A new measure for team performance: Measuring inter-brain synchrony of engineering students when designing and building

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Abstract

This research paper examines the patterns of inter-brain synchrony among engineering student teams and the relationship between inter-brain synchrony and team cooperation and performance. A pilot study was conducted with eight two-person teams of fourth-year undergraduate civil engineering students. Three collaborative design and build tasks were assigned to each team. Two independent raters carried out the behavioral analysis, scoring team cooperation. Each team member wore a functional near-infrared spectroscopy (fNIRS) device to measure inter-brain synchrony during the tasks. The results showed that inter-brain synchrony occurred during the team task, but the patterns varied between groups and tasks. Elevated levels of inter-brain synchrony were observed in the left ventrolateral prefrontal cortex (VLPFC) and left dorsolateral prefrontal cortex (DLPFC). The left VLPFC and left DLPFC are often associated with cognitive processes such as problem-solving, working memory, decision-making, and coordinated verbal exchange. Inter-brain synchrony was positively correlated with task performance and cooperation when teams were asked to design and build a structure given limited time and money but negatively correlated with cooperation and performance on other more open-ended design sketching tasks. The study's findings suggest that inter-brain synchrony exists when engineering students work together as a team, but the results are inconsistent between task types. Inter-brain synchrony could be a useful metric for measuring team cooperation and performance, particularly in tasks that require coordinated verbal exchange, problem-solving, and decision-making. However, the study's small sample size limits the generalizability of the results. Future studies with a larger sample size and more diverse groups of engineers are needed to validate the findings and explore their implications further.

Introduction

The performance of engineering project teams is more than the sum of each team member's contribution. The collective performance of engineering project teams results from team members sharing ideas and actions, and this collaboration shapes their values toward common goals. A potential explanation for team performance is inter-brain synchrony, the coordinated brain activation across individuals (Crivelli and Balconi, 2017; Czeszumski et al., 2020). Inter-brain synchrony is observed more often when teams communicate and infer intentions from one another (Cui et al., 2012).

Inter-brain synchrony is often a better predictor of team performance than self-assessment because it objectively measures how well team members communicate and collaborate (Liu et al., 2021). It could also be used to develop interventions to improve performance. For example, if a team lacks inter-brain synchrony during a brainstorming session, this might suggest that they do not understand each other's perspectives or ideas. Further analysis of individual team members could determine inhibition in the dorsolateral prefrontal cortex, a region often associated with perspective-taking (Zoh et al., 2022). An intervention such as active listening training (Kubota et al., 2004) or a perspective-taking exercise (Todd and Galinsky, 2014) could help promote greater understanding. Using inter-brain synchrony in the future as a tool for developing an intervention and performance evaluation could help engineering project teams achieve higher success levels and create more efficient outcomes.

The research presented in this study lays the foundation for future research to explore the role of inter-brain synchrony more deeply in engineering project teams. Inter-brain synchrony is observed in other disciplines but not adequately studied in engineering project teams. The possibility of observing the neural activities in such interactions and finding correlations in neural activities between coupled brains opens new avenues of understanding the neural basis of behaviors that shape engineering team dynamics.

Background

Many studies provide insight into the understanding and influence of team dynamics on the collective performance of teams (Kozlowski and Ilgen, 2006). Delice et al. (2019) reviewed articles detailing the science behind nearly fifty novel methodology tools and approaches when studying team dynamics. Many of the constructs studied are primarily measured through self-reported survey questionnaires, interviews, and observations. For instance, Svalestuen et al. (2015) used interviews to report the characteristics of highly efficient building design teams but was limited to interviews with five building design managers and validated the key characteristics through a survey of thirty-two design team members from one contracting company. Similarly, Carmenado et al., (2012) developed and deployed a questionnaire to evaluate teamwork in project management skills training on university students, using a Project Based Learning model, to improve teaching strategies. Buffinton et al. (2002) used Kirton Adaption-Innovation Inventory (KAI) scores to determine the cognitive styles of engineering and management students while studying their problem-solving techniques and team interactions. Psychometric tools can provide insight into an individual's cognitive and behavioral styles. However, the underlying neural activity for such behavioral traits provides a deeper understanding and more objective measure of the individuals in a team.

