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Time varying patterns of directed connectivity during transitive reasoning tasks

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Abstract. Time-varying connectivity patterns were studied for a transitive reasoning task. The short-time directed transfer function based on the multivariate autoregressive model was used. The transmissions within local circuits situated in the frontal and parietal regions prevailed. These main centers of activity exchanged information transiently.

Keywords: short-time directed transfer function, directed functional connectivity, multivariate autoregressive model, transitive reasoning task

1. Introduction

Recent progress in brain imaging brought a vast body of evidence concerning brain locations activated in particular tasks. Diffusion tensor imaging gives some information about connections between brain sites, however the information processing in brain is effected in a short time scale, which is elusive to the fMRI or PET techniques. The dynamic mechanisms of information processing may be elucidated only by investigation of electrical activity of brain, which can be measured with a good time resolution and is directly connected with the neural activity.

The method which allows for estimation of the EEG propagation is the short-time directed transfer function (SDTF) [Kaminski et al., 2001] which is a time varying version of the directed transfer function (DTF) [Kaminski and Blinowska, 1991]. SDTF was successfully applied for the determination of the dynamic propagation during performance of finger movement and its imagination [Ginter et al., 2001; Ginter et al., 2005; Kus et al., 2006]. The results were coherent with known phenomena of event related synchronization (ERS) and desynchronization (ERD) [Pfurtscheller and Lopes da Silva, 1999]. Other applications of SDTF concerned evaluation of transmission during cognitive experiments. The results for the Continuous Attention Test (CAT) [Blinowska et al., 2010] confirmed the engagement of pre-frontal and frontal structures in the task and supported the hypothesis of an active inhibition by pre-supplementary motor area and right inferior frontal cortex.

Here, we shall study the dynamical patterns of communication between brain structures engaged in the transitive reasoning task.

2. Material and Methods

2.1. The experiment

Seventeen healthy right-handed adults participated in the study. In all tasks we used capital letters as a premise and the symbol “>” (indicating relation between elements) was additionally presented. Every premise was shown for 5 seconds, the fixation point (inter-stimulus interval) between them was shown randomly for 3.5, 4 or 4.5 seconds. There were two phases of each task—learning and testing. During learning phases of each trial subjects were required to create a mental representation of stimuli by integrating incoming information and in the testing phase the subjects have to infer the right dependencies between the symbols.

EEG was recorded from 64 Ag/AgCl electrodes (referenced to linked mastoids) with 512 Hz sampling rate and then signals were offline downsampled to 128 Hz. Five second long epochs were studied (1 s before the stimulus onset and 4 seconds after).

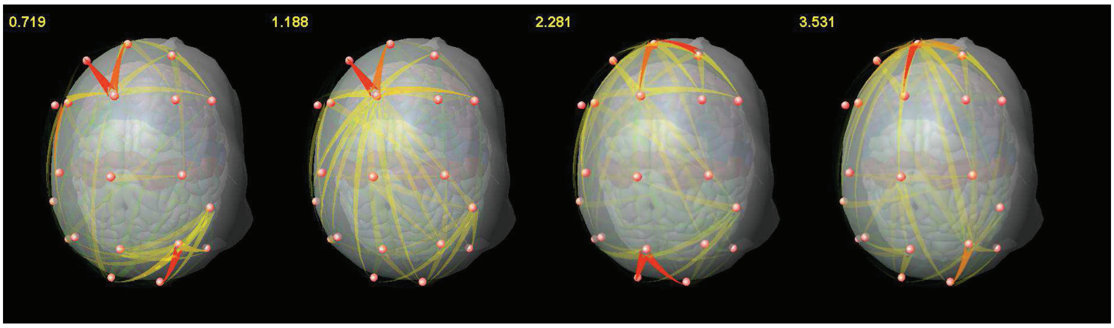

Figure 1. *Snapshots from the animation representing transmission in the theta band during TRT task for the representative subject. The strength of the propagation is coded in the color of arrows (red is the strongest). The numbers in the left upper corners correspond to time (s) after the presentation of stimulus.*

2.2. The method

The multivariate autoregressive model was fitted to the data and then the DTF function was estimated. DTF may be considered as an extension of the Granger causality principle [Granger, 1969] to the arbitrary number of channels [Kaminski et al., 2001]. In a case of a system of interdependent channels it is absolutely crucial to fit all channels simultaneously into the model. The bivariate measures may give in this case misleading results [Blinowska et al., 2004; Kus et al., 2004].

