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Study of the Functional Hyperconnectivity between Couples of Pilots during Flight Simulation: an EEG Hyperscanning Study

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***Abstract*—Brain Hyperscanning, i.e. the simultaneous recording of the cerebral activity of different human subjects involved in interaction tasks, is a very recent field of Neuroscience aiming at understanding the cerebral processes generating and generated by social interactions. 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 activities in the brains of the subjects interacting together. In this EEG hyperscanning study we explored the functional hyperconnectivity between the activity in different scalp sites of couples of Civil Aviation Pilots during different phases of a flight reproduced in a flight simulator. Results shown a dense network of connections between the two brains in the takeoff and landing phases, when the cooperation between them is maximal, in contrast with phases during which the activity of the two pilots was independent, when no or quite few links were shown. These results confirms that the study of the brain connectivity between the activity simultaneously acquired in human brains during interaction tasks can provide important information about the neural basis of the "spirit of the group".**

I. Introduction

STUDYING the so called "social brain" is one of the most interesting and challenging issues in neuroscience. Though many studies approached the problem from a behavioural point of view, we still know little about the neural correlates of social behaviour and differences in performances achieved during tasks that require common effort from multiple individuals.The simultaneous recording of the brain activity from different subjects engaged in an interaction task ("hyperscanning") was firstly introduced in 2002 [1] in the hemodynamic field to investigate 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 subjects interacting 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 a more natural way. Studying the EEG hyperconnectivity between subjects engaged in the Prisoner's Dilemma it was possible to classify their brain activity to predict a cooperative or defective behaviour before 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 common effort is needed to accomplish the task.

By simultaneously recording the neuroelectric 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 only one pilot, while the other is left to control the plane) we aim at understanding the modification of the connectivity network between the two brains in relation to different cooperation level in the behaviour of the subjects.

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 execute a simulation flight in a professional flight simulator. In Fig.1 we show a picture of the flight simulator where the flight 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

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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 neuroelectric hyperscannings were performed with two 15-channel EEG acquisition devices, in the cabin of a flight simulator where the crew members were seated. The EEG was recorded at 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 in all the EEG devices, to adjust their sensitivities before and after the execution of the EEG hyperscanning recordings, in order to equalize the different gains of the different acquisition devices.

C. 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 [7].

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) [8,9,10] 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 [11]. 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 is used, the squared PDC, due to its higher performances highlighted in previous simulation studies [12].

D. Statistical Assessment of Connectivity Estimate: Asymptotic Statistic

In order 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 lack of transmission between considered ROIs (null hypothesis). Threshold values were estimated using asymptotic statistic [13], a method recently introduced, which is based on the assumption that PDC in the null case follows a χ^2 distribution [14]. 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.

E. Functional Hyperconnectivity Estimation

The implementation of methods for computing the functional connectivity between EEG signals estimated in different subjects, has been performed by generating a unique MVAR model based on the EEG data from two subjects belonging to the same crew. Data coming from different subject 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 connectivities between the cortical signals estimated in the brains of the two pilots 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: (Theta: 3–7 Hz, Alpha: 8–12 Hz, Beta: 13–29 Hz, Gamma: 30–40 Hz) and mapped on scalp model.

III. Results

The spectral activity over the scalp electrodes was evaluated for both subjects of each couple during the considered tasks time intervals (Takeoff, Landing, BCI-Rest phase, Rest-BCI phase). A significant increase ($p<0.05$) in the Power Spectral Density (PSD) was revealed in the theta band over the frontal electrodes (F3, Fz and F4), together with a desynchronization in the Alpha band in the corresponding parietal sites (P3, Pz and P4) in the member of the crew who had the responsibility to perform the required task (Captain during the takeoff and First Officer during the landing, due to a simulated breakdown of the Captain instrumentation during this phase).