New techniques from neuroscience to measure inter-brain synchrony provide a complementary approach to studying project teams that can offer supporting evidence about existing theories. For example, inter-brain synchrony might correspond to Tuckman's stages of group development (Tuckman, 1965) or how "getting on the same wavelength" might be more than just a metaphor. It could represent a neurological phenomenon of brain-to-brain coordination when teams work well together. Team development theories such as Tuckman and Jensen (1977) suggest that teams change and evolve as a function of their development over time. It can be postulated that during such development, the synchrony in thought and behavior between team members also increases, which could result in improved team performance. Lu et al. (2019), in their study to investigate the occurrence of inter-brain synchrony during collaborative tasks and its trajectory over time, found that as cooperation behavior increased over time, so did inter-brain synchrony.

Inter-brain synchrony may also predict future behavior and cognition within teams. For instance, inter-brain synchrony in a classroom environment between students consistently predicted class engagement and social dynamics (Dikker et al., 2017). Inter-brain synchrony is high among parent-child dyads (Nguyen et al., 2021), so early detection of low inter-brain synchrony among teams could be used to intervene, improve cooperation, or increase trust among team members.

The results of a study carried out by Reinero et al. (2021) suggests that inter-brain synchrony can help understand collective performance among teams where self-report measures fail to capture behavior. A study investigating how cooperative and competitive modes affect creative performance revealed that groups with higher inter-brain synchrony showed higher creativity and originality in the cooperative mode (Lu et al., n.d.). Antonenko et al. (2019) explored synchrony during cyber-enabled collaborative problem-solving using a social or epistemic script and found that synchrony was positively correlated with collective problem-solving performance, suggesting epistemic scripts supported collaborative problem-solving compared to social scripts.

These prior studies demonstrate that inter-brain synchrony occurs among teams and that inter-brain synchrony relates to team performance. However, engineering teams are unique because they involve individuals with technical backgrounds who collaborate to develop complex systems. This presents a unique set of challenges regarding team dynamics because engineers tend to have specialized knowledge and skills that others may not easily understand. Moreover, engineering projects often have high stakes and require high precision and attention to detail.

Purpose

The purpose of the research presented in this paper was to establish the existence of inter-brain synchrony among engineering student project teams. The expectation was that inter-brain synchrony is observable among engineering student teams, increases over time as teams collaborate, and is related to their performance. The specific research questions were:

1. What patterns of inter-brain synchrony are observable among engineering student teams?
2. What is the relationship between inter-brain synchrony and team collaboration?

Method

A pilot study was carried out with 16 undergraduate fourth-year civil engineering students. The students were paired to form eight dyads. Each dyad was asked to complete multiple collaborative design and build tasks. The students forming each dyad were familiar with each other. They had worked together on an unrelated semester-long project before the study.

Tasks

The study included three tasks. Task-1 provided the teams with a set of wooden components of varying shapes and sizes and a budget. Each wooden part was assigned a unit cost. Teams could exchange imitation money for components. They were told they had 10 minutes to design and build the tallest structure within their budget and timeframe. Structures were evaluated based on the total height and cost per inch at the end of 10 minutes.

Task-2 was more open-ended than Task-1. Teams were instructed to design a structure made of 3D-printed structural elements. They were told to design their elements using pencil and paper and given a unit cost per cubic inch of material and a budget based on the total volume. Teams were given 15 minutes to design their structural components and evaluated based on staying within their budget, finishing within the 15 minutes, and the conceptual height of the structure.

Task-3 slightly changed the constraints from Task-2. Teams were asked to design a pier foundation, but instead of a budget, they were asked to design it with as few resources as possible. They were provided additional information about the size of the foundation, types of connections, and dead loads that it needed to support. Unlike the previous two tasks, task three had no time constraint for completion. The kind of task and constraints varied to explore how this may change team behavior and underlying inter-brain synchrony.

Figure 1: Sequence and timing of engineering tasks

Teams were video and audio recorded while completing the tasks. The audio data was transcribed, and the number of conversational turn-takings between team members was counted. The video recordings of teams completing the tasks were analyzed for behavioral traits. Each two-minute segment of the video was analyzed and scored on a 10-point Likert scale based on three behavioral traits: degree of participation (0 = only one person was involved; 10 = both persons equally involved), degree of dominance (0 = one person controlled the team; 10 = equal contribution) and degree of agreement (0 = complete disagreement; 10 = total agreement). The overall *cooperation score* for a team was then computed as average scores of the three behavioral traits. Two independent raters carried out the behavioral analysis and scoring, and the scores from both the independent raters were checked for inter-rater reliability measured by Inter Class Coefficient (ICC), which was satisfactory ICC: 0.83 (Balters et al., n.d.; Li et al., 2021; Mayseless et al., 2019).

