EEG hyperscanning study of inter-brain synchrony during cooperative and competitive interaction

Nishant Sinha, Tomasz Maszczynk, Zhang Wanxuan, Jonathan Tan, and Justin Dauwels
School of Electrical and Electronics Engineering,
Nanyang Technological University, Singapore
Email: nishant002@e.ntu.edu.sg, jdauwels@ntu.edu.sg

Abstract—Social cognition is the study of how people interact with each other in a social situation. An effective interaction would require higher degree of cognitive involvement between the participants and consequently, an enhanced synchrony between their neural mechanisms. In this study, twelve pairs of subjects interacted with each other via a cognitively engaging experimental paradigm in which they either competed or cooperated with each other for performing a task. While they were performing the task we incorporated electroencephalographic (EEG) hyperscanning techniques by simultaneously recording the EEG activities of the interacting subjects. We quantified these interactions by computing the inter-brain synchrony (IBS) and studied the changes in IBS under different experimental conditions. We found that the inter-brain synchrony between the subjects was significantly higher when they cooperated with each other as compared to the competitive scenario. Furthermore, we found that IBS was significantly enhanced when the subjects were physically separated i.e. they cooperated via an intranet network. In this work, we have demonstrated how EEG hyperscanning technique can be employed to study inter-brain synchronization under different conditions.

Index Terms—EEG Hyperscanning, Inter-Brain Connectivity, Social Neuroscience, Team Based Learning, Cognition

I. INTRODUCTION

Hyperscanning is a technique to study neural mechanisms during real-time social interactions between multiple subjects by simultaneously recording their neural activities. Simultaneous recording of ongoing cerebral processes can elucidate temporal co-variance of neural activity as a result of ongoing behavioural and social exchanges [1], [2], [3]. Investigation of these emerging neural processes between the brains of interacting subjects is potentially useful to elicit how a particular task may be effectively executed in a team based learning (TBL) environment as well as in composing teams [4].

Several hyperscanning studies have been performed to measure multi-subject real-time interactions, the first of which was reported by [5] in which two fMRI acquisition systems located several miles apart were connected via internet. Though majority of studies in the last decade have been performed using fMRI, we focus on EEG hyperscanning technique which are relatively inexpensive, (potentially) mobile, and can be incorporated in a more naturalistic setting to measure motor and cognitive interactions [6], [7], [8], [9], [10], [11].

In a team-based learning environment, cooperation and competition are crucial social interactions which alter the brain mechanisms of the interacting subjects. For instance, [12] has reported synchronous neural activities between brains of the subjects as they play guitar together, reflecting interpersonal coordination. Significant involvement of orbitofrontal regions in terms of connectivity has been reported by [8] during cooperative and competitive interaction. It has been demonstrated by [13] that graph analysis of hyper-brain networks can be used to predict non-cooperative interactions during decision-making phase of participants. These results encourage application of EEG hyperscanning technique for evaluating peer interactions in a TBL setting which is a relatively unexplored field.

With the advent of virtual reality (VR) environments, the bounds between physical and virtual interactions are becoming blur. VR environments are being increasingly used to simulate social interactions and natural events for various neuroscience research and therapy [14]. In a TBL setting, virtual interactions among peers are often encouraged via virtual classrooms. However, little is know about the effects on the brain synchronization of subjects as a result of physical and virtual interactions.

In this study, we have investigated the effect of cooperative and competitive interactions in both physical and virtual space by computing the synchronization between the brains of the subjects. We aim to study the interactions that may lead to a higher inter-brain synchrony, with a hypothesis that an enhanced synchronization between participants is desirable for an efficient task execution.

II. METHODS

A. Experiment design

The goal of our experimental framework was to simulate competition and cooperation between a pair of subjects. Accordingly, we designed a computerised pong-game, similar to that of a table tennis, in which the objective of a player was to defeat the opponent by hitting a ball back and forth using a paddle (vertical bar) that can be controlled in one dimension. We designed the game in Python programming environment (Python Language Reference, version 2.7). In order to make the game more engaging, the speed of the ball was increased arbitrarily with the progress of the game.

