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Estimation of the Cortical Activity from Simultaneous Multi-subject Recordings during the Prisoner's Dilemma

L. Astolfi, F. Cincotti, D. Mattia, F. De Vico Fallani, S. Salinari, M.G.Marciani, C. Wilke, A. Doud, H. Yuan, B. He and F. Babiloni

Abstract—**One of the most challenging questions open in Neuroscience today is the characterization of the brain responses during social interaction. A major limitation of the approaches used in most of the studies performed so far is that only one of the participating brains is measured each time. 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. In this paper, we present the results of the simultaneous neuroelectric recording of 5 couples of subjects engaged in cooperative games (EEG hyperscanning). The simultaneous recordings of couples of interacting subjects allows to observe and model directly the neural signature of human interactions in order to understand the cerebral processes generating and generated by social cooperation or competition. We used a paradigm called Prisoner's dilemma derived from the game theory. Results collected in a population of 10 subjects suggested that the most consistently activated structure in social interaction paradigms is the orbitofrontal region (roughly described by the Brodmann area 10) during the condition of competition.**

I. Introduction

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 is an important one. The simultaneous recording of neuroelectric activity of the brain is called "EEG hyperscanning". In this paper we present the results obtained by EEG hyperscannings performed on a group of subjects engaged in a cooperation/competition task, and how it is possible to depict the synchronization between different cortical areas of different subjects interacting during such game by using appropriate processing methodologies. The game theory has been proved to be useful in the investigation of the neural basis of social interaction, since it allows a formal definition of social situation in which the players may profit or loose by cooperating or competing [1] like in the Prisoner's Dilemma, in which you have to decide whether to cooperate with an opponent, or defect [2]. By simultaneously recording the neuroelectrical brain activity in two players during the execution of the Prisoner's Dilemma game, we aim at understanding the modification of brains activity during such social interactions and to investigate the existence of possible cortical markers related to the behaviour of the subjects during the game.

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L. Astolfi, Dep. of Computer Science of the Univ. of Rome "Sapienza" , Dep. of Physiology and Pharmacology of the Univ. of Rome "Sapienza", and IRCCS "Fondazione Santa Lucia", Rome, Italy. (phone: +39-06-51501466; e-mail: laura.astolfi@uniroma1.it). F. Cincotti and D. Mattia, Fondazione Santa Lucia, Rome, Italy. S. Salinari, Dep. of Computer Science of the Univ. of Rome "Sapienza". M. G. Marciani, Dep. of Neuroscience, University of Tor Vergata, and "Fondazione Santa Lucia", Rome, Italy. B. He, C. Wilke, H. Yuan and A. Doud, Department of Biomedical Engineering, University of Minnesota, Minneapolis, Minnesota, USA. F. De Vico Fallani and F. Babiloni, Dep. of Physiology and Pharmacology of the University of Rome "Sapienza".

II. Methods

A. Experimental Design

The Prisoner's Dilemma game involves two players and two possible moves: cooperate or defect. If both the players cooperate, they have small wins (Cooperation condition). If one player cooperates and the other defects, the cooperator has a big loss and the defector has a big win. If both players defect, they have small losses (Defeat condition). In the so-called Tit-for-Tat, each player imitates its opponent's move in the next move (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 both the subjects. 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. A 96-channel system (BrainAmp, Brainproducts GmbH, Germany) was used to record EEG electrical potentials by means of an

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electrode cap, while electromyogram (EMG) and electrooculogram (EOG) signals were also recorded. Sampling rate was 200 Hz. EEG signals were then corrected from eye movements and muscular artifacts were filtered from all recordings. Only artifact-free trials were then processed in all the subjects and submitted to the following analysis.

B. High Resolution EEG and estimated spectral maps

High-resolution EEG technologies have been developed to enhance the poor spatial information content of the EEG activity [3,4]. In this study the estimation of cortical activity from high-resolution EEG recordings was performed by solving the associated linear inverse problem by using the average head model available from McGill University. Estimation of the current density strength for each dipole was obtained by solving the linear inverse problem, according to techniques described in previous papers [5,6]. 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, such spectral activity was 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 used by using Bonferroni correction to reach a nominal value of $p^*<0.05$.

III. RESULTS

A. Statistical Spectral Maps

Fig. 1 shows the statistical 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. First column: results for the Cooperation condition. Second column: Defeat condition. Third column: Tit-for-Tat condition. The results in the four 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 Defeat 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. The Tit-for-Tat condition is characterized by a cortical activity different from the rest condition in the prefrontal cortical areas of the right hemisphere. 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, signalled by the blue hues in the color bar. Such cortical zones are located mainly on the occipital cortical regions.

IV. DISCUSSION

The aim of the present study was 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 from couples of subjects playing the Prisoner's Dilemma game. The analysis of statistical power spectra data suggested that the Defeat conditions elicited the greater cortical activity in the theta and frequency band when compared to the other conditions. It could be hypothesized that this greater power spectra activity reflects the major efforts in the generation of a sudden decision by the subjects, when compared to the Cooperation and the Tit-for-Tat decisions. In fact, the Defeat conditions occurs randomly in the game, in the middle of series of Cooperation or Tit-for-Tat conditions. The higher cortical activity elicited by this condition is then consistent with the efforts generated by the cortical decision system to generate the interruption of the Cooperation or Tit-for-Tat sequence with the Defeat decision.

