + \tau), y(T + 2\tau), \ldots, y(T + (N-1)\tau)\},
\]

where \(T\) is the initial time point, \((N-1)\tau\) is the time period of signal registration, \(\tau\) is the time interval of signal discretization.

Mean values \(\langle X \rangle, \langle Y \rangle\), fluctuations \(\delta x_j, \delta y_j\) and dispersions \(\sigma_x^2, \sigma_y^2\) for a set of random values of random variables \(X, Y\) can be written as follows:

\[
\langle X \rangle = \frac{1}{N} \sum_{j=0}^{N-1} x(T + j\tau), \quad x_j = x(T + j\tau), \quad \delta x_j = x_j - \langle X \rangle, \quad \sigma_x^2 = \frac{1}{N} \sum_{j=0}^{N-1} \delta x_j^2;
\]

\[
\langle Y \rangle = \frac{1}{N} \sum_{j=0}^{N-1} y(T + j\tau), \quad y_j = y(T + j\tau), \quad \delta y_j = y_j - \langle Y \rangle, \quad \sigma_y^2 = \frac{1}{N} \sum_{j=0}^{N-1} \delta y_j^2.
\]

To describe the probabilistic relation between the sequences of random variables \(X, Y\) we use the normalized time-dependent cross correlation function (CCF):

\[
c(t) = \frac{1}{(N-m)\sigma_x \sigma_y} \sum_{j=0}^{N-m-1} \delta x(T + j\tau) \delta y(T + (j+m)\tau),
\]

\[t = m\tau, \quad 1 \leq m \leq N - 1.\]

The memory functions \(M_{n-1}^{XY}(t)\) of a higher order, as well as the expressions for kinetic \(\lambda_n^{XY}\) and relaxation \(\Lambda_n^{XY}\) parameters are calculated on the basis of CCF:

\[
M_{n-1}^{XY}(t) = \frac{\langle W_n^{XY} \hat{L} W_{n-1}^{XY} \rangle}{\langle W_n^{XY} W_n^{XY} \rangle}, \quad \lambda_n^{XY} = \frac{\langle W_n^{XY} \hat{L} W_{n-1}^{XY} \rangle}{\langle W_n^{XY} W_n^{XY} \rangle}, \quad \Lambda_n^{XY} = i \frac{\langle W_n^{XY} W_n^{XY} \rangle}{\langle W_n^{XY} W_n^{XY} \rangle}.
\]

Here \(W_n^{X}, W_n^{Y}\) are the orthogonal dynamic variables derived by vectors of state \(A_0^0(0), B_0^0(0)\) using the recurrence relations:

\[
W_0^X = A_0^0(0), \quad W_1^X = (i\hat{L} - \lambda_1^{XY})W_0^X, \quad W_2^X = (i\hat{L} - \lambda_2^{XY})W_1^X - \Lambda_1^{XY} W_0^X - \ldots,
\]

\[
W_0^Y = B_0^0(0), \quad W_1^Y = (i\hat{L} - \lambda_1^{XY})W_0^Y, \quad W_2^Y = (i\hat{L} - \lambda_2^{XY})W_1^Y - \Lambda_1^{XY} W_0^Y - \ldots,
\]

\[
\Lambda_k^X = A_k^0(0) = \{\delta x_0, \delta x_1, \ldots, \delta x_{k-1}\},
\]

\[
\Lambda_k^Y = B_k^0(0) = \{\delta y_0, \delta y_1, \ldots, \delta y_{k-1}\},
\]

\(\hat{L}\) - Liouville's quasioperator.

The power spectra of memory functions are used for frequency-phase synchronization analysis:

\[
\mu_0^{XY}(v) = \left| \Delta t \sum_{j=0}^{N-1} c(t_j) \cos 2\pi v t_j \right|^2, \quad \ldots, \quad \mu_1^{XY}(v) = \left| \Delta t \sum_{j=0}^{N-1} M_1^{XY}(t_j) \cos 2\pi v t_j \right|^2.
\]
In paper we use also the correlation coefficient:

\[ k(X, Y) = \frac{\langle XY \rangle}{\sigma_X \sigma_Y}. \]

3. Results and Discussion
At the first stage, based on the correlation coefficient for each stimulus, we determined the cerebral cortex areas whose interaction (on average for the group) for different stimuli differs most strongly. Then, from the obtained sample, we identified pairs of sensors for further analysis. Analyzing the correlation coefficient values showed that the interaction between the occipital and frontal areas is most differentiated (4 sensor combinations). Table 1 shows the selected combinations of sensors and the ratio of the average values (for the group) of the correlation coefficient for the considered stimuli.

Table 1. Ratio of averaged value of correlation coefficient \( k(X, Y) \) for Red-Blue and Red-Green stimuli.

| Sensor combinations | \( \frac{k_{RB \text{ average}}}{} \) | \( \frac{k_{RG \text{ average}}}{} \) |
|---------------------|-------------------------------|-------------------------------|
| 14–55               | 38.4                          |                               |
| 14–54               | 25.15                         |                               |
| 20–54               | 20.17                         |                               |
| 20–52               | 17.34                         |                               |

The location of the detected sensor combinations is noteworthy: the 20th and 14th sensors are located in the frontal lobe of the cortex, while sensors No. 52, 54, 55 are located in the occipital area. Occipital area is the visual center. The frontal plays a crucial role in the formation of complex nervous activity.

For the second stage, we selected subjects with the most typical (by their characteristics) MEG signals induced by a stimulus. In addition, for each subject, we investigated the response to various stimuli.

Figure 1 shows the phase portraits of the dynamic orthogonal variables for the 6th subject (SQUIDs 14 (frontal area) and 55 (occipital area)), for stimuli RB (a–d) and RG (e–h). We observe a striking difference in the structure of phase clouds associated with a different response to a stimulus.

![Figure 1. Phase portraits for the 6th subject (SQUIDs 14 (frontal area) and 55 (occipital area)), for stimuli RB (a–d) and RG (e–h). We observe a striking difference in the structure of phase clouds.](image-url)
Figure 2 demonstrates the power spectra of the initial CCF and of the higher order memory functions for the 6th subject (SQUIDs 14 (frontal area) and 55 (occipital area)), for stimuli RB (a–d) and RG (e–h). A comparative analysis shows that differences in the response to a stimulus are observed in changes in the height and frequency of the highest bursts. For example, for $\mu_1^{XY}(\nu)$ (figures 2b, 2f), the height of the dominant burst differs by 3 times, and for $\mu_2^{XY}(\nu)$ (figures 2c, 2g) by 100 times. In addition, the structure of the spectra also changes, which we see in the appearance of additional peaks.

Figure 2. Power spectra of the initial CCF and of the higher order memory functions for the 6th subject (SQUIDs 14 (frontal area) and 55 (occipital area)), for stimuli RB (a–d) and RG (e–h). We observe the differences in the height and frequency of the highest bursts. Also we see the appearance of additional peaks.

4. Conclusions
In this paper, we discussed the differences in the neuromagnetic responses [5, 6] of the cerebral cortex of healthy people to two visual flickering stimuli [7]. We carried out an analysis of the correlation of MEG signals which allowed us to identify areas whose interaction is most significantly different when exposed to a particular combination of color stimuli. We have analyzed the structure of phase clouds and the power spectra of memory functions. We have found the differences in dynamic, spectral and stochastic characteristics of the cerebral cortex MEG signals under the influence of the stimuli. The results obtained provide an opportunity for a deeper understanding of the processes of the spread of excitation in the cerebral cortex with visual stimuli [8, 9].

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