The final designs from each task, created by the teams, were also evaluated and scored on a 10-point Likert scale. The first and the second task were evaluated on height, cost, time for completion, design creativity, and design effectiveness. The third task, which had different design requirements than the previous two, was scored on the cost per volume, compliance with design parameters, design uniqueness (relative to the other teams), and design effectiveness. The average scores of all the factors were computed to give the *task performance scores* for each team.

Instruments

Each participant wore a functional near-infrared spectroscopy (fNIRS) NIRSIT headband from OBELABS (see figure 2). The data was recorded using the OBELABS fNIRS software. fNIRS was used over electroencephalogram (EEG) because of the superior signal to noise ratio during movement of fNIRS. Data acquisition occurred for each design task. Changes in oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) levels in individual dyads were recorded separately on two computers while synchronizing the tasks' start and end times.

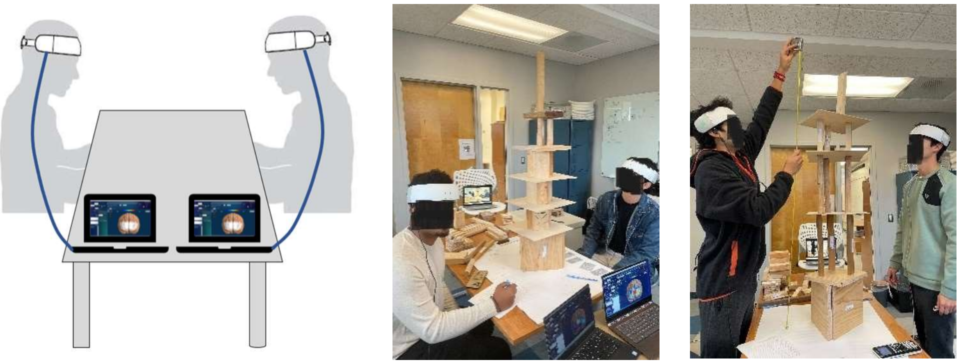

Figure 2: Experimental set for hyper-scanning during collaborative design task

The prefrontal cortex was the region of interest because of its role in executive functions. The fNIRS device comprises 24 laser sources (780/850 nm). The device provides multiple source-detector spacing at 1.5 cm, 2.12 cm, 3.00 cm, and 3.35 cm, thereby providing 204 channels for measurement. The 3 cm channels are the most commonly used and offered 48 channels of measurement (Dong et al., 2013; Shin et al., 2017; Yu et al., 2020). The 48 channels of the fNIRS device were divided amongst eight regions (four on the left and four on the right hemisphere) of the prefrontal cortex as illustrated in Figure 3.

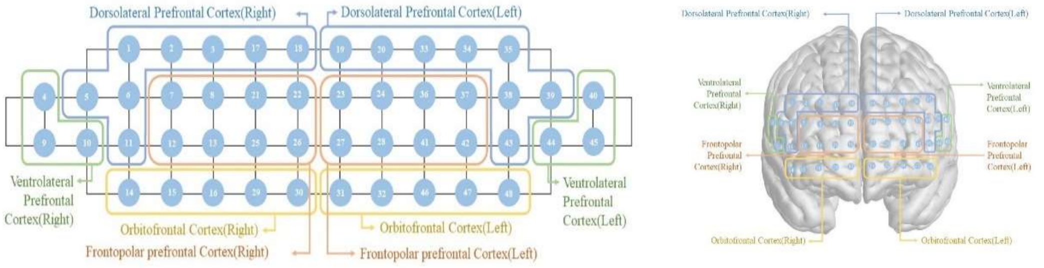

Figure 3: Placement of sensors on 3cm channel configuration along the regions of the prefrontal cortex.