It could be also hypothesized that a large involvement of the frontal regions during the Defeat condition is generated by the effort of the decision system, located by previous studies also in the orbitofrontal regions. This is consistent with the vision of the orbitofrontal regions as the site in which decisions are made on the base of both rational but also emotional conditions [8]. Speculations could be made about the more difficult emotional situation to generate a Defeat decision for a player against the other player. The fact that the cortical activity patterns are similar in the beta and gamma frequency bands across the all conditions suggest that the right prefrontal cortical areas interested are related to the stress of the task performed against the other player.

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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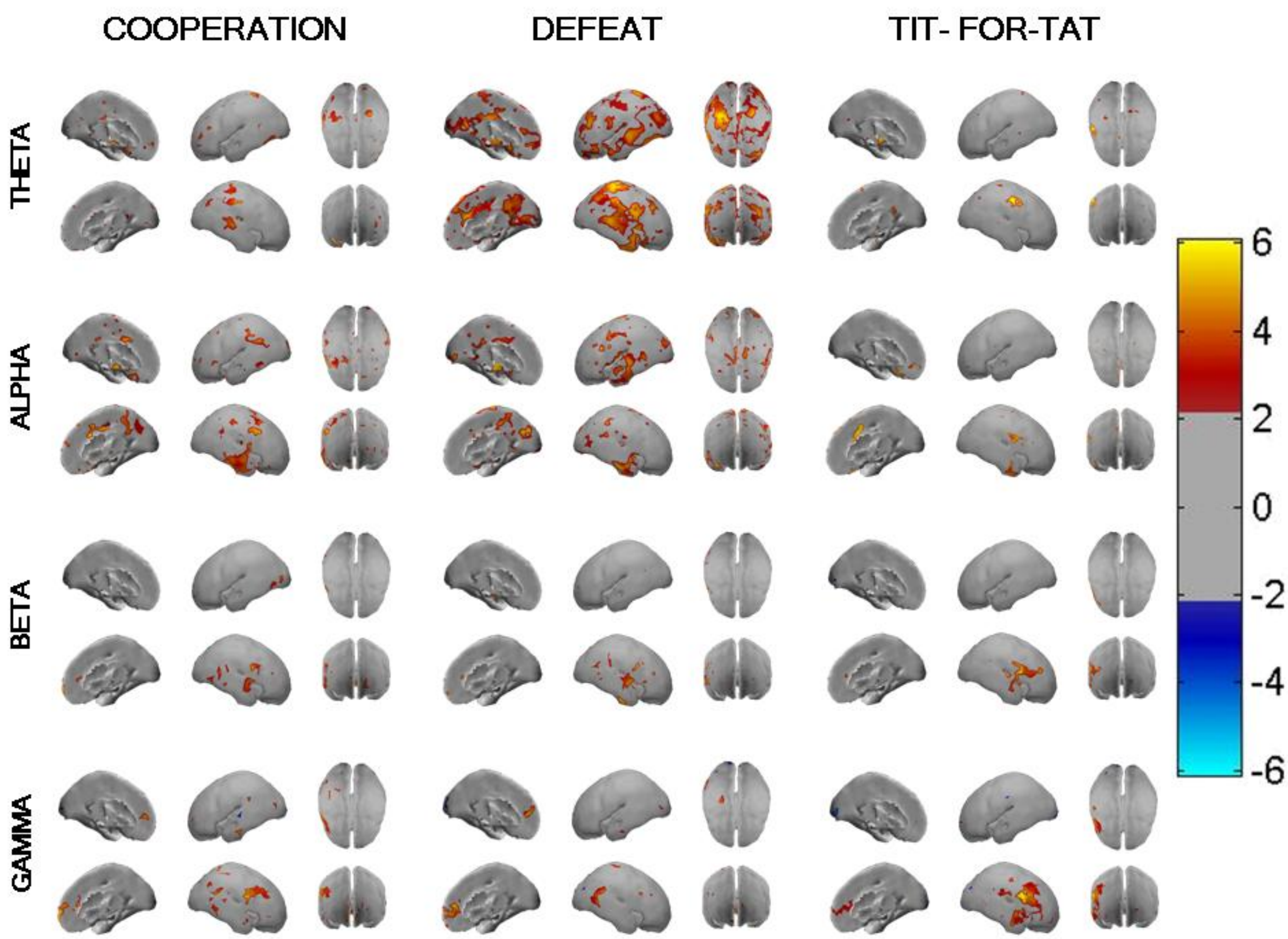

Fig. 1. Distributions of the statistically significant differences in power spectra for the three conditions: Cooperation (first column), Defeat (second column) and Tit-for-Tat (third column). Results were depicted on the average cortex model used in the study, seen from 6 different perspectives. In 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 (see color bar on the right).