A competition task was simulated when two subjects played against each other. Similarly, cooperation task was simulated when the subjects played as a team, with each player having a control on a paddle to hit the ball back and forth, for defeating
a computer program. Depending on the mode of delivery of the game, we investigated cooperative and competitive tasks via two mode of interactions: physical and virtual. We incorporated the interaction in physical space by positioning the subjects in the same experimental facility, such that they were in sight of each other but separated far enough to avoid any interference between the EEG recording systems. On the other hand, we incorporated the interaction in virtual space by positioning the players in distant experiment facilities while delivering the game via an intranet connection. This way our experimental framework, enabled us to test four different paradigms:

1) Cooperation vs. competition in physical space
2) Cooperation vs. competition in virtual space
3) Cooperation in physical space vs. virtual space
4) Competition in physical space vs. virtual space

B. EEG Data Collection and Pre-processing

Twelve pairs of healthy subjects participated in our study. We used 14 channel EEG acquisition system for simultaneously recording the EEG signals from each pair of subjects while they were engaged in the performing tasks detailed in section II-A. The electrodes were placed as per the international 10-20 electrode location system. We positioned the subjects far enough to ensure that there was no interference between the EEG acquisition equipments. All subjects gave their written informed consent to participate in the study.

The EEG data were bandpass filtered between (1 – 45) Hz, and each EEG signal was normalized. We used a common average reference for the data analysis. We applied Independent Component Analysis (ICA), using logistic infomax ICA algorithm, to decompose the EEG data into independent components [15], [16]. By visual inspection, some of the components containing artefacts, such as the eye blinks, were rejected and the artifact-free EEG signals were obtained by combining the artifact-free ICA components. Finally, we segregated the EEG signal into the following four frequency bands: $\theta(3 – 7)$Hz, $\alpha(8 – 12)$Hz, $\beta(13 – 29)$Hz, and $\gamma(30 – 40)$Hz.

C. Estimation of Inter-brain Synchrony

In order to estimate the inter-brain synchrony, we applied the Pearson Correlation Coefficient, as it has been shown to be less prone to spurious hyper-connection [17]. Furthermore,
in our study we compare two scenarios (cooperation vs. competition, physical vs. virtual space) and only retain the edges that are significantly different between these two scenarios. Spurious connections are most likely removed through such comparison.

Specifically, we first divided 4 min of EEG recording into segments of 1s duration such that each segment overlapped with the previous segment with 0.5s. We computed the cross-correlation between the EEG signals for each segment for different lags and chose the maximum value of cross-correlation for each segment. Therefore, we obtained a $14 \times 14$ matrix denoting the synchronization between the brains of the interacting individuals for each one second overlapping intervals. By averaging all these matrices across all the 1s segments, we computed the net inter-brain synchrony as a representative of the entire 4 min duration.

We repeated the same procedure for all the 12 pairs of subjects. Therefore, we obtained 12 sets of inter-brain connectivity matrices for each experiment. This has been illustrated in Fig. 1 where $P_{Comp}$ and $V_{Comp}$ denotes the inter-brain synchrony between all pairs of subjects competing in physical and virtual space respectively. Similarly, $P_{Coop}$ and $V_{Coop}$ represents the inter-brain synchrony between all pairs of subjects cooperating in physical and virtual space respectively. Note that each of these matrices have 3 dimensions $(i \times j \times n)$ where $(i = 1, 2, \cdots 14)$ and $(j = 1, 2, \cdots 14)$ represents the EEG channels of player A and player B respectively and $(n = 1, 2, \cdots 12)$ represents the number of trails (or pair of different subjects) in our experiments. An example of inter-brain synchrony resulting from interactions between the two players is illustrated in Fig. 2. Note the each element of $P_{Comp}, V_{Comp}, P_{Coop}, V_{Coop}$ represents an edge i.e. a hyper-connection between the brain areas under a pair of electrodes of the two players.

In order to study the differences in the inter-brain synchrony between different experimental scenarios, we made the statistical comparisons across each edge vector to determine significantly different edges between a) $(P_{Comp} \text{ vs. } P_{Coop})$, b) $(V_{Comp} \text{ vs. } V_{Coop})$, c) $(P_{Coop} \text{ vs. } V_{Coop})$, d) $(P_{Comp} \text{ vs. } V_{Comp})$. Specifically, we made a group-level, pair-wise statistical comparison between the edge vector for each of these scenarios and retained only significantly different edges. For instance, to determine if the edge linking the cortical area under the electrode labelled 1 in group A with the corresponding cortical location in group B, is significantly different in two scenarios, we compared the vector $\{r_{P_{Comp}}(1, 1, n) \mid n = 1, 2, \cdots 12\}$ with $\{r_{P_{Coop}}(1, 1, n) \mid n = 1, 2, \cdots 12\}$. For statistical comparison, we applied Wilcoxon signed-rank test with a strict threshold on p-values at 0.01. We corrected the type I errors to compensate for multiple comparisons by applying false discovery rate correction at a significance level of 5%.

