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Propagation of EEG activity during continuous attention test

R. KUŚ[1]*, K.J. BLINOWSKA[1], M. KAMIŃSKI[1],
and A. BASIŃSKA-STARZYCKA[2]

[1]Institute of Experimental Physics, Department of Biomedical Physics, Warsaw University, 69 Hoża Str., 00-681 Warsaw, Poland
[2]Institute of Psychiatry and Neurology, 9 Sobieskiego Str., 02-957 Warsaw, Poland

Abstract. The propagation of EEG activity during the Continuous Attention Test (CAT) was determined by means of Short-time Directed Transfer Function (SDTF). SDTF supplied the information on the direction, spectral content and time evolution of the propagating EEG activity. The differences in propagation for target and non-target conditions were found mainly in the frontal structures of the brain.

Key words: propagation, EEG activity, continuous attention test.

1. Introduction

In the last years techniques of brain imaging such as Computer Tomography (CT), Positron Emission Tomography (PET), Nuclear Magnetic Resonance (MRI) and Functional Magnetic Resonance (fMRI) became popular in clinical applications, however EEG measurements did not loose its diagnostic importance. EEG is still the cheapest and most widespread technique. Moreover it gives the direct information on the brain electrical activity and has the highest temporal resolution. From EEG spectral characteristics the information about the contribution of the specific rhythms in brain information processing can be found.

These features of EEG are especially important in cognitive research and clinical neuroscience. Particularly it concerns applications involving cognitive processes impairment and attention deficits, which are common in psychiatric disorders. The cognitive processes involve change of the spectral content of brain activity and the pattern of EEG propagation between brain structures. However, despite of numerous studies on the localization of brain structures taking part in cognitive processes, still little is known about transmissions between the involved sites. The assessment of the mutual interactions between the brain structures requires a proper estimator, allowing for determination of the information flow. Such an estimator should provide the information about the direction, time course of the propagation and its spectral content. The measure, which fulfills this requirement is the Short-time Directed Transfer Function (SDTF), which is a time-variant version of the Directed Transfer Function [1–4]. SDTF was successfully applied in the investigations concerning the motor task performance and its imagination [5–7]. In this study we aim to show that it can be also appropriate measure to evaluate the information processing during cognitive task.

In this work Continuous Attention Test – CAT [8] was used. The CAT is a specific differentiation tool in studies on deficits of attention. Topographic ERP studies, concerning the same CAT paradigm by means of the low-resolution electromagnetic tomography (LORETA) [9], were focused on finding the most active sites in the non-target and target condition (the latter involving a motor reaction). Although they revealed the most prominent brain activity in posterior areas, the strictly cognitive activity, reflected by inter-condition differences (switching from non-target to target condition) was found mainly in prefrontal-cortex structures (anterior cingulum and ventromedial prefrontal cortex), corresponding with the surface early-P3 component at the midline frontal derivation (Fz). However in the former study, the role of the rhythmic brain activity was not considered. In this work we shall concentrate on the oscillatory EEG activity and the determination of its propagation.

2. Material and methods

The subjects were 10 male normal subjects. The CAT experiment consisted of 720 consecutively displayed geometrical patterns (Fig. 1). The target was defined as any immediately repeated pattern. After the appearance of the target the subject had to press the button with his right thumb. EEG was recorded from 21 electrodes (10–20 system) referenced to the linked mastoids. The signal was sampled at 250 Hz, 1 second long epochs after each stimulus were evaluated. Since we were interested mainly in the beta band we have filtered the signal in the $(15 \div 45)$ Hz frequency band.

The trials concerning both CAT conditions were synchronized with respect to the onset of the visual CAT items and processed separately for detected target and non-target stimuli. Mean value was subtracted from the data and a random noise of small amplitude (16% of signal amplitude) was added in order to avoid computational instabilities.

