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Hypermethods for EEG hyperscanning

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Abstract—**Until now, in EEG studies the activity of the brain during simple or complex tasks have been recorded in a single subject. Often, during such EEG recordings, subjects interacts with the external devices or the researchers in order to reproduce conditions similar to the those usually occurring in the real-life. However, in order to study the concurrent activity in subjects interacting in cooperation or competition activities, the issue of the simultaneous recording of their brain activity became mandatory. The simultaneous recording of hemodynamic or neuroelectric activity of the brain is called "hyperscanning". We would like present results obtained by EEG hyperscannings performed on a group of subjects engaged in cooperative games. The EEG hyperscannings have been performed with the simultaneous use of high resolution EEG devices on groups of three and four subjects while they were playing cooperative games. The analysis of such data have been conducted with analysis method that taken into account the particular nature of the data simultaneously gathered from different subjects.. We called these methods *hypermethods*. In particular, we estimate the concurrent activity in multiple brains of the group and we depicted the causal connections between regions of different brains (*hyperconnectivity*). The resulting causality patterns will link certain areas of the brain of a subject to the waveforms obtained from the other brain areas of another subject of the same group. Results obtained in a study of several groups recorded by the hyperscanning reveals causal links between prefrontal areas of the different subjects when they are performing cooperative games in different frequency bands. Hypermethods for hyperscanning will open a different area for the study of neuroscience, in which the activity of multiple brains during social cooperation could be investigated. In such area the importance of EEG will be relevant due to its temporal and spatial resolution now obtainable with the high resolution EEG techniques.**

Keywords— **EEG Hyperscanning, hypermethods, hyperconnectivity, high resolution EEG recordings, Theory of Mind**

I. Introduction

Although one of the most relevant characteristic trait of human behaviour is the cooperation between individuals[1-2], little is know about the neural substrates that instantiate such attribute during "*de visu*" (i.e. face by face) performances, due also to the technical difficulty of the brain imaging techniques to track simultaneously different human brains during cooperative interactions [3]. In the last ten years, the field of neuroscience, with the powerful brain scanning devices like functional Magnetic Resonance Imaging (fMRI) or high resolution EEG (HREEG) has been able to provide important insights on the neural basis for memory, decision-making and other cognitive functions at the basis of social interaction. The standard experimental paradigm consists in measuring the brain activity in individual subjects (using fMRI, EEG or other imaging methods) during the performance of an identical sensory, cognitive or motor task. Similar experimental paradigms have been applied for studying the brain activity during social interactions. Due to technological limitations, most studies on social interaction have used offline designs, in which scanned subjects do not actually take part in social interaction.. More recently 'online-designs' have been used in which subjects under investigation actually interact with con-specifics—or at least are told so [4-6]. Typically, in such designs, the neural responses are measured in individual subjects during simulated situations in which he/she interacts with a computer or with another person (normally the experimenter, which is outside the scanner) that communicates with him/her through electronic devices (like video, headphones etc).

In the investigation of the neural basis of social interaction, the use of game theory has been proved useful In fact, game theory allows a formal definition of social situation in which the players may profit or loose by cooperating or competing [7]. Researchers have begun to investigate what happens in the brain of subjects when they are involved in games like the prisoner's dilemma or the Ultimatum game [8-10]. Furthermore, studies have been conducted that investigate social interactions in a moral context, e.g. social exclusion or the consequences of suppressing prejudice and moral decision-making [11].

The main results of these studies can be summarized by saying that cooperative social interaction does activate the core structures of the reward circuitry whereas non-cooperative behaviour does not. Furthermore, the insula has been found to be active during an interactive game. The most consistently activated structure in social interaction paradigms is the medial prefrontal cortex, which is found to be active when playing against humans but not against computers. A major limitation of the approach used in the majority of the studies described above, is that neural activity, during social interaction, is actually measured in only one of the participating brains. The "interaction" between cooperating, competing or communicating brains is thus not measured directly, but inferred by independent observations aggregated by cognitive models and assumptions that link behavior and neural activation.

This approach appears clearly unsatisfactory if one wants, as proposed in this project, to measure entities such as “spirit of the group” or “leadership”. Such an endeavour requires indeed a direct observation of the “interaction” emerging between brains of different subjects and that can be obtained only by measuring the activity of the participating brains simultaneously.

Here we show as it could be possible to track the simultaneous activity of several human brains during a cooperation card game by using several electroencephalographic recordings (EEG hyperscanning), and how it is possible to depict the synchronizations between different cortical areas of different subjects members of the same team during such game by using appropriate processing methodologies described in the supplementary information. With the use of such methodologies, we can characterize the existence of particular functional synchronicity of the neuroelectric activity estimated between different cortical areas of the subject’s brains belonging to different position within a team.

