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Cortical Activity and Functional Hyperconnectivity by Simultaneous EEG Recordings from Interacting Couples of Professional Pilots

L. Astolfi, J. Toppi, G. Borghini, G. Vecchiato, E J. He, A. Roy, F. Cincotti, S. Salinari, D. Mattia, B. He and F. Babiloni

***Abstract*—Controlling an aircraft during a flight is a compelling condition, which requires a strict and well coded interaction between the crew. The interaction level between the Captain and the First Officer changes during the flight, ranging from a maximum (during takeoff and landing, as well as in case of a failure of the instrumentation or other emergency situations) to a minimum during quiet mid-flight. In this study, our aim is to investigate the neural correlates of different kinds and levels of interaction between couples of professional crew members by means of the innovative technique called brain hyperscanning, i.e. the simultaneous recording of the hemodynamic or neuroelectrical activity of different human subjects involved in interaction tasks. This approach allows the observation and modeling of the neural signature specifically dependent on the interaction between subjects, and, even more interestingly, of the functional links existing between the brain activities of the subjects interacting together. In this EEG hyperscanning study, different phases of a flight were reproduced in a professional flight simulator, which allowed, on one side, to reproduce the ecological setting of a real flight, and, on the other, to keep under control the different levels of interaction induced in the crew by means of systematic and simulated failures of the aircraft instrumentation. Results of the procedure of linear inverse estimation, together with functional hyperconnectivity estimated by means of Partial Directed Coherence, showed a dense network of connections between the activity in the two brains in the takeoff and landing phases, when the cooperation between the crew is maximal, while conversely no significant links were shown during the phases in which the activity of the two pilots was independent.**

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L. Astolfi (Corresponding Author. Phone: +39-06-51501466; e-mail: laura.astolfi@uniroma1.it) J. Toppi and F. Cincotti are with the Department of Computer, control, and management engineering, Univ. of Rome "Sapienza" and with the Fondazione Santa Lucia Hospital, Rome, Italy.

G. Borghini and D. Mattia are with Fondazione Santa Lucia, Rome, Italy. S. Salinari is with the Department of Computer, control, and management engineering, Univ. of Rome "Sapienza, Rome, Italy. E J He is with School of Engineering and Applied Sciences, University of Pennsylvania, USA. B. He and A. Roy are with the Department of Biomedical Engineering, University of Minnesota, Minneapolis, Minnesota, USA. G. Vecchiato and F. Babiloni are with the Dept. of Physiology and Pharmacology of the University of Rome "Sapienza" and with Fondazione Santa Lucia, Rome, Italy.

I. INTRODUCTION

THE simultaneous recording of hemodynamic or neuroelectrical brain activity from different subjects engaged in an interaction task ("hyperscanning") was firstly introduced in 2002 [1] in an fMRI experiment aimed at investigating the basis of a deception game, performed by couples of subjects interacting via monitor while lying in two functional Magnetic Resonance Imaging (fMRI) scanners. Later, the study of the synchronization between the activities in the brains of the two interacting subjects lead to the concept of "functional hyperlinks" [2].

Electroencephalographic (EEG) hyperscanning [3,4,5,6], with respect to fMRI, provides the possibility to let the subjects stand face to face and interact in an ecological setting, as well as to capture the dynamic of the functional connections between different parts of the system. The study of EEG hyperconnectivity between subjects engaged in the Prisoner's Dilemma allowed to classify, with an excellent accuracy, their brain activity to predict a cooperative or defective behaviour before it was overtly expressed [6].

In this paper we present the results obtained by EEG hyperscannings and hyperconnectivity performed on couples of Civil Aviation pilots during a flight in a professional simulator. The coordinated activity of the two members of the crew (Captain and First Officer) during a flight is a very compelling situation, in which the coordination between the two pilots is crucial and a common effort is needed to accomplish the task.

By simultaneously recording the neuroelectrical brain activity during specific phases of the flight requiring strong cooperation (takeoff, landing) or, on the contrary, no interaction between the subjects (mental task performed by one pilot, while the other is left to control the plane) we aim at understanding the modifications of the connectivity network between the two brains in relation to different cooperation level in the behaviour of the subjects. A linear inverse estimation procedure [7] allows to estimate the cortical activity and to define hyperconnectivity between cortical regions of interest [8].

II. METHODS

A. Experimental Design

Three couples of Civil Aviation pilots participated in the study. Informed consent was obtained from each subject after explanation of the study, which was approved by the local institutional ethics committee.