The DTF method is based on fitting a multivariate autoregressive model (MVAR) to the signal [10]. In terms of the model a k-channel process can be represented as a vector $\boldsymbol{X}$

*e-mail: rafal.kus@fuw.edu.pl

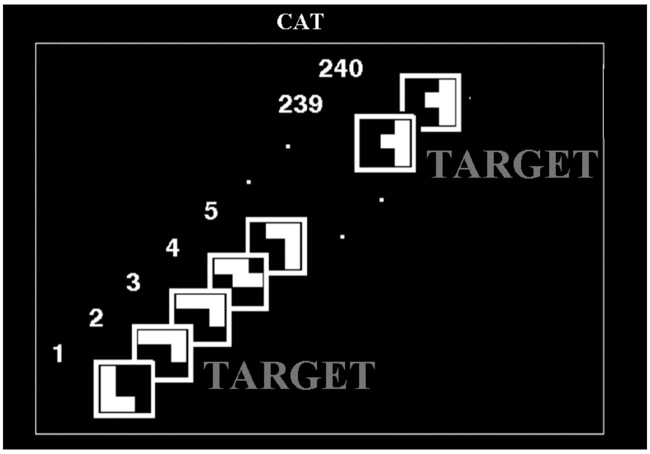

Fig. 1. Scheme of the experiment

of k EEG signals recorded in time: $\boldsymbol{X}(t) = (X_1(t), X_2(t), \ldots, X_k(t))$. Then the MVAR model can be expressed as:

$$\boldsymbol{X}(\mathrm{t}) = \sum_{i=1}^{p} \boldsymbol{A}(i)\boldsymbol{X}(t-i) + \boldsymbol{E}(t), \tag{1}$$

where $\boldsymbol{X}(t)$ is the data vector in the time t, $\boldsymbol{E}(t)$ is the vector of white noise values, $\boldsymbol{A}(i)$ are the model coefficients and p is the model order.

Previously [10], the sensitivity of MVAR performance depending on the model order was tested and it was demonstrated that small changes of model order do not influence results. The model order can be found by means of criteria derived from information theory; in [10] the AIC criterion [11] was found as the most satisfactory. It was used in this work for MVAR model fitting, usually the model order 5 was used.

After transforming the model equation to the frequency domain we get:

$$\boldsymbol{X}(f) = \boldsymbol{A}^{-1}(f)\boldsymbol{E}(f) = \boldsymbol{H}(f)\boldsymbol{E}(f). \tag{2}$$

The $\boldsymbol{H}(f)$ matrix is called a transfer matrix of the system, f denotes frequency. From the transfer matrix, we can calculate power spectra $\boldsymbol{S}(f)$ and coherences. If we denote by $\boldsymbol{V}$ the variance matrix of the noise $\boldsymbol{E}(f)$, the power spectrum is defined by (asterisk means transposition and complex conjugate):

$$\boldsymbol{S}(f) = \boldsymbol{H}(f)\boldsymbol{V}\boldsymbol{H}^{*}(f). \tag{3}$$

Transfer matrix $\boldsymbol{H}(f)$ is not symmetric and its non-diagonal elements give the information about the causality relations between corresponding channels. Directed Transfer function (DTF) was first introduced in [1] in the form:

$$\gamma_{ij}^2(f) = \frac{|H_{ij}(f)|^2}{\sum\limits_{m=1}^{k} |H_{im}(f)|^2}. \tag{4}$$

Normalization of DTF was performed in such a way that γ_{ij} described the ratio between the inflow from channel j to channel i to all the inflows of the activity to the destination channel i. Such ratio takes values from [0, 1] range. Its value close to 1 indicates that most of the signal in channel i consists of signal from channel j, values of DTF close to 0 indicate that there was no flow from channel j to channel i at this frequency.

Non-normalised version of DTF (denominator omitted) is equivalent to the Granger causality measure, which was introduced for two channels [12]. The concept of Granger causality was extended later to the arbitrary number of channels [13].