II. Methods

High-resolution EEG were performed during the execution of a cooperative game by using cards in a group of healthy subjects. The card game was one of the most popular Italian game, called “tressette”. The game is played with two couple of subjects, those sitting at north and south against those set at west and est. The player to the dealer's left leads to the first card on the deck; the other players, in clockwise order, play a card to the deck and must follow suit by playing a card of the suit led if they have one. The round is won by the highest card of the suit. The player of a team have a special role in the case in which one of them has the first move in the card game. In fact, such player will put a card in order to increase the chance of the team member to win the round. Also, such player has some expectance for the other member of the team. So, the cortical activity and connectivity when the team has the player that opens the game has been specially investigated. The estimation of cortical activity from high-resolution EEG recordings was performed by solving the associated linear inverse problem, as described elsewhere [11-12]. The cortical activity was then estimated in particular cortical areas called regions of interest (ROI) depicted on the realistic reconstruction of the cortical model. In particular, the considered ROIs are related to the frontal, prefrontal, and parietal cortical areas, including the Brodman areas (BA) 8, 9, 10, 6 lateral, 7, as well as the Anterior Cingulate Cortex (ACC) and Cingulate Motor Area (CMA) resembling the BA 40 .From the cortical estimated waveforms, the functional links between ROI of the same subjects have been computed with the the Partial Directed Coherence (PDC) technique [13]. PDC is a full multivariate spectral measure, used to determine the directional influences between any given pair of signals in a multivariate data set. It is computed on a Multivariate Autoregressive model (MVAR) that simultaneously models the whole set of signals. The use of MVAR process in order to study the functional connectivity between cortical estimated waveforms has been previously presented [11-12]. The improvement in the case of the EEG hyperscanning is the possibility to adapt the MVAR processes to the brain activities estimated on different brains. The estimation of the functional links between different cortical areas of several brains (hyperconnectivity) will be considered by taking into account different ROIs belonging to different brains engaged in the cooperation games. In particular, the cortical waveforms obtained from the couple of subjects during the card game were inserted in a unique MVAR, and the successive functional links by PDC was estimated. The statistical significant PDC links between ROIs of different brains will constitute a functional connection between different brain areas, called hyperconnectivity. Such hyperconnectivity measurements have been investigated for the extraction of meaningful pattern of group behavior.

III. Results

The EEG hyperscannings were performed in 5 groups of 4 subjects during a cooperative card game that involved groups of two subjects against other two (see Fig. 1).

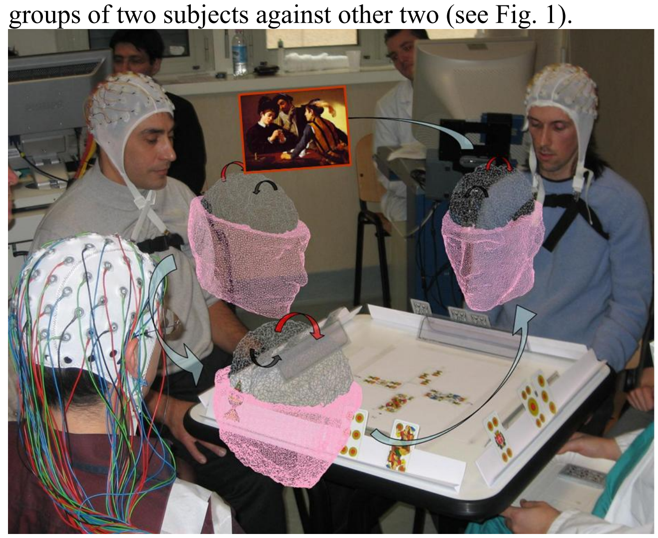

Fig.1.*EEG hyperscanning performed by using several high resolution EEG devices while a card game was played. Realistic models of the individual subject’s heads, including scalp, and cortical envelopes are presented in front each subject. The arrows depicted over the cortical surface of each cortex depicts the statistical significant connections between the cortical areas during a phase of the game. The arrows start from a cortical region and points toward another cortical region. The causal links means that the activity in the target cortical region can be modelled better by including the activity on the source region. The picture on the wall is a reproduction of the “The Cardsharps” of Michelangelo Merisi, known as Caravaggio, 1594 (Kimbell Art Museum, Fort Worth, Texas)*

The cortical activity estimates for all the ROIs considered in each one of the first players in all the groups analyzed were then subjected to the functional connectivity analysis via PDC algorithm. The results were then summarized as total outflow of functional links from a specified cortical areas toward all the others (of the same subject). This measurement of the particular ROI considered is called outdegree. It is also possible observe the total amount of the functional links from all the other cortical areas toward the considered ROI. Such measure is called indegree. Fig. 2 presents the average values for the outdegree and the indegree for all the considered ROIs for a group of 7 subjects when they play as first player (i.e. player that performs the first move on the deck). Data are relative to the beta band, that is representative of the results obtained in the other frequency bands. It is possible to observe a large activity of the outdegree values in the ACC and CMA areas for both right and left hemisperes. The maximum of the activity for the indegree values is located instead on the frontal regions (BA 10) as well in the parietal areas (BA7).