Each crew was asked to perform a simulated flight in a professional flight simulator. Fig.1 shows the setting of the flight simulator where the experiment was performed. The flight was composed by four different phases, each associated to a particular level and kind of interaction between the two pilots: 1) Takeoff phase, during which the Captain controlled the aircraft and the First Officer helped him in the operation, by checking the aircraft instrumentation; 2) BCI-Rest phase, during which the Captain performed a Brain Computer Interface (BCI) experiment and the First Officer held the route; 3) Rest-BCI phase, during which the First Officer executed a BCI experiment and the captain held the route; 4) Landing phase, during which, due to a systematic failure at the Captain side instrumentation, the First Officer piloted the aircraft while the Captain helped him in the operation. The first and the last phases corresponded to flight segments characterized by a strong interaction between the two pilots. This interaction went in two different directions during Take Off and Landing, thanks to the introduced failure. The other two phases were characterized by lack of interaction between the crew members.

Fig. 1. Experimental setup in the simulator cabin.

B. Simultaneous multi-subject EEG recordings

The neuroelectrical hyperscannings were performed with two 64-channel EEG acquisition devices, in the cabin of a flight simulator where the crew members were seated. The sampling rate was 256 Hz. To eliminate the sources of variance between the different EEG scanners, due to the electrical noise and the electrodes impedance, the same calibration signal was delivered to all the EEG devices, to adjust their sensitivities before and after the execution of the recordings, to equalize the different gains of the different acquisition devices.

C. Estimation of cortical activity and connectivity

The cortical signals were estimated from high resolution EEG recordings, by using realistic head models and a cortical reconstruction made by an 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 as described in [7]. The cortical activity was then estimated in ROIs generated by the segmentation of the Brodmann areas on the accurate cortical model used. In details, we employed for both left and right hemispheres the orbitofrontal areas (BA 10), the dorsal medial prefrontal cortex corresponding to the BA8, the superior parietal cortex (BA7), the dorsolateral prefrontal cortex (BA 9-46) and the Anterior Cingulate Cortex (ACC).

D. Multivariate connectivity estimation

Supposing that the following MVAR model is an adequate description of the dataset Y:

$$\sum_{k=0}^{p} \Lambda(k) Y(t-k) = E(t) \qquad (1)$$

where Y(t) is the data vector in time, E(t) is a vector of multivariate zero-mean uncorrelated white noise processes, Λ(k) is the matrix of model coefficients at lag k and p is the model order. In the present study, p was chosen by means of the Akaike Information Criteria (AIC) for MVAR processes [9]. To investigate the spectral properties of the examined process, (1) is transformed to the frequency domain:

$$\Lambda(f) Y(f) = E(f), \; \Lambda(f) = \sum_{k=0}^{p} \Lambda(k) e^{-j2\pi f \Delta t k} \qquad (2)$$

where Δt is the temporal interval between two samples.

The Partial Directed Coherence (PDC) [10, 11, 12] is a full multivariate spectral measure, used to determine the directed influences between any given pair of signals in a multivariate data set. This estimator was demonstrated to be a frequency version of the concept of Granger causality [13]. PDC is defined as:

$$\pi_{ij}(f) = \frac{\Lambda_{ij}(f)}{\sqrt{\sum_{k=1}^{N} \Lambda_{ki}(f) \Lambda_{ki}(f)}}, \; \sum_{n=1}^{N} \left| \pi_{ni}(f) \right|^2 = 1 \;, \qquad (3)$$

In this work, a modified formulation of PDC, the squared PDC, is used for its higher performances highlighted in previous simulation studies [14].

E. Statistical Assessment of Connectivity Estimates: Asymptotic Statistic

To assess the significance of the estimated connectivity patterns, the value of functional connectivity for a given pair of electrodes, obtained by computing PDC, must be statistically compared with a threshold level which is related to the null hypothesis (lack of transmission between considered ROIs). In this study, threshold values were estimated by means of an asymptotic statistic, a method recently introduced [15], based on the assumption that PDC follows a χ^2 distribution in the null case [16]. The statistical threshold is achieved obtaining a χ^2 distribution by applying

Monte Carlo method and evaluating a percentile related to the significance level imposed.

F. Functional Hyperconnectivity Estimation

Inter-brain functional connectivity was estimated by generating a unique MVAR model based on the EEG data from couples of subjects belonging to the same crew. Data coming from different subjects were normalized (by subtracting the mean value and dividing by the standard deviation) to avoid spurious results due to different power spectra of the data. Then, the functional connectivity links between the cortical signals estimated in the brains of the two pilots (intra-brain and inter-brain) were estimated by means of PDC and validated through asymptotic statistic, imposing a significance level of 5%, False Discovery Rate corrected for multiple comparisons. Finally the validated PDC values were averaged in four band of interest, defined according to the Individual Alpha Frequency (IAF) [17]: Theta (IAF-6, IAF-4), Alpha (IAF-2/IAF+2), Beta (IAF+2, IAF+15), Gamma (IAF+15, IAF+30), and mapped on the cortical model.

III. Results

The hyperconnectivity between each couple of subjects was estimated by means of the application of Partial Directed Coherence to the spatially averaged waveforms related to different ROIs considered in the study, as described in the Methods section.

