Investigating the Neural Basis of Cooperative Joint Action. An EEG Hyperscanning Study

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Abstract— **The aim of the present study is to investigate the neurophysiological basis of the cognitive functions underlying the execution of joint actions, by means of the recent technique called hyperscanning. Neuroelectrical hyperscanning is based on the simultaneous recording of brain activity from multiple subjects and includes the analysis of the functional relation between the brain activity of all the interacting individuals. We recorded simultaneous high density electroencephalography (hdEEG) from 16 pairs of subjects involved in a computerized joint action paradigm, with controlled levels of cooperation. Results of cortical connectivity analysis returned significant differences, in terms of inter-brain functional causal links, between the condition of cooperative joint action and a condition in which the subjects were told they were interacting with a PC, while actually interacting with another human subject. Such differences, described by selected brain connectivity indices, point toward an integration between the two subjects' brain activity in the cooperative condition, with respect to control conditions.**

I. INTRODUCTION

UNDERSTANDING the neural mechanisms responsible for human social behaviour is a challenging issue. Although human social nature has been studied and described since ancient times, only in the last decades Neuroscience started to investigate the brain activity at the basis of social interactions. The brain functions taking all together the name of "social cognition" include, at large, all the cognitive processes necessary to properly understand and store the information from the self as well as the other persons, including the rules at the basis of the interaction with other humans. Neuroscientists have started to investigate the cerebral structures underlying social cognition processes moving from the experimental evidences drawn from brain lesion studies [1] and autism [2] . First experimental studies on healthy volunteers involved a single subject monitored during his/her interaction with an external agent (human or computer) in a social context re-created in laboratory. Major limitations of this approach include the fact that the reaction to another person's behaviour is necessarily linked to kind of relation arising between the subject and the specific person he (or she) is interacting with, which is not usually simply described by behavioural data. This may take advantage of a direct and simultaneous observation of the brain activity of all the subjects involved in the social exchange.

The recent field of simultaneous multi-subjects recordings (hyperscanning) was born as an answer to these research needs. It consists of collecting the brain activities of all the subjects involved in the investigated interaction. The idea is to study the neurophysiological basis of such interaction considering the group of interacting subjects as a complex system, and taking into account not only the internal structure of each subject's brain activations, but also the relations arising between the brain activations of different subjects [3-5].

In this study, we adopted a hyperscanning approach to investigate the basis of a joint action paradigm in which participants must continuously take into account the actions of their partner and adjust their own behaviour online accordingly [6-8].

II. MATERIAL AND METHODS

A. Experimental Design

16 pairs of healthy subjects took part to the experiment. The Joint Action paradigm was implemented through a computer game. The experimental paradigm included three main conditions:

1. Joint Condition (J)
2. Solo Condition (S)
3. PC Condition (P)

The subjects' task throughout all experimental conditions was to lift a rolling ball up to a particular target region located at the top of the screen by controlling both sides (left and right) of a virtual bar that carries the ball. In order to increase complexity, we introduced an obstacle in the middle

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of the screen. The goal of the game was to lift and balance the objects so that the rolling ball could reach the target area without falling to the ground or hitting the obstacle.

In the Joint Condition, both subjects worked together on the same task. Here each subject controlled only one response button (for lifting the left or right side of the virtual bar). Solving this task in cooperation with someone else requires a high level of interpersonal motor coordination.

In the Solo Condition, both subjects were asked to solve the task individually. Also in this condition participants played the game simultaneously. However, instead of playing as a team, they played alone by controlling both sides of the virtual bar. In case one person finished a trial before the other did, the game of this subject would pause in order to assure that all trials started simultaneously.

In the PC Condition, each subject was told to play together with a computer. As matter of a fact, this was a cover story, as they actually played the game together. Different LCD monitors used to show stimuli to each subject prevented them to realize they were playing together. In other words, the PC- and the Joint condition were actually the same condition that differed only in the way we instructed the subjects.

Each of the three experimental conditions consisted of 60 trials that lasted approximately 8 seconds (inter-trial interval = 2 s). The conditions were presented blockwise, in random order.

A resting condition (subjects looking at the monitor) was also recorded to provide a baseline. Stimulus presentation was realized by using MATLAB (The MathWorks, Version R2009b). Stimuli were displayed on two 19" LCD monitors (Fujitsu Siemens Scenicview L9ZA, resolution 1280 x 1024) at a refresh rate of 150 Hz.

B. Multi-subjects connectivity estimation

EEG signals were recorded simultaneously on both participants, by two 64-channel EEG acquisition devices (BrainAmp, Brainproducts GmbH, Germany). 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 both EEG devices, to adjust their sensitivities and to equalize the different gains.

Data were band pass filtered (1-45 Hz + 50Hz Notch) and segmented according to the markers indicating the start and the end of each run of the computer game.

Behavioral data (outcome of the game, trial duration, height reached by the ball) were also collected.