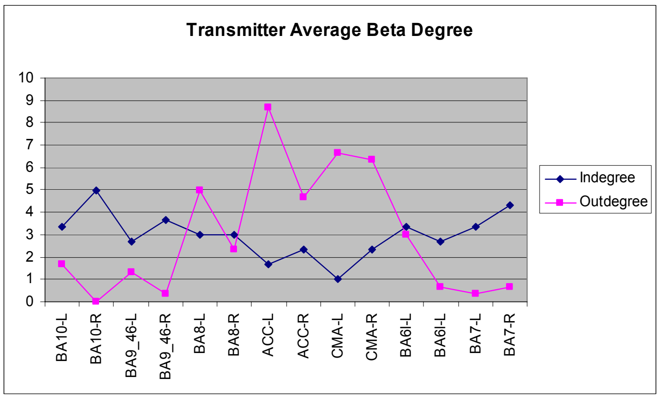

Figure.2.*Average graph of the indegree (blu line) and outdegree (red line) along the different Brodman Areas. On the x axes the name of the ROI considered, with the postfix L for left and R for right hemisphere, respectively. The y axes show the number of functional connections that in average arrives (blu lines) or departs (red lines) from the considered BA.*

IV. Discussion

A. *Novelty of the proposed computational approachs*

The novelty of the proposal is demonstrated by several facts and considerations:

1) In the specialized literature, only two reports of an hyperscanning, i.e. the simultaneous recording of the neural activity measured by the hemodynamic activity in two interacting subjects can be found [3,6]. From the same USA group it was published a paper on Science related to the neural responses measured simultaneously in two persons during a economic negotiation, based on the hemodynamic brain responses as measured from the fMRI. It is interesting to note that the two subjects were distant 1500 Km apart one to each other and then just the information on a computer screen were visualized to the subjects during the task. In such a case no "direct social interaction" can be assessed.

2) A web-search in the MEDLINE (that is the database including all scientific literature related to biomedical sciences) with the terms "Hyperscanning" or "hyperbrain" only the relation to the Montague's works is found. In particular, the USA foundation devoted to the study of this issue by using the hemodynamic measurements can be found at the following link for The Hyperscan Development Group at Baylor College of Medicine, USA at http://www.hnl.bcm.tmc.edu/hyperScan.html.

3) There is no neuroscientific study in which several "brains at work" have been scanned simultaneously with the EEG during "social interactions". This means that all the interactions that occur at a temporal scale shorter than few seconds (that are the majority in real life) have not yet been investigated.

4) There is no neuroscientific study that addresses the issue of measuring brain activity as derived from neuroelectric or hemodynamic signals during the "leader" – "working team" relation

The aim of the present work is instead to measure simultaneously the neural activity of different brains during day-life interactions, in order to understand the neural processes generating and generated by social cooperation or competition. Such activities have been estimated by using the simultaneous recordings of EEG activity through several high resolution EEG systems running in parallel, will allow us to monitor and model the activity of a larger group of subjects engaged in cooperation or competition games.

B. *Imaging brain connectivity during cognitive process*

The results depicts that anterior cingulated cortex (ACC) is maximally active in the brain of the player that put the first card on the deck for the specified round (called the leader), while his/her companion (that put the third card on the deck) develops a correlated activity in the right prefrontal and parietal areas before playing his/her card in response (after that the other competitor's card was played). Such results, obtained in all the teams investigated are fully plausible with previous separated studies on isolated brains that indicated as the ACC is the cortical site in which humans represent the other's intentions in the brain (theory of mind [14-15]). Such area is elicited in the activity of the team leader while his/her "companion" develops a synchronized brain activity related to the recall of pictorial material (i.e the cards, see Fig.1) according with the current brain memory theories [16-17].

These results suggest that the EEG hyperscanning methodology opens a new way to address the analysis of brain functions, allowing to study brain activity of group of humans during real-life social interactions. This technology can be used by all the scientists interested to the analysis of neural substrates of the human social behaviour. In this context the hypermethods developed ad-hoc for this kind signal analysis allows to estimate synchronizations and causality relation between different cortical areas of the different subject's brains. In many day-life situations, we often observed that components of a successful working group are recognized to possess a shared feeling, a "*spirit of cooperation*" or the "*spirit of the group*", which characterizes and promotes their collaboration and social interactions successes. In this context, the "**spirit of the group**" is the graph of the patterns of functional connectivity between the neuroelectric cortical waveforms measured simultaneously in different brain regions of the subjects belonging to the group during the performance of the cooperative task.

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