To study dynamics of nonstationary phenomena we can use a modification of the original AR model fitting algorithm, as described in [13] and [14]. When multiple repetitions of the given experiment are available, the information from all the repetitions can be used to increase statistical significance of the estimated functions. This approach allows to fit the MVAR model to much shorter data segments. Namely, the correlation matrix, used for the calculation of MVAR coefficients is estimated by means of ensemble averaging over realizations according to the formula:

$$\begin{aligned}\tilde{R}_{ij}(s) &= \frac{1}{N_T}\sum_{r=1}^{N_T} R_{ij}^{(r)}(s) \\ &= \frac{1}{N_T}\sum_{r=1}^{N_T}\frac{1}{n-|s|}\sum_{t=1}^{n-|s|} X_i^{(r)}(t)X_j^{(r)}(t-s),\end{aligned} \tag{5}$$

where N_T is the number of the realizations, $R_{ij}^{(r)}(s)$ denotes the elements of the correlation matrix calculated for time lag $t = s$ in the realization r, and n is the length of the data window. This procedure was performed for short time overlapping windows; each time correlation matrix was calculated by ensemble averaging and MVAR coefficients were fitted. In this way time varying power spectra, coherencies or estimates describing propagation can be found and presented as time-frequency maps. In the framework of this approach the short-time directed transfer functions in their non-normalised form were calculated. The details of the procedure may be found in [13] and [14].

A MVAR model was applied to 10 channels simultaneously; the ensemble averaging over trials was used in computation of the model correlation matrix. The MVAR was fitted to 50 samples long data window, which was consecutively moved in time by 3 samples. In this way the Short-time Directed Transfer Functions (SDTFs) describing the propagations between all the channels as a function of time and frequency were determined. We have analyzed SDTFs integrated in $15 \div 30$ Hz frequency band as functions of time. The variability of the SDTFs was estimated by means of the bootstrap method [15]. 150 randomly selected pools of trials served for estimation of the corridors of variability.

In order to assess the differences between target and non-target condition by means of parametric test we have to transform the results to get the normal distribution. The SDTFs were transformed by means of the Box-Cox procedure [16] and their normality was checked. Then we have applied the t-test to find the differences in the flows between the target and non-target condition. The test of the hypothesis of the difference was corrected for multiple repetitions.