The hyperconnectivity between each couple of subjects was estimated by means of the application of Partial Directed Coherence to the normalized waveforms related to different scalp electrodes, 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 (high interaction) and BCI-rest (low interaction) phases of the flight. The arrows start from a scalp electrode of one subject and points toward a scalp electrode of the other subject, depicting the statistically significant connections estimated between the activity recorded from the two pilots. The arrows color and size code the strength of the functional connectivity estimated between the source and the target electrodes. From this result, it can be noted that during the takeoff phase (panel A) the strong interaction between the two subjects is reflected in a high number of arrows linking especially the frontal and parietal electrodes and mainly directed from the First Officer to the Captain. On the contrary, the results obtained during a phase characterized by zero interaction (panel B) show an almost complete lack of interactions, represented by the absence of significant links.

Similar results were obtained for the other two conditions, with a dense connectivity network during Landing and few connections during the rest-BCI phase.

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.

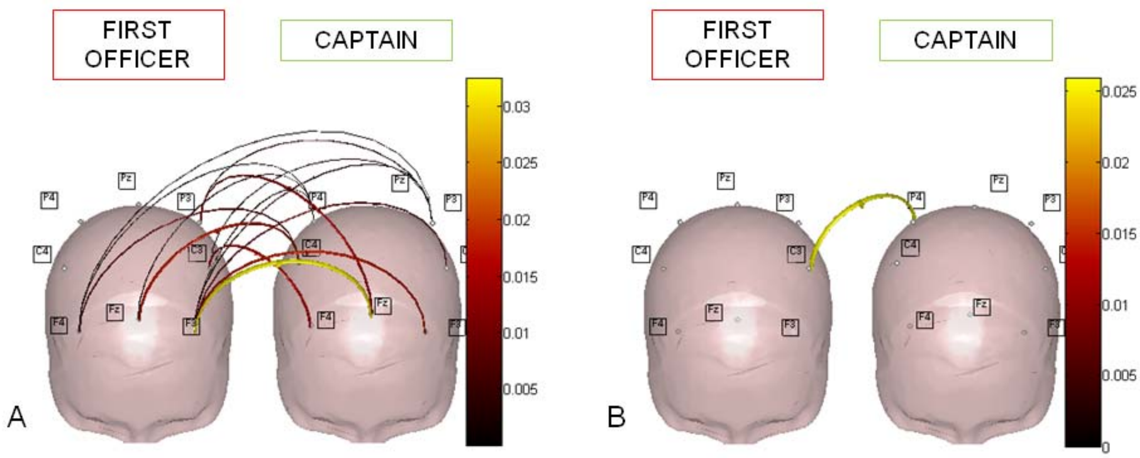

Fig. 2. Hyperconnectivity links in Alpha Band (IAF-2/IAF+2 Hz) estimated during the takeoff (high interaction, A) and BCI-rest (low interaction, B) phases of the flight. The arrows depict the statistically significant connections estimated between the activity recorded from the two subjects. The color 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 phase (on the left, A) the strong interaction between the two subjects is reflected in a high number of arrows linking especially the frontal and parietal electrodes. On the contrary, the results obtained during a phase characterized by zero interaction (on the right, B) show an almost complete lack of connectivity.

IV. Discussion

The aim of the present study was investigating the neural basis of the cooperative behavior which is established between the members of an aircraft crew during the flight phases.

The results of the spectral analysis of scalp data during the most demanding phases of the flight is in accordance with previous studies related to attention and cognitive functions. In fact, the suppression of the PSD in the Alpha band in the parietal sites has been correlated to an increase of the cognitive processes performed by the subjects, while the synchronization in Theta band in the frontal sites is usually related to an increase of the resources employed for the information processing by the cortex [15, 16].

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 scalp data. Hyperconnectivity patterns linking the frontal and parietal areas of the scalp 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 electrodes, and were directed from the First Officer toward the Captain. This is in accordance with the task performed, in which the First Officer had the role of controlling the instrumentation while the Captain physically controlled the plane. The temporal delay between the activitry of the two subjects is at the basis of the causality estimation performed by means of Granger based estimators like PDC [11]. 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 a few number. 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 approach can 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.

