Methods for the EEG Hyperscanning. Simultaneous Recordings from Multiple Subjects during Social Interaction

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Abstract— **In this paper we show how the possibility of recording simultaneously the cerebral neuroelectric activity in different subjects (EEG hyperscanning) during the execution of different tasks can return useful information about the "internal" cerebral state of the subjects. We present the results obtained by EEG hyperscannings during ecological task (such as the execution of a card game) as well as those obtained in couples of subjects during the performance of the Prisoner's Dilemma Game. The simultaneous recordings of couples of interacting subjects allows to observe and to model directly the neural signature of human interactions in order to understand the cerebral processes generating and generated by social cooperation or competition. Results obtained in a study of different groups recorded during the card game revealed a larger activity in prefrontal and anterior cingulated cortex in different frequency bands for the player that leads the game when compared to other players. Results collected in a population of 10 subjects during the performance of the Prisoner's Dilemma suggested that the most consistently activated structure is the orbitofrontal region (roughly described by the Brodmann area 10) during the condition of competition in both the tasks. It could be speculated whether the pattern of cortical connectivity between different cortical areas in different subjects could be employed as a tool for assessing the outcome of the task in advance.**

Keywords: EEG, Hyperscanning, Hyercnnectivity

I. Introduction

Although one of the most relevant characteristics of human behavior is the cooperation between individuals little is known about the neural substrates that implement such attribute during "de visu" (i.e. face to face) performances. This is due also to the technical difficulty of the brain imaging techniques to track simultaneously different human brains during cooperative interactions [1]. A major limitation of the approach used in the majority of the studies performed so far, is that the neural activity, during social interaction, is actually measured in only one of the participating brains. The "interaction" among 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 can be unsatisfactory if one wants to measure the neural substrates underlying the cooperation/deception between individuals that occur simultaneously. To reveal the neural substrates supporting the development of the cooperation/deception between individuals, a direct observation of the "interaction" emerging between the brains of different subjects is necessary, and this can be obtained by measuring simultaneously their activity.

Recently, hemodynamic recordings of brain activity and their advanced analysis showed that it is possible to extract common characteristics shared by humans during the simultaneous observation of a movie or during the interaction in an "economic" transaction [1]. Montague et al called such simultaneous scanning of two people, using a functional magnetic resonance imaging (fMRI) device, "hyperscanning". In addition, the need for the adoption of different statistical tools, different from the standard tools used in fMRI analysis, was also suggested for the analysis of fMRI hyperscanning recordings. These new analysis tools have to take into account the fact that the data from fMRI hyperscannings derive from different subjects scanned at the same time.

In the past few decades, the measurement of the neuroelectrical cortical activity from non invasive scalp recordings has become a useful and consistent tool for the investigation of brain functions [2-9]. Here, we show that it is possible to track the simultaneous activity of different human brains during cooperation/competition activity in a different task, by neuroelectrical simultaneous recordings through the use of different electroencephalographic devices (EEG hyperscannings). Furthermore, we illustrate a methodology for the estimation of functional connectivity values from the EEG data in different subjects. This methodology is based on the concept of Granger causality but extends its applicability to the case of multi-subject analysis, which is necessary to analyze the data from the EEG hyperscannings. Such approach was suggested as a possible computational tool to be used in the EEG hyperscanning experiments, since it could complement the usual "one subject" analysis currently performed in neuroscience.

II. METHODS

A. Experimental Design for the Prisoner's Dilemma

The Prisoner's Dilemma game involves two players and two possible choices: to cooperate or defect. If both the players cooperate, they have small incomes (Cooperation condition). If one player cooperates and the other defects, the cooperator has a big loss and the defector has a big income. If both players defect, they have small losses (Defect condition). In the so-called Tit-for-Tat, each player imitates its opponent's past behavior in his/her next decision (Tit-for-Tat condition). The aim of the game is to reach the highest score. Ten healthy subjects (5 couples) took part in the experiment. They were all informed about the aim of the EEG recordings and approved the study. Subjects interacted seated one beside the other. A screen displaying the information necessary to the games and generating the timing of the tasks was disposed in front of them. They expressed their choice (decision to cooperate or to defect) through a keyboard and the computer recorded each subject's response and generated a mark on the subject's EEG traces for successive off-line analysis. The choice was blind to the other player. The general timeline of each trial is as follow: the trial starts with the presentation of the payoff matrix related to the decision that a subject could make in the game. Then, the players are prompted to enter their choices and afterwards the results of the trial is showed to them for an interval of 4 seconds, reporting the cooperation/defection choice made by the other player and the total score obtained by each subject. The EEG analysis was performed within this 4 seconds period, considered significant for the successive decisions. Figure 1 presents a typical setup for the EEG hyperscanning during the Prisoner's Dilemma task.

Figure 1. A typical setup for the execution of the Prisoner's Dilemma. The brain activities are recorded simultaneously with two or three EEG systems. The time period for the EEG analysis is the 4 seconds window before the subjects perform their overt decision.