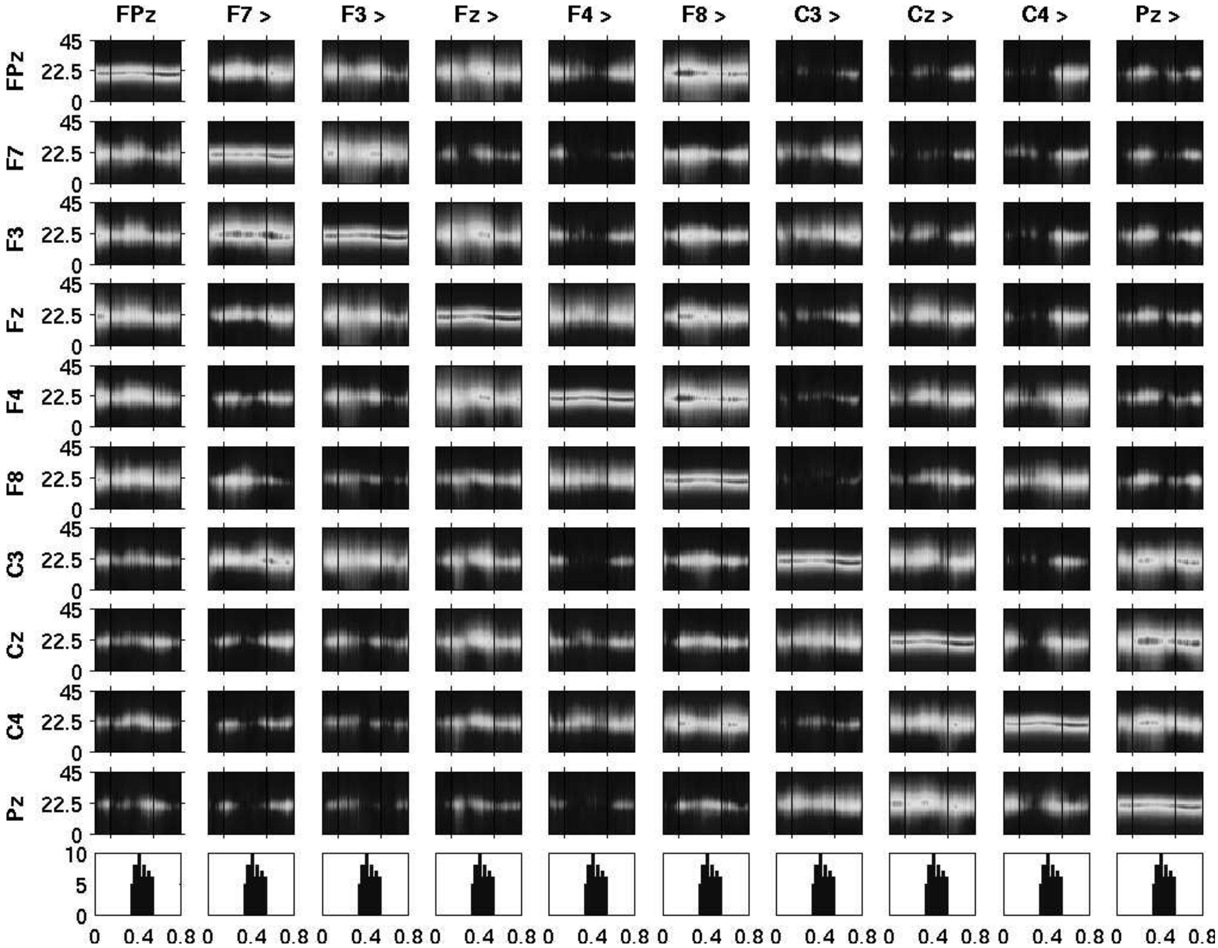

Fig. 2. Results of SDTF analysis for one of subjects. In each box – SDTFs representing the propagation of the EEG activity in time (horizontal) and frequency (vertical); intensity of flow in the shades of gray; target condition. The propagation from the electrode marked above each box toward electrode marked at the left of the figure. At the bottom of the picture the histograms of response times. Vertical lines separate time epochs defined in the Results section

3. Results

The time-course of the propagation obtained for different subjects depended on their reaction times to the appearance of the target, therefore the time evolution of the EEG activity was considered with respect to the time-histogram of the reaction times. Considering the length of the time window used in the SDTF analysis (50 samples), three epochs were defined. Epoch one (prior to the motor reaction) included all time windows not containing reaction to the stimulus: from the stimulus presentation (time 0) to the fastest reaction time minus window length. Epoch two (coincident with motor reaction) included all the windows covering reactions time period. Epoch three covered the time period after motor reactions. The borders of epochs are marked in Figs 2 and 3 as vertical lines. In Fig. 2 the example of the SDTFs are shown for the target condition together with the histograms of the reaction times. One can observe the changes of propagation in the beta band correlated with the task performance.

An example of the time evolution of the propagation in the beta band for the target and non-target condition is shown in Fig. 3. The time period between vertical lines (epoch two) represents the time span during which the reaction occurred (different in different trials). The general tendency, which can be readily perceived is that in the case of non-target condition there was less variability in the time course of the EEG flows between electrodes – the curves were more “flat”.

The tests of the hypothesis of a lack of difference between target – non-target condition was rejected for all subjects, which means that EEG propagation changes significantly in the target condition.

Prior to the motor reaction (epoch one) an enhanced outflow in the target condition was visible at electrode Fpz in 6 subjects and for the others four it occurred at F3 and/or F4. It seemed that, depending on a subject, the increase in transmission was more medial or lateral, but it was always observed at frontal locations. Occasionally this initial increase was visible also at another electrodes, but there was no systematical tendency among the subjects.

In the epoch two, coincident with the motor reaction, the prevailing tendency in the target condition as compared to the non-target one, was the decrease in the propagation from the frontal electrodes at the side contralateral in respect to the