According to the definition given in [Kaminski and Blinowska, 1991] the directed transfer function is expressed as:

$$\mathrm{DTF}^2_{j\rightarrow i}(f) = \frac{\left|H_{ij}(f)\right|^2}{\sum_{m=1}^{k}\left|H_{im}(f)\right|^2} \qquad (1)$$

where H_{ij} is a transfer function of the MVAR model.

DTF describes causal influence of channel *j* on channel *i* at frequency *f*. The above equation defines a normalized version of DTF, which takes values from 0 to 1 producing a ratio between the inflows from channel *j* to channel *i* to all the inflows to channel *i*.

In order to account for the non-stationarity of the signal and describe the time-varying connectivity the measurement window has to be short. On the other hand in order to properly fit the model the number of data points should be preferably bigger by an order of magnitude than the number of the model parameters which, in case of MVAR, is equal to k^2p (*k* is number of channels, *p* is the model order). We have to effectively increase the number of data points (which equals kN_S, where N_S is number of points in the data window). If the experiment is repeated several (N_T) times, we can increase the number of samples by taking into account the multiple realizations of the test. Then the model coefficients may be estimated by means of ensemble averaging of the covariance matrix of the model over the realizations. Such averaged correlation matrix takes a form:

$$\tilde{R}_{ij}(s) = \frac{1}{N_T}\sum_{r=1}^{N_T} R_{ij}^{(r)}(s) = \frac{1}{N_T}\sum_{r=1}^{N_T}\frac{1}{N_S}\sum_{t=1}^{N_S} X_i^{(r)}(t)X_j^{(r)}(t+s) \qquad (2)$$

Please note that the data are not averaged. The approach makes possible to use a short sliding window for estimation of time-varying SDTF. Here we have used a data window of 200 samples, which was shifted by 20 samples.

3. Results

The EEG recordings were visually inspected for any artifacts and the trials with artifacts were rejected from further processing. For the purposes of DTF analysis, a set of 20 electrodes was chosen. SDTF functions were integrated in the frequency bands: theta (4-8 Hz), alpha (8-12 Hz), beta (15-30 Hz) and gamma (35-60 Hz). From the SDTF functions corresponding to the above EEG rhythms we have made animations showing EEG transmissions as a function of time. The inspection of the animations indicated that sites where from the activity was propagated were located predominantly in the parietal and left frontal areas. The snapshots from the animation are shown in Fig. 1. This result is in agreement with the fMRI data obtained for the same experiment [Brzezicka et al., 2011b]. Another observation concerned the temporal microstructure of propagations. In all subjects the epochs of the short-range transmissions prevailed, namely for the most of time there was a cross-talk in the sites localized in frontal and parietal areas. Then from time to time the transmission between the distant main centers of propagation was observed. Fig. 1 shows this alternating pattern of functional connectivity.

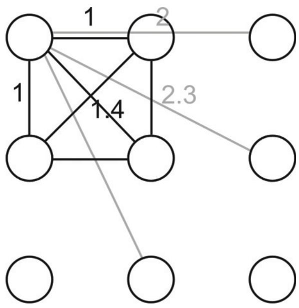

Figure 2. *The scheme of local (black line) and distant (gray line) electrode selection.*

In order to characterize these patterns of propagation more quantitatively we have applied the simplified formalism of graph theory taking into consideration local and distant connections separately. We have defined as local: connections between the neighboring electrodes along the grid lines and these on the diagonal (Fig. 2). All other connections we have considered as distant. Then in four frequency bands we have integrated all distant and all local connections separately. The average strength of the local connections was about 1.5 times bigger than for the distant ones, similarly for every frequency band. In order to compare the time-courses of the local and distant connections better, we have subtracted the mean values. The results are shown in Fig. 3.

We can observe that before the stimulus local and distant connections often go together (in phase). Around 1 sec time, both distant and local connections have a minimum in most cases. Later, distant and local connections go in anti-phase (sometimes not exactly in anti-phase, but slightly shifted). When distant connections increase, local ones reduce their values.