B. Experimental Design for a card game

Fourteen pairs of healthy subjects 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. The subjects were asked to play an Italian card game, called *tressette*. The game is played with two couples, with one couple sitting at north and south, and the other couple at east and west, like in "Bridge". All the subjects were already able to play this game and were aware of the game rules. The player to the dealer's left places the first card on the deck; the other players, in a clockwise order, play a card of the leading suit if they have one, otherwise a card of another suit. The round is won by the highest card of the suit. Ten cards were distributed and played for each game by every subject. Ten rounds represent an entire match. A total number of ten matches were played between the two opposite couples. Each round took about 30–45 seconds, while each player was involved in making a decision for about 5–12 seconds. This is the time needed to generate a decision and make an overt verbal communication to the experimenter who was charged to move physically the card on the deck.

In Fig. 2 it is possible to observe the experimental setup for the card game. The players sit around a table and the cards are placed on the desk disposed in front of them. The players are indicated by the signs N (North), E (East), S (South) and W (West). Team A is composed by the players N and S, while team B is composed by the player E and W. Two experimenters near the players during the EEG recording session moved the cards according to the subjects' verbal instructions.

Fig. 2. EEG hyperscanning performed by using 4 high resolution EEG devices while a card game was played. The players have to verbally indicate the card they want to play.

C. High Resolution EEG and estimated spectral maps

High resolution EEG recordings, the estimation of the cortical activity by using accurate head modeling, the solution of the distributed inverse problem and the connectivity estimation are performed in agreement with the previously published papers [3, 4]. From the cortical estimated waveforms, the spectral activity during the task time interval was first estimated for each one of the thousands dipoles for the cortical model, then statistically compared with those related to a rest period. In the rest period, each subject seated in front of the screen, watched to images similar to those used in the game, but without any relation with the game itself. T-test values between the power of the frequency spectra during the task and the rest were then mapped on the cortical model in the different frequency bands: Theta 3-6 Hz, Alpha 7-12 Hz, Beta 13-29 Hz, and Gamma 30-40 Hz. Due to the multiple comparisons issue, the statistical threshold was subjected to Bonferroni correction to reach a nominal value of $p^*<0.05$. Different regions of interest (RoIs) coincident with the Brodmann areas (BA) have been selected for this study. They include the areas 5, 7, 8, 9, 10, 11 and the Anterior Cingulate Cortex (ACC) for both hemispheres.

III. RESULTS

A. Statistical Spectral Maps for Prisoner's Dilemma

Fig. 3 shows the statistically significant average spectral power distribution of the group of subjects investigated. Results were depicted on the average cortex model used in the study, seen from 6 different perspectives. In grey, the areas which showed no significant difference with respect to the rest period. In colour, the areas which showed a statistically significant activation with respect to the rest. Only Bonferroni-corrected statistically significant spectral differences in cortical areas common to at least 7 of 10 subjects were represented. The color scale codes for the average value of the t-test in that pixel across population.

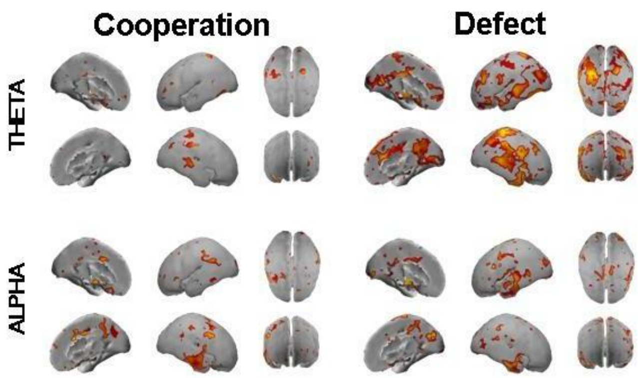

Fig. 3. Distributions of the statistically significant differences in power spectra for the two conditions: Cooperation (first column), Defect (second column). Results were depicted on the average cortex model used in the study, seen from 6 different perspectives. In grey, the areas which showed no statistical significant difference with respect to the rest period. In color, the areas which showed a significant activation with respect to the rest. The color scale codes for the average value of the t-test in that pixel across population (the lighter the higher).

First column: results for the Cooperation condition. Second column: Defect condition. The results in two frequency bands are shown for comparison. It can be noted that the power spectra activity is statistically significant when compared to the rest state in the parietal, central and frontal regions in the theta and alpha frequency bands in the Defect condition. In such condition the spectral activity in the beta and gamma frequency bands is not relevant. In the Cooperation condition the most preponderant activity is noted in the theta and alpha frequency bands. It is interesting to note that the statistically significant cortical activity is similar across all the conditions in the beta and gamma bands, interesting the prefrontal areas of the right hemisphere. Almost all the statistical significant cortical activity generated by the proposed task is greater than the cortical activity observed during the rest conditions. This is reflected by the large zone with positive t-values (red and yellow hues). Few cortical areas in the gamma frequency band displayed significant reduction of cortical activity, (not shown in the Fig.3). Such cortical zones are located mainly in the occipital cortical regions.