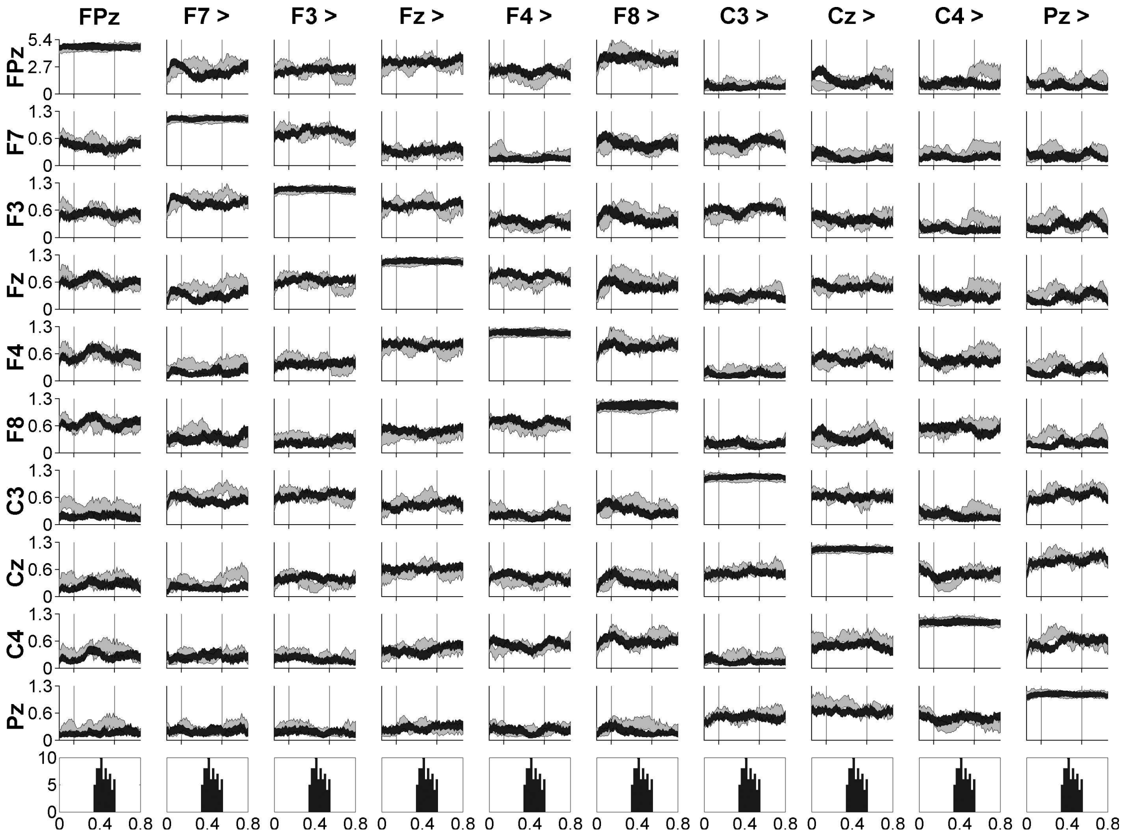

Fig. 3. The time evolution of EEG flows in the beta band (SDTFs integrated in the beta range), together with corridors of errors estimated by the bootstrap method. Non-target condition – gray, target condition – black At the bottom of the picture the histograms of response times. Vertical lines separate time epochs defined in the Results section

moving thumb (F3, F7). This decrease accompanied by consecutive increase was observed especially in propagation to the other frontal electrodes and electrode C3, which is located over the sensorimotor cortex connected with the right hand. In Fig. 3 the time courses of flows in the beta band are shown together with the corridors of variability. The differences in communication between frontal locations as well as between frontal and C3 derivation in target and non-target conditions are visible.

The most characteristic feature for the epoch three (after the movement) was the increase in propagation from C3. This observation is compatible with the resynchronization or rebound effect found in the experiments connected with the finger movement and the patterns of propagations found for the motor task e.g. [5]. The resynchronization effect was visible also in power spectra calculated in the framework of MVAR model.

For the other central and posterior electrodes the time evolution of flows for the target condition was less consistent across the subjects. In the posterior electrodes the increase in outflows as compared to the non-target condition was visible in the phase two (and sometimes also in the phase one) of the experiment.

In Fig. 4 the topographic representation of the t statistics representing differences in the target and non-target condition are illustrated for the two epochs: 0–200 ms and 700–900 ms after the stimulus onset. The difference were observed mainly in the left hemisphere. The communication between both hemispheres was also subject to change in the target condition.

