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Estimation of Time-frequency Causal Influences Between Cortical Areas During a Combined Movement of Foot and Lips

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Abstract— **In this paper we propose the use of an adaptive multivariate approach to define time-varying multivariate estimators based on the Directed Transfer Function (DTF) and the Partial Directed Coherence (PDC), two frequency-domain estimators that are able to describe interactions between cortical areas in terms of the concept of Granger causality. Time-varying DTF and PDC were obtained by the adaptive recursive fit of an MVAR model with time-dependent parameters, by means of a generalized recursive least-square (RLS) algorithm, taking into consideration a set of EEG epochs. We provide an application to the cortical estimations obtained from high resolution EEG data, recorded from a group of healthy subject during a combined foot-lips movement, and present the time-varying connectivity patterns resulting from the application of both DTF and PDC. Two different cortical networks were detected, one constant across the task and the other evolving during the preparation of the joint movement.**

I. Introduction

DESCRIBING how different cortical areas communicate during the execution of a motor or cognitive task is an important step to the understanding of the brain functional organization. Among the multivariate methods for the connectivity estimation the Directed Transfer Function (DTF) [1] and the Partial Directed Coherence [2] characterize at the same time direction and spectral properties of the interaction between brain signals, and require only one MVAR model to be estimated from all the time series. However, the classical estimation of these methods requires the stationary of the signals; moreover, with the estimation of a unique MVAR model on an entire time interval, transient pathways of information transfer remains hidden.

In this paper we propose the use of the adaptive multivariate approach based on DTF and PDC, to follow rapid changes in the connectivity between the cortical activities as estimated by means of advanced high resolution EEG techniques. We applied the time-varying DTF/PDC to the cortical activity estimated in particular regions of interest (ROIs) of the cortex, obtained from high resolution EEG recordings during the execution of a combined foot-lips movement in a group of 5 healthy subjects.

II. Methods

The Directed Transfer Function (DTF) [1] and the Partial Directed Coherence (PDC) [2] are two methods to determine the directed influences between any given pair of signals in a multivariate data set. The approach is based on a multivariate autoregressive model (MVAR) simultaneously modeling the whole set of signals. In this study, we used an adaptive formulation of DTF and PDC, based on an adaptive MVAR (AMVAR) model. The time dependent parameter matrices were estimated by means of the recursive least squares (RLS) algorithm with forgetting factor, as proposed in [3,5]. The estimation procedure allows the simultaneous fit of one mean MVAR model to a set of single trials, each one representing a measurement of the same task.

Five right-handed healthy subjects (mean age 24.1 ± 1.5) participated to the study after the informed consent was obtained. They were asked to perform a brisk protrusion of their lips (lips pursing) while they were performing a right foot movement. Electrical potentials were recorded by means of a 58-channel EEG system, accordingly to an extension of the 10-20 international system. Structural MRIs of the subject's head, necessary for the realistic head modelling of each subject, were taken. The analysis period for the potentials time-locked to the movement execution was set from 1500 ms before to 0 time (EMG trigger). We studied connectivity between the cortical signals estimated from high resolution EEG recordings, by using realistic head models and a cortical reconstruction with on average of 5,000 dipoles uniformly disposed along such cortical surface. The estimation of the cortical activity was obtained by the application of the linear inverse procedure [4]. Cortical activity were then estimated in ROIs generated by

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the segmentation of the Brodmann areas on the accurate cortical model used.

III. Results

Time-frequency distribution of the instantaneous PDC and DTF were obtained for all the subjects from the set of cortical waveforms estimated in the 12 ROIs considered. The time interval is relative to the 1500 milliseconds preceding the EMG onset, which served as zero time. High values of connectivity could be noted in particular in the alpha and gamma bands, and involved mainly the PMd areas from the left and right hemispheres, the M1F left and right, the SMAp left and right and the CMAc left and right.

Fig. 1 shows the time-varying connectivity patterns in the alpha band, extracted at -500, -250 and 0 milliseconds before the movement onset, provided for a representative subject. Results are presented on the realistic reconstruction of the head and cortex of the subject, obtained from sequential MRIs. The different ROIs selected are depicted in different colors and described by labels. The connectivity links are represented by arrows, pointing from one cortical area ("the source") toward another one ("the target"). The color and size of the arrows code for the interaction strength, with the minimum strength coded in dark red and the maximum value coded in light yellow.

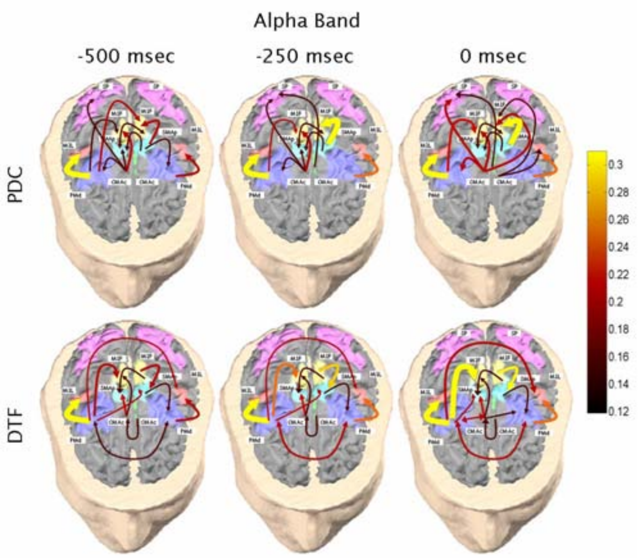

Fig. 1. Time-varying connectivity patterns in the alpha band, extracted at -500, -250 and 0 milliseconds before the movement onset. First row: results obtained with time-varying DTF. Second row: results of time-varying PDC. Reconstruction of the head and cortex of the subject, obtained from sequential MRIs. The color and size of the arrows code for the interaction strength (see color bar on the right). Similarities can be seen between the results obtained with the two methods, as well as an evolution in time of the connectivity during the movement preparation.

IV. Discussion

The analysis performed with the aid of the time-varying connectivity estimators here derived suggested the existence of two different cortical networks, subserving the preparation and the execution of the joint movement of lips and right foot. In particular, one network is constant during the preparation of the movement, and involves the PMd, CMA, SMA, M1Lips and M1F ROIs located on the right hemisphere. Results obtained suggest that such links connect cortical ROIs that are rather involved in the resource allocation for the behavioural task performed instead of in the monitoring of the actual execution of the joint movement. In this respect, the cortical network depicted by such time-invariant links does not change its activation state during the preparation of the joint movements of lips and foot. In fact, PMd and CMA are activated continuously during the preparation of the movement and generate the sequence of generic activation command towards the primary motor areas responsible for the activation of the specific motoneurons that will trigger the movement for lips and feet. The second network of cortical areas involved in the preparation and generation of the joint movements is, instead, dependent on the time-course of the task. In particular, the results suggested the existence of a network that increases in strength during the few hundreds milliseconds preceding the movement execution. Such network involves connections between the PMd_Right area and the M1F_Rigth area, between the PMd_Left to the M1Lips_Left and between the SMA_Left and M1F_Left. The cortical networks estimated by the two methods are rather similar, and allow to conclude positively about the applicability of these estimators on high resolution EEG recordings. It is worth of note that the information on the increasing connectivity strength in the second cortical network would be loose with the application of the standard connectivity estimators which assumes the stationarity of the analyzed data.

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