Figure 2 shows the hyperconnectivity links estimated in the Alpha band for a representative couple of pilots during the takeoff, landing (high interaction) and BCI-rest (low interaction) phases of the flight. The arrows start from a cortical ROI of one subject and points toward a cortical ROI of the other subject, depicting only the statistically significant connections. The color and size of arrows code the strength of the functional connectivity estimated between the source and the target ROIs. From this result, it can be noted that during the takeoff phase (panel a) and the landing phase (panel c) the strong interaction between the two subjects is reflected in a dense network linking especially the frontal and the parietal regions. On the contrary, the results obtained during a phase characterized by zero interaction (panel b) show a complete lack of interactions, represented by the absence of significant links.

This behaviour was common to all the couples of subjects analysed in the study, which shared a high number of connections during the interaction tasks (takeoff and landing) and very few connections during the rest-BCI phases.

IV. Discussion

The aim of the present study was to investigate the neural basis of the cooperative behavior, which is established between the members of an aircraft crew during the flight phases. The estimation of hyperconnectivity links during the different phases of the flight returned results which are in agreement with the degree of behavioral interaction required to the subjects and with the results of the spectral analysis of the cortical data. Hyperconnectivity patterns linking the frontal and parietal areas of the two subjects were detected, in a statistically significant way, during the phases involving a strong interaction between the crew (Takeoff and Landing). In particular, the strongest connections involved the frontal areas and the frontal to parietal areas, directed from the Captain to the First Officer. This is in accordance

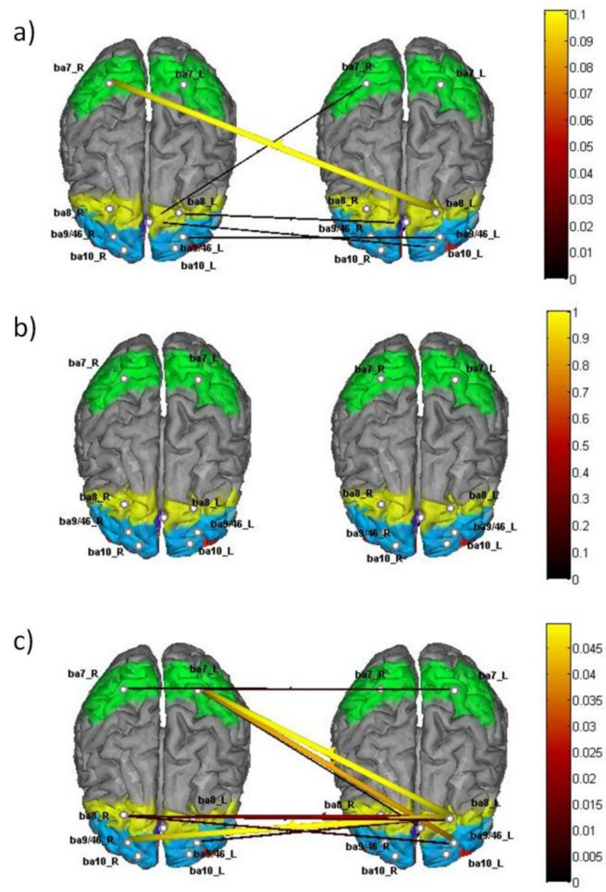

Fig. 2. Hyperconnectivity links in Alpha Band (IAF-2/IAF+2 Hz) between the Captain (Right part of each panel) and First Officer (left part of each panel) estimated during: a) the takeoff (high interaction), b) BCI-rest (low interaction) and c) landing phases of the flight. The arrows depict the statistically significant connections estimated between the activity recorded from the two subjects. The color and size of the arrows code for the strength of the interaction, as reported by the colorbar on the right (normalized values). It can be noted that during the takeoff (a) and landing (c) phases, the strong interaction between the two subjects is reflected in a high number of arrows linking especially the frontal and parietal areas and are directed from the Captain to the First Officer. On the contrary, the results obtained during a phase characterized by zero interaction (b) show a complete lack of connectivity. All the represented links are statistically significant at $p<0.001$, Bonferroni corrected for multiple comparisons.

with the hierarchical role of the crew members. The temporal delay between the activity of the two subjects is at the basis of the causality estimation performed by means of Granger based estimators like PDC [12]. During the execution of a BCI task by one of the pilots, when the other was not involved in the same task, the number of inter-connections broke down to nil. This is in accordance with the behavioral data, since no cooperation was needed to perform the task in that phase of the simulated flight.

As a whole, these results suggest that the EEG hyperscanning is an appropriate tool to provide new insights into the study of the social brain, and that neuroelectrical hyperconnectivity estimation can be a possible way to measure the "spirit of the group" at the basis of human cooperative behavior.

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