4. Discussion and conclusions

The information derived from SDTF contains not only amplitude, but also the phase information and determines the pattern of transmissions, which makes difficult the comparison with the other methods, concerned mainly with ERP amplitudes. However general tendencies are consistent with the previous studies. The target related increase in the propagation, observed mainly in the frontal areas within the first, pre-motor epoch (reflecting cognitive stimulus evaluation) is in agreement with the result of the former ERP study [6]. The results are consistent with the known evidence concerning the dorsolateral prefrontal cortex, functionally connected with medially-located anterior cingulum within the dorsal memory system and responsible for contextual visual object recognition [17]. Anterior cingulate has been shown to be involved in directed [18] and sustained [19] attention. Furthermore, anterior cingulate participates in stimulus evaluation and may determine the speed of motor reaction [20]. We can conjecture that the decision concerned with the stimulus identification is connected with an enhanced communication between frontal structures, and a flow of information toward the motor areas.

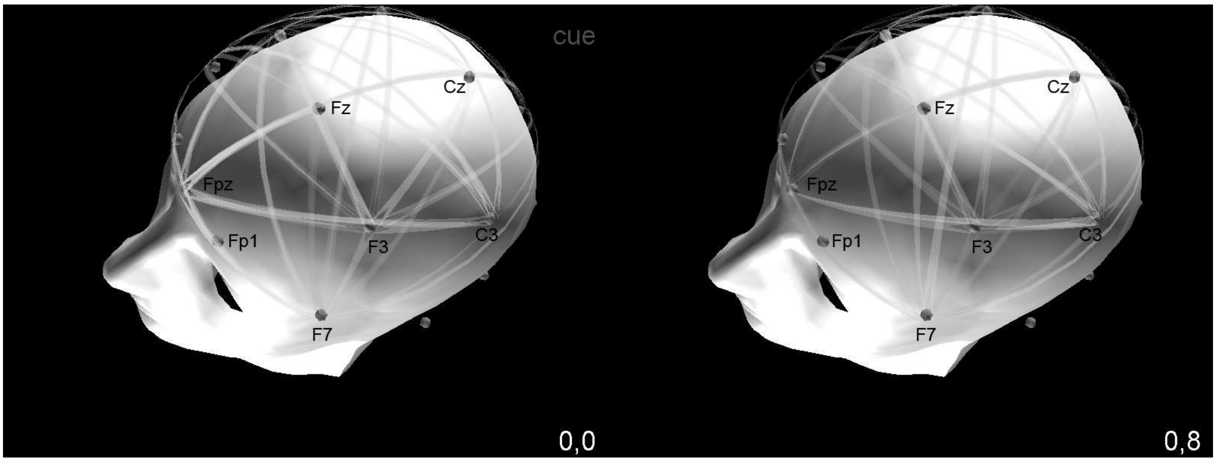

Fig. 4. Topographical illustration of the changes of EEG propagation. The arrows show the values of t statistics representing differences of target versus non-target condition in two epochs (0 – 200 ms) and (700 – 900ms) after stimulus

This study indicates that the application of multivariate approach for the determination of the information flow in brain structures brings very rich and important information about the interactions between brain structures. The failure of the previous methods aimed at determination of the propagation between brain structures was connected with the fact that they were based on bivariate measures of propagation. The lack of success of this approach caused the withdrawal of researchers interested in topographical features of information processing from the EEG analysis to the others techniques. The reason for that was the use of improper methods of EEG analysis. It has been shown in [21] and [22] that pair-wise estimates – bivariate Granger causality or bivariate coherence may give totally confusing results. On the contrary, multivariate methods allow for determination of the consistent pattern of propagation of brain activity during information processing.

This work demonstrates advantages of the application of mutivariate autoregressive model and Short-time Directed Transfer Function in the cognitive research and offers a powerful tool for the investigation of attention deficits. It opens the way to the understanding of communication between brain structures during information processing and allows for the elucidation of the role of the different brain structures during active performance.

References

[1] M. Kamiński and K.J. Blinowska, "A new method of the description of the information flow in the brain structures", *Biol. Cybern.* 65, 203–210 (1991).

[2] P.J. Franaszczuk and G.K. Bergey, "Application of the directed transfer function method to mesial and lateral onset temporal lobe seizures", *Brain Topography* 11, 13–21 (1998).

[3] A. Korzeniewska, S. Kasicki, M. Kamiński, and K.J. Blinowska, "Information flow between hippocampus and related structures during various types of rat's behavior", *J. Neurosci. Meth.* 73, 49–60 (1997).