REFERENCES

[1] P. R. Montague, G. S. Berns, J. D. Cohen, S. M. McClure, G. Pagnoni, M. Dhamala, "Hyperscanning: simultaneous fMRI during linked social interactions", *Neuroimage, vol.* 16, pp. 1159-64, 2002.

[2] B. King-Casas, D. Tomlin, C. Anen, C. F. Camerer, S. R. Quartz, P.R. Montague, "Getting to know you: Reputation and trust in a two-person economic exchange", *Science*, vol. 308, pp. 78-83, Apr. 2005.

[3] F. Babiloni, F. Cincotti, D. Mattia, M. Mattiocco, F. De Vico Fallani, A. Tocci, L. Bianchi, M. G. Marciani, L. Astolfi, "Hypermethods for EEG hyperscanning", *Conf Proc IEEE Eng Med Biol Soc*, vol. 1, pp. 3666-3669, 2006.

[4] L. Astolfi, J. Toppi, F. De Vico Fallani, G. Vecchiato, S. Salinari, D. Mattia, F. Cincotti, F. Babiloni, "Neuroelectrical hyperscanning measures simultaneous brain activity in humans", *Brain Topography*, vol. 23, pp. 243-56, May 2010.

[5] L. Astolfi, F. Cincotti, D. Mattia, F. De Vico Fallani, S. Salinari, M. G. Marciani, C. Wilke, A. Doud, H. Yuan, B. He, F. Babiloni, "Estimation of the cortical activity from simultaneous multi-subject recordings during the prisoner's dilemma", *Conf Proc IEEE Eng Med Biol Soc,*.pp. 1937-1939, Sept. 2009.

[6] F. De Vico Fallani, V. Nicosia, R. Sinatra, L. Astolfi, F. Cincotti, D. Mattia, C. Wilke, A. Doud, V. Latora, B. He, F. Babiloni, "Defecting or not defecting: how to "read" human behavior during cooperative games by EEG measurements", *PLoS One*, vol. 5, e14187, Dec. 2010.

[7] H. Akaike, "A new look at statistical model identification". *IEEE Trans Automat Control*, vol. 19, pp. 716–723, 1974.

[8] L. A. Baccalá e K. Sameshima, "Partial directed coherence: a new concept in neural structure determination", *Biological Cybernetics*, vol. 84, pp. 463-474, 2001.

[9] K. Sameshima e L. A. Baccalá, "Using partial directed coherence to describe neuronal ensemble interactions", *Journal of Neuroscience Methods*, vol. 94, pp. 93-103, Dec. 1999.

[10] L. A. Baccalá, D. Y. Takahashi, K. Sameshima, "Generalized Partial Directed Coherence", in *Proc. 15th International Conference on Digital Signal Processing*, pp. 162-166, 2007.

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

[12] L. Astolfi, F. Cincotti, D. Mattia, M. G. Marciani, L. A. Baccalà, F. De Vico Fallani, S. Salinari, M. Ursino, M. Zavaglia, F. Babiloni, "Assessing cortical functional connectivity by partial directed coherence: simulations and application to real data", *IEEE Transactions on Bio-Medical Engineering*, vol. 53, pp. 1802-1812, Sept. 2006.

[13] D. Y. Takahashi, L. A. Baccalà, K. Sameshima, "Connectivity Inference between Neural Structures via Partial Directed Coherence", *Journal of Applied Statistics,* vol. 34, pp. 1259-1273, 2007.

[14] B. Schelter, M. Winterhalder, M. Eichler, M. Peifer, B. Hellwig, B. Guschlbauer, C. H. Lucking, R. Dahlhaus, J. Timmer, "Testing for directed influences among neural signals using partial directed coherence", *Journal of Neuroscience Methods*, vol. 152, pp. 210-219, Apr. 2006.

[15] P. Luu and D. M. Tucker, "Regulating action: alternating activation of midline frontal and motor cortical networks", *Clinical Neurophysiology*, vol. 112, pp. 1295-1306, 2001.

[16] W. Klimesch, "EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis", *Brain Research Reviews,* vol. 29, pp. 169-195, 1999.