Therefore, for each pair-wise comparisons, we obtained inter-brain synchrony matrices consisting of only significantly different edges. Finally, we computed the inter-brain synchronization strength (IBS) for each pair of subjects by summing up all the significantly different edges. For instance, in case of pair-wise comparison between cooperation and competition in physical space, first we obtained $P_{Comp}$ comprising of only the significantly different edges and then we computed the IBS vector as: $\text{IBS}_{P_{Comp}} = \left\{ \sum_i \sum_j r_{P_{Comp}}(i, j, n) \mid n = 1, 2 \cdots 12 \right\}$, where $i,j$ are the indices corresponding to the significantly different edges.

III. Results

![Fig. 3](image_url) Statistically significant inter-brain connections are illustrated for a) cooperation vs. competition in physical space, b) cooperation vs. competition in virtual space, c) cooperation in virtual space vs. physical space, and d) competition in virtual space vs. physical space. Note that only in panel (a) and (c) significantly different inter-brain connectivities were found.

![Fig. 4](image_url) (a) Average inter-brain synchrony is significantly higher ($p = 0.0039$) for cooperation compared to competition in physical space (b) Cooperation via virtual interactions results in a significantly higher synchrony ($p = 0.0068$).
A) Competition vs. cooperation in physical space

B) Competition vs. cooperation in virtual space

C) Cooperation in physical space vs. virtual space

D) Competition in physical space vs. virtual space

\[ \alpha (\text{8-12 Hz}) \]
\[ \theta (\text{3-7 Hz}) \]
\[ \beta (\text{13-29 Hz}) \]
\[ \gamma (\text{30-40 Hz}) \]

A) Competition vs. cooperation in physical space

We compared the average inter-brain synchrony at group level between different tasks as detailed in section II-A. The brain schematics in Fig. 3 illustrate the locations of significantly different hyper-connections. Note that we found statistically significant inter-brain connections only in Fig. 3(a) and (c), corresponding to the comparison between cooperation vs. competition in physical space and cooperation in virtual space vs. physical space respectively.

Fig. 3(a) and Fig. 4(a) illustrate the comparison of net inter brain synchrony between competition in physical space, \( P_{\text{Comp}} \), with the cooperation in physical space, \( P_{\text{Coop}} \). We observe that the cooperation scenario leads to a significantly higher inter-brain synchrony as compared to the competing scenario. This is evident from Fig. 4(a) where, \( \text{IBS}_{P_{\text{Comp}}} < \text{IBS}_{P_{\text{Coop}}} \) and \( p = 0.0039 \).

In Fig. 3(c) and Fig. 4(b), we compared cooperation in virtual space, \( V_{\text{Coop}} \), with the cooperation in physical space, \( P_{\text{Coop}} \). It can be seen that cooperation in virtual space enhances inter-brain synchrony as compared to the cooperation in physical space since \( \text{IBS}_{V_{\text{Coop}}} > \text{IBS}_{P_{\text{Coop}}} \) and \( p = 0.0068 \).

B. Consistency across different frequency bands

We investigated the inter-brain synchrony across different frequency bands for the two cases, \( (P_{\text{Comp}} \text{ vs. } P_{\text{Coop}}) \) and \( (P_{\text{Coop}} \text{ vs. } V_{\text{Coop}}) \), where we found enhanced synchrony. The frequency bands where we discovered significant difference between the aforementioned comparisons are summarized in Fig. 6. The specific links that were found to be different are illustrated in 5.

As shown by Fig. 6(a)-(b), only the \( \alpha \) and \( \beta \) frequency bands indicated an enhanced inter-brain synchronization for the comparison between the competition and cooperation in physical space i.e. \( (\text{IBS}_{P_{\text{Comp}}} < \text{IBS}_{P_{\text{Coop}}}) \) with \( p = 0.0039 \) for both \( \alpha \) and \( \beta \) bands. However, we did not find any significant difference in the other frequency bands.
Inter-brain synchrony was found to be significantly different across all the frequency bands in the physical space versus virtual space. Note that only significant difference was found in the α band. 