[4] M. Kamiński, K.J. Blinowska, and W. Szelenberger, "Investigation of coherence structure and EEG activity propagation during sleep", *Acta Neurobiol. Exp.* 55, 213–219 (1995).

[5] J. Ginter Jr., K.J. Blinowska, M. Kamiński, and P.J. Durka, "Phase and amplitude analysis in time-frequency space – application to voluntary finger movement", *J. Neurosci. Meth.* 110, 113–124 (2001).

[6] K.J. Blinowska, J. Ginter, M. Kamiński, and R. Kuś, "Propagation of EEG activity as a function of time and frequency", *Proceedings of MEDICON* 2004, Ischia, Italy CD ROM 31 July-5 August, (2004).

[7] J. Ginter Jr., K.J. Blinowska, M. Kamiński, P. J. Durka, G. Pfurtscheller, and C. Neuper, "Propagation of EEG activity in beta and gamma band during movement imagery in human", *Methods Inf. Med.* 44, 106–113 (2005).

[8] B. Tiplady, "A continuous attention test for the assessment of the acute behavioural effect of drugs", *Psychopharmacol. Bull.* 24, 213–216 (1988).

[9] A. Basińska-Starzycka and R.D. Pasqual-Marqui, "Prefrontal structures involved in the continuous attention test performance as localised by the low-resolution electromagnetic tomography", in: *Recent Advances in Human Brain Mapping*, Elsevier, Intern. Congress Serie, 123, 433–437 (2001).

[10] P.J. Franaszczuk, K.J. Blinowska, and M. Kowalczyk, "The application of parametric multichannel spectral estimates in the study of electrical brain activity", *Biol. Cybern.* 51, 239–247 (1985).

[11] H. Akaike, "A new look at statistical model identification", *IEEE Trans. Autom. Control* AC–19, 716–723 (1974).

[12] C.W.J. Granger, "Investigating causal relations by econometric models and cross-spectral methods", *Econometrica* 37, 424–438 (1969).

[13] M. Kamiński, M. Ding, W. Truccolo, and S. Bressler, "Evaluating causal relations in neural systems: Granger causality, directed transfer function and statistical assessment of significance", *Biol. Cybern.* 85, 145–157 (2001).

[14] M. Ding, S.L. Bressler, W. Yang, and H. Liang, "Short-window spectral analysis of cortical event-related potentials by adaptive multivariate autoregressive modeling: data preprocessing, model validation, and variability assessment", *Biol. Cybern.* 83, 35–45 (2000).

[15] B. Efron and R.J. Tibshirani, *An Introduction to the Bootstrap*, Chapman & Hall, 1993.

[16] G.E.P. Box, D.R. Cox, "An analysis of transformations", *Journal of the Royal Statistical Society* 2, 211–252 (1964).

[17] M. Mishkin and E.A. Murray "Stimulus recognition", *Curr. Opin. Neurobiol.* 4, 200–206 (1994).

[18] M. Brazdil, I. Rektor, M. Dufek, P. Daniel, P. Jurak, and R. Kuba "The role of frontal and temporal lobes in visual discrimination task – depth ERP studies", *Neurophysiol. Clin.* 29 (4), 339–50 (1999).

[19] R.A. Cohen, R.F. Kaplan, D.J. Moser, M.A. Jenkins, and H. Wilkinson "Impairments of attention after cingulotomy", *Neurology* 53, 819–824 (1999).

[20] E. Naito, S. Kinomura, S. Geyer, R. Kawashima, P.E Roland, and K. Zilles "Fast reaction to different sensory modalities activates common fields in the motor areas, but the anterior cingulate cortex is involved in the speed of reaction", *J. Neurophysiol.*, 83 (3), 1701–9 (2000).

[21] R. Kuś, M. Kamiński, and K.J. Blinowska, "Determination of EEG activity propagation: pair-wise versus multichannel estimate", *IEEE Trans. on BME* 51, 1501–1510 (2004).

[22] K.J. Blinowska, R. Kuś, M. Kamiński, "Granger causality and information flow in multivariate processes", *Phys. Rev. E*, 70, 050902 (2004).