Cortical connectivity within and between different subjects was computed by means of an adaptation of Partial Directed Coherence (PDC) [9] to the multiple subjects condition. A unique Multivariate Autoregressive (MVAR) model was identified on the EEG data simultaneously recorded from the two subjects. Four sub-matrices of parameters were obtained: two related to the cortical connectivity of each individual subject and two related to inter-subject functional links. All PDC values were averaged in four frequency bands of interest: (Theta: 3–7 Hz, Alpha: 8–12 Hz, Beta: 13–29 Hz, Gamma: 30–40 Hz).

C. Statistical assessment of connectivity patterns

To reliably isolating the brain to brain causality specifically related to the interaction between subjects and discard spurious connectivity results being not related to the true interaction between the subjects (which may be detected as a consequence of the fact that the subjects are involved in a similar and temporally related task, and they are exposed to the same stimuli and environment) we performed a t-test on each connectivity link, between each level of cooperation and its appropriate control condition, on the population. Joint condition was contrasted with the PC condition, PC condition with the Solo condition and the Solo condition with the resting state baseline. Each test isolated connectivity related to the according degree of cooperation.

D. Brain connectivity indices and analysis of variance

Once isolated the intra- and inter-subject connectivity patterns, it is possible to quantify their main properties by means of a set of indices that can be derived from classical graph theory [10] or can be defined ad hoc to capture relevant properties of the multiple subjects connectivity framework. In this study, preliminary results were achieved by means of the inter-brain density and of the divisibility.

A directed graph of N nodes can be represented by a NxN adjacency matrix $\mathbf{W}=\{W_{ij}\}$, where $W_{ij}>0$ is the weight associated to the directed arc from node i to node j (in our case a PDC-based connectivity link directed from channel i to channel j). In general, $W_{ij} \neq W_{ji}$, since PDC indicates directed connectivity.

Inter-brain density is defined as the number of statistically significant inter-subject connectivity links for each condition (contrasted to its baseline) normalized by the maximum number of possible inter-brain connections:

$$IBD = \frac{I_{12}+I_{21}}{2N^2} \tag{1}$$

where N is the number of electrodes used for each subject and I_{12} and I_{21} are the number of significant connections directed from subject 1 to subject 2 and from subject 2 to subject 1, respectively.

Divisibility is defined as follows [4]:

$$D = \frac{W}{\sum W_{ij}\left[1-\delta\left(C_i, C_j\right)\right]+k} \tag{2}$$

where C_i indicates the community to which the node i belongs (here we can have either C_i = first subject or C_i = second subject); the δ function yields 1 if vertices i and j are in the same community (i.e. in the same brain), and 0 otherwise; W is the total weight of the network, that is the sum of all arc weights in the graph; k is a positive constant (here set equal to W) to avoid possible divergence of D. Divisibility quantifies how well the general connectivity network (including intra- and inter-brain subnetworks) can be divided into two sets of nodes, corresponding to the brains of the two subjects.

Inter-brain density and divisibility were computed for all 16 couples of subjects and for all levels of cooperation, and then subjected, as dependent variables, to an Analysis of Variance (ANOVA) with the level of cooperation as within factor.

III. RESULTS

Figure 1 shows the hyperconnectivity links estimated for a representative couple of subjects and for the three levels of interaction, in the Theta band. Functional links are here assessed against the null hypothesis. Before contrasting each level with its control condition, the existence of links significantly different from chance can be noted for each condition, as a result of the spurious effects described in the Introduction. However, a reduction of the number of links moving from the Joint to the PC and to the Solo condition can be appreciated.