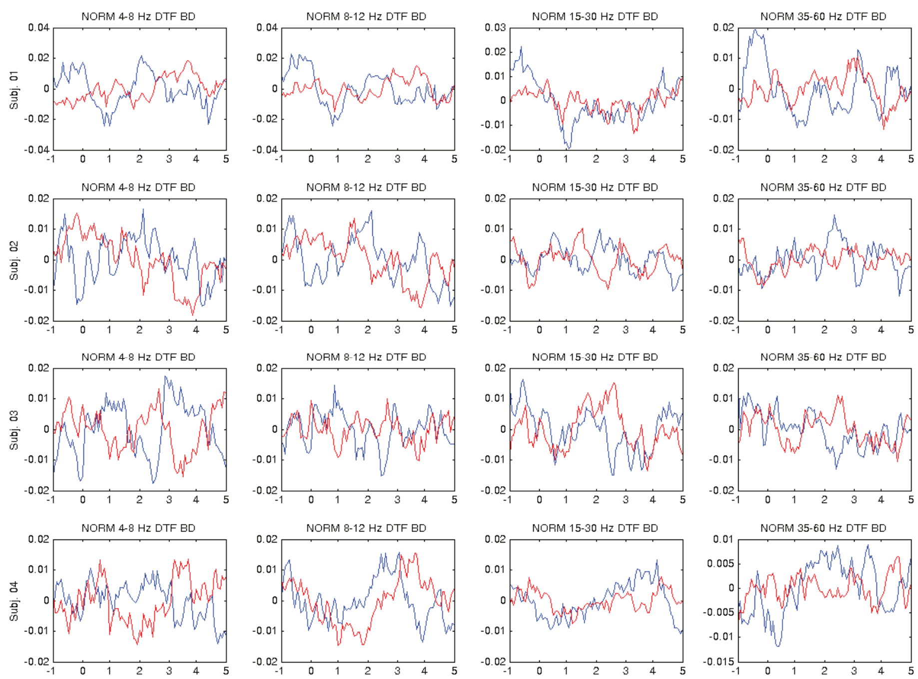

Figure 3. *The time courses of average value of local (blue) and distant (red) DTF values for 4 subjects (rows) in theta, alpha, beta and gamma frequency bands (columns). Each panel has time on horizontal axis (–1-5 s) and function values on vertical axis.*

In order to integrate these findings we have calculated the correlation function between the local and distant connections time-courses for lag 0, in the epoch 0-4 s. The results are summarized in Table I.

Table 1.

	theta	**alpha**	**beta**	**gamma**
number of subjects with negative correlation in epoch 1-4 s	13	13	9	7
number of subjects with positive correlation in epoch 1-4 s	4	4	8	10

4. Discussion.

The application of SDTF allowed to identify dynamical patterns of the information transfer for the transitive reasoning task (TRT). It should be noted that the applied here DTF method is truly multivariate which is important in causal relations analysis. In contrary to other methods, where separate pairs of signals are analyzed (like coherence analysis), we treat the whole set of channels as one system, avoiding possible mistakes in interpretation of the results [Blinowska et al., 2004; Kus et al., 2004].

The main centers of propagation were found in frontal and parietal areas. Involvement of frontal and parietal areas in working memory and reasoning processes was shown in many neuroimaging experiments (see for example [Colette and Van der Linden, 2002; Fangmeier et al., 2006]). Similarly, this fronto-parietal pattern of activation was confirmed in EEG studies—the increase of theta and gamma power in these regions was reported when subjects performed tasks with greater working memory system requirements or with a bigger memory load and heightened attention (e.g.: [Onton et al., 2005; Scheeringa et al., 2009]). The enhancement of information exchange in theta and gamma bands between frontal and parietal regions during solving TRT was also reported in, [Sauseng et al., 2005; Bhattacharya et al., 2001] and [Brzezicka et al., 2011]. Results presented here provided a new insight for the nature of these information flows. The SDTF results showed that instead of continuous information exchange between frontal and parietal areas, the connection between these two regions is established only for brief periods of time. The evidence obtained in this study is compatible with the knowledge gathered in earlier studies based on fMRI and invasive electrophysiological techniques. However, our results provide the new information about the dynamic interactions accompanying information processing in the brain. The method of estimation the EEG propagation based on SDTF provides an insight on processes acting in the scale of tens of milliseconds and allows understanding of the dynamical interactions between brain structures engaged in the given mental activity. Although the information obtained by SDTF technique is not as precise in a spatial dimension as the one obtained by the BOLD technique, however it reflects the direct brain activity and gives the possibility of establishing the relationships between the main centers involved in information processing at a given time This study provided evidence of usefulness of SDTF technique in exploring complex, higher-order cognitive processes like reasoning and working memory.

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