Preprocessing of raw data obtained from the fNIRS software (Tak and Ye, 2014) included converting raw light density to Optical Density (OD), removing motion correction using the Temporal Derivative Distribution Repair (TDDR) method (Fishburn et al., 2019) and physiological artifacts using bandpass filtering (Pinti et al., 2019). The data was then converted from OD to hemoglobin (Hb) signal using the Modified Beer-Lamberts Law (MBLL) and regressing out global physiological noise based on the short distance channels (Mayer wave noise from blood pressure) (Sato et al., 2016).

Wavelet Transform Coherence (WTC)

Wavelet Transform Coherence (WTC) was used to measure coherence between signals from the two team members (Czeszumski et al., 2020). WTC has been used in prior neuroscience experiments such as cooperative/competitive gaming (Cui et al., 2012; Lu et al., n.d.), coordination tasks (Hu et al., 2017), and parent-child interaction (Nguyen et al., 2021; Reindl et al., 2018). For each measurement from either pair in the dyad, there are two HbO time series. A WTC analysis of the signal pair would result in a coherence map.

Data analysis was carried out in MATLAB. The 'wcoherence' function in MATLAB was used to calculate the coherence values of two HbO time series from the participating dyads. The pre-processed Hb file contains oxygenated Hemoglobin (HbO) and de-oxygenated hemoglobin (HbR) values. Since only HbO values refer to the amount of blood flow during neuron activation, only the HbO values were extracted. Both the files from each dyad were compared using WTC analysis. The sampling frequency used for the WTC analysis was 10.2 Hz (Balters et al., n.d.; Cui et al., 2012). Data from dyad participant 1 had excessive noise and was excluded from further analysis resulting in seven of the eight teams being included in the results.

Inter-brain synchrony

Inter-brain synchrony (IBS) is the extent of neural coherence observed between team participants involved in a cooperative or creative task. WTC analysis is an approach to measure IBS. WTC on the two HbO time series from the seven remaining dyads (since one group was removed due to excessive noise) resulted in a 2D coherence heat map. The coherence map shows the locally phase-locked behavior between the two-time series by measuring the cross-correlation between time series as a function of time and frequency (Cui et al., 2012; Mayseless et al., 2019; Torrence and Compo, 1998).

Figure 4 shows a typical coherence plot of one dyad for the entire experiment duration; the cone of influence (COI), marked by a white line, is an area in a coherence plot that identifies potential edge effects that can affect the accuracy of the results. The COI acts as a boundary for the region of the wavelet power spectrum where wavelets are extended over the signal, leading to potential distortions in the time-frequency plane. Due to these distortions, the wavelet coherence values outside the COI may be unreliable. For an in-depth explanation on WTC, refer to Chang and Glover (2010) and Grinsted et al., (2004).

A red line on the coherence plot marks the time when tasks occur on the time-frequency domain. It can be seen from the coherence plot that the frequency range in which tasks occur is 0.01 – 0.125 Hz, which is the frequency band of interest (FOI). This frequency band allows for the exclusion of frequencies above 0.2 Hz, which is associated with cardiac and respiration, and frequencies below 0.01 Hz, which are considered low-frequency fluctuations (Balters et al., 2023; Molavi and Dumont, 2012). Regions of coherence are displayed on correlation scale of 0 to 1, where yellow regions are of the highest coherence while blue marks lowest.

To further explore the occurrence of coherence or synchrony during each task, WTC analysis was carried out for each task. Using the trigger index, each task's start and end time, and the HbO values related to each task were extracted for each person in a dyad. Plotting task level coherence magnifies the level of synchrony for each task and enables the visualization periods of synchrony between the dyads**.**

Wavelet Transform Coherence for Cerebral Regions of Interest (ROI)

WTC was computed for each of the ROI with the rest of ROIs in the converted HbO time series, between frequencies of interest 0.01Hz – 0.125Hz. There are 64 possible combinations of ROIs (8 ROIs x 8 ROIs). The coherence values for the same pair of ROIs were then averaged. For example, the coherence value for ROI2 of participant 1 and ROI3 of participant 2 was averaged with the value for ROI2 of participant 2 and ROI3 of participant 1. This averaging process resulted in 36 ROI pairings (Balters et al., 2023; Li et al., 2021; Mayseless et al., 2019). The paired ROI coherence values were subtracted from the Resting State coherence (baseline) values, resulting in a coherence increase from the resting state. The averaged coherence values are computed in correlation values, before carrying out any statistical tests; these values were converted to Fisher z-statistics (Chang and Glover, 2010; Cui et al., 2012).