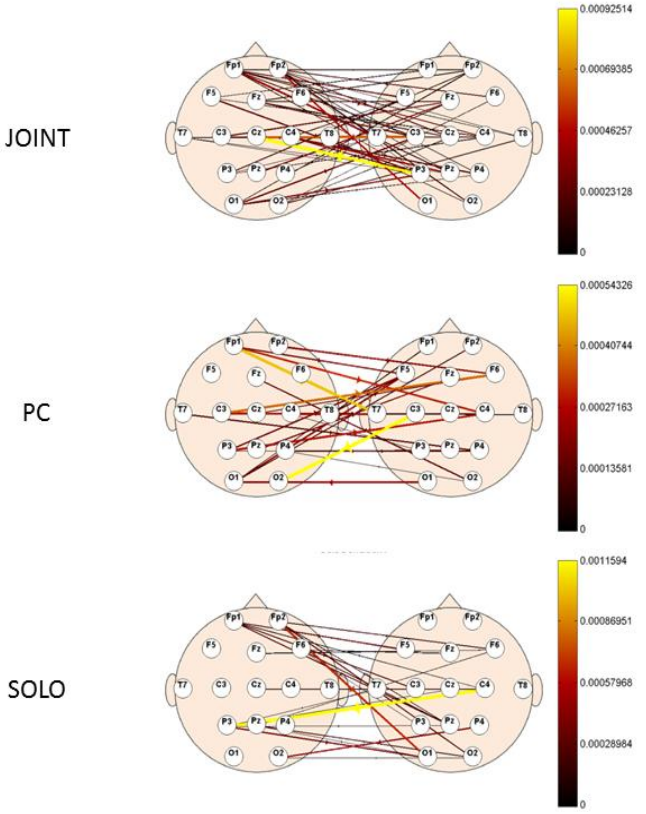

Figure 1. Inter-brain causality patterns obtained for a representative pair of subjects in Theta band, for the three levels of interaction. The heads are seen from above, the nose pointing to the upper part of the page. The arrows indicate the existence of a statistical causality between the activity recorded at different sites of the scalp of the two subjects.

The statistical contrast of each condition with the immediately lower level of cooperation returned a major difference between the Joint and the PC condition, while no significant differences in inter-brain connectivity were noted between PC and Solo condition, as can be inferred from Figure 2, reporting the results of ANOVA performed on inter-brain density and divisibility, in Alpha band. ANOVA returned a significant effect of the level of cooperation on both indices. In particular, post-hoc test returned values of IBD significantly higher in the Joint condition with respect to PC, while the divisibility was significantly reduced in the same condition. No significant difference was obtained between the PC and Solo conditions.

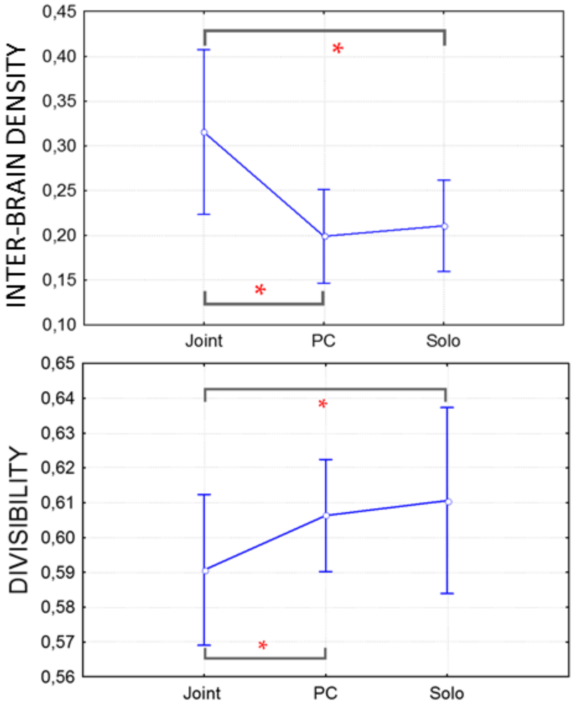

Figure 2. Results of the ANOVA performed on the IBD and the divisibility of the entire inter-brain network in alpha band. IBD: $F(2, 30) = 24{,}19$; $p < 0.00001$; divisibility: $F(2, 30) = 4{,}03$; $p = 0.03$. Red asterisks indicate statistically significant differences as returned by the Duncan post-hoc tests.

IV. DISCUSSION

As described in the Methods section, the condition of cooperation between the subjects for jointly controlling the moving bar was, as a matter of a fact, perfectly identical to the so called "PC" condition, with the only difference provided by the instructions given to the subjects. In fact, during the PC condition, subjects were told they were playing with a computer instead that a human agent. PC condition was designed to reproduce all possible confounding effects (due to the synchronization of the motor activity, to the simultaneous stimulation, to the similarity of the task performed) so that it might provide an appropriate control condition for the true interaction, i.e. the Joint condition. The statistical comparison between Joint and PC condition, as well as between Joint and Solo condition, returned significant differences in terms of inter-brain functional causal links, which can be attributed only to the interaction between the subjects aimed to reach a common goal. In fact, such a social cognitive function characterizes the Joint condition with respect to the PC, in which they believed they were merely synchronizing with a machine. In particular, the properties of the multiple brains network summarized by the selected brain connectivity indices point toward an integration between the two subjects' brain activity in the Joint condition, and to a segregation in the PC and Solo conditions.

The results of this study indicate that the analysis of a multiple brain functional network, as obtained from EEG hyperscanning, can provide a deeper insight into the understanding of the neural basis of joint action tasks. It can be easily guessed that the existence of statistically significant correlation or covariance between different brain signals is not based on a direct physical communication channel between the brains. Instead, it can be seen as an indication of an indirect chain of events that starts from specific brain regions belonging to the first subject and ends in the cerebral processes elicited in brain areas of the second subject. Hence, the inter-brain statistical links here obtained can be seen as a sort of spatio-temporal mapping of cortical regions involved in the generation of the social task investigated. Future development of this study will focus on the characterization of the role of specific regions in the investigated task, with the aim to build a comprehensive model of the neural substrates of human social cognitive functions.

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