B. Estimation of cortical activity and connectivity during a card game

The estimation of the functional connectivity between the signals estimated in the cortical areas of different subjects has been performed for all the possible pairs of subjects that participated in the same game session. Results suggested that the players playing together in the same team, across the different tables, showed statistically significant functional connectivity between different cortical areas, at the chosen level of statistical significance ($p<0.001$ Bonferroni corrected for multiple comparisons). In particular, Fig. 4 presents the average statistically significant functional connectivity pattern obtained by Partial Directed Coherence [10] across all the pairs of players considered in this experiment in the beta and gamma bands. This means that the represented functional links between different cortical areas in different subjects are present in all the couples analyzed.

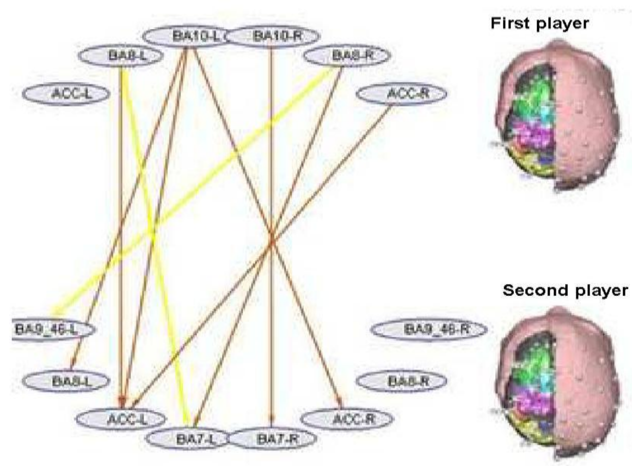

Fig. 4 Representation of the functional connectivity obtained for all the teams analyzed in the present experiment. The arrows depict functional connectivity between different ROIs in the two sets of players. Yellow arrows depict the functional links that are statistically significant in all the pairs of players investigated, while the orange arrows depict functional links that are statistically significant in all the couples but one. The time interval between the first player's move and the response of their companion (i.e the "second player") was analyzed with EEG hyperscanning. BAx-L label means Brodmann Areas x, left hemisphere.

The arrows in Fig. 4 coded the direction of the Granger causality between the signals estimated in two cortical areas. The color of the connection returned the information about the number of couples sharing such connectivity link. For instance, if a functional connectivity link is depicted in yellow, this means that it is present in all the couples analyzed; if it's depicted in orange it means that such link is shared by all the couples but one. It is interesting to note how those functional links are directional, as resulted from the properties of the employed PDC estimator. Such functional connectivity causally put in connection the signals estimated from the ROIs of the first player with the signals estimated in the ROIs of the second player. Resulting functional connectivity links suggest a causal relation between the signals estimated from the prefrontal areas 8 and 9/46 of the first player and the signals estimated mainly in the anterior cingulate cortex and the parietal areas of the second player.

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IV. Discussion

A. Methodological considerations

We presented a methodology for gathering the EEG activity in several subjects simultaneously (EEG hyperscanning). In addition, we proposed the use of a modified functional connectivity estimator to assess Granger-causal relationships between the signals estimated in ROIs of different subjects. The functional connectivity computed in this study expressed statistical and mathematical properties of the estimated cortical time series in the analyzed population. Here, an extension of the hyperscanning methodology already provided by using hemodynamic signals [11] is performed by using neuroelectric signals of brain activity. The presented methodology could prove useful for the evaluation of the cerebral activity of a group of subjects that interact. It must be clear that the functional connectivity estimation is a mathematical entity that obviously does not describe a "passage" of some physical quantity between two brains, but rather describes the statistical and mathematical properties of signals estimated from different cortical areas of the subjects.

B. Experimental considerations

The particular results, presented here for illustrative purposes only, are obtained with the application of the described methods to the EEG hyperscannings of card players during a cooperative game. In summary, results in the card game show that the signals estimated in the anterior cingulate cortex (ACC) of the second players of the team showed a statistically significant Granger-causality link with the signals estimated in different cortical areas of the first players of the same team. Moreover, in the first players of the analyzed teams, the signals estimated from the prefrontal areas (BA8) on both brain hemispheres develop a statistically significant Granger-causality link with the signals estimated in the regions of the brain of their companions (ACC, BA7). In the Prisoner's Dilemma game, some statistically significant activated area in the Defect conditions, in theta band, differed from those activated in the Cooperation condition. From these results, it seems that in the Defect condition a major activation and planning is necessary with respect to the choice of cooperate.

As a whole, 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 add new and useful instruments to the analysis of neural substrates of the human social behavior.

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