**TABLE I**

<table>
<thead>
<tr>
<th>Bands</th>
<th>IBS$_{Coop}$</th>
<th>σIBS$_{Coop}$</th>
<th>IBS$_{Comp}$</th>
<th>σIBS$_{Comp}$</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1-45)Hz</td>
<td>0.7206</td>
<td>0.0854</td>
<td>0.6671</td>
<td>0.0710</td>
<td>0.0039</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>1.0000</td>
</tr>
<tr>
<td>α (8-12)Hz</td>
<td>2.0403</td>
<td>0.0317</td>
<td>2.0077</td>
<td>0.0273</td>
<td>0.0039</td>
</tr>
<tr>
<td>β (13-29)Hz</td>
<td>0.3567</td>
<td>0.0066</td>
<td>0.3518</td>
<td>0.0066</td>
<td>0.0039</td>
</tr>
<tr>
<td>γ (30-40)Hz</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<table>
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<tr>
<th>Bands</th>
<th>IBS$_{Coop}$</th>
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<th>IBS$_{Comp}$</th>
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<tr>
<td>(1-45)Hz</td>
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<td>0</td>
<td>0</td>
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<td>1.0000</td>
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<tr>
<td>θ (3-7)Hz</td>
<td>0</td>
<td>0</td>
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<td>α (8-12)Hz</td>
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<td>0.0338</td>
<td>1.5407</td>
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<tr>
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<tr>
<td>γ (30-40)Hz</td>
<td>1.1906</td>
<td>0.0383</td>
<td>1.1785</td>
<td>0.0453</td>
<td>0.0068</td>
</tr>
</tbody>
</table>

For the comparison between cooperation in physical space and virtual space, we found significant difference across all frequency bands which is shown in Fig. 6(c)-(f). Note that for all frequency bands $IBS_{Coop} < IBS_{Comp}$. Additionally, p-values for θ, α, β and γ were found to be 0.0020, 0.0137, 0.001 and 0.0068 respectively. Table I summarizes the mean and standard deviation of strength of inter-brain synchrony (IBS) for each pair-wise comparisons. Moreover, the p-values for each comparisons discussed above are also tabulated.

**IV. DISCUSSION AND CONCLUSION**

In this study, we have investigated the following questions: (i) For a given cognitively engaging task, are the brains of the subjects more synchronized during cooperation or competition? and (ii) What is the efficacy of cooperation and competition via physical and virtual interaction on brain synchronization between peers?

We applied EEG hyper-scanning techniques as detailed in section II-A. As shown in Fig. 1, we obtained $P_{Comp}$, $P_{Coop}$, $V_{Comp}$ and $V_{Coop}$ which are the set of full, non-symmetric matrices computed by applying cross-correlation between the EEG signals as elaborated in section II-C. Note that each element of $P_{Comp}$, $P_{Coop}$, $V_{Comp}$ and $V_{Coop}$ denotes an edge i.e. hyper-connection between brain areas, represented by an electrode pair, of the two players. These hyper-connections need not be symmetric because the inter-brain synchrony matrices are not symmetric.

The objective of our study is to find the difference in synchronization level under different scenarios. Therefore, we perform a pair-wise, group-level statistical comparison...
between each edge of $P_{\text{Comp}}$, $P_{\text{Coop}}$, $V_{\text{Comp}}$ and $V_{\text{Coop}}$ and we retain only those edges which we detect as significantly different. The brain schematics in Fig. 3 and Fig. 5 illustrate the locations of significantly different hyper-connections, wherever detected. Fig. 4 and Fig. 6 depict the net strength of connection for the two cases under comparison, which enables us to draw conclusions about the difference in synchronization level of various scenarios.

We found that cooperation results into significantly higher synchronization as compared to competition. Lower inter-brain synchrony during competition can be explained because as the participants play against each other, they would have different strategy to defeat the opponent. Moreover, the information perceived and processed from the interactions in the game will also be different for each subjects.

For our second question of interest, we found that cooperating via virtual environment enhances synchrony compared to the physical environment. This scenario is interesting because it may be extrapolated to a cooperative task in a team based learning environment. Our result suggests that if peers are facilitated to collaborate via virtual interactions, they may perform more effectively. An inherent, though intuitive, assumption is that inter-brain synchrony is positively correlated with performance metrics.

A closer look at different EEG frequency bands shows that the results for both cases remains significantly different in the β frequency band, which is known to be associated with active thinking and focus.

In this study, we have offered a basic framework towards a more comprehensive study to assess team based learning using a multi-subject EEG hyperscanning technique. In future, we plan to employ these techniques in a real-time team based learning setting, in which inter-brain synchrony, especially in specific frequency bands, can quantitatively represent the cognitive state of a subject in real-time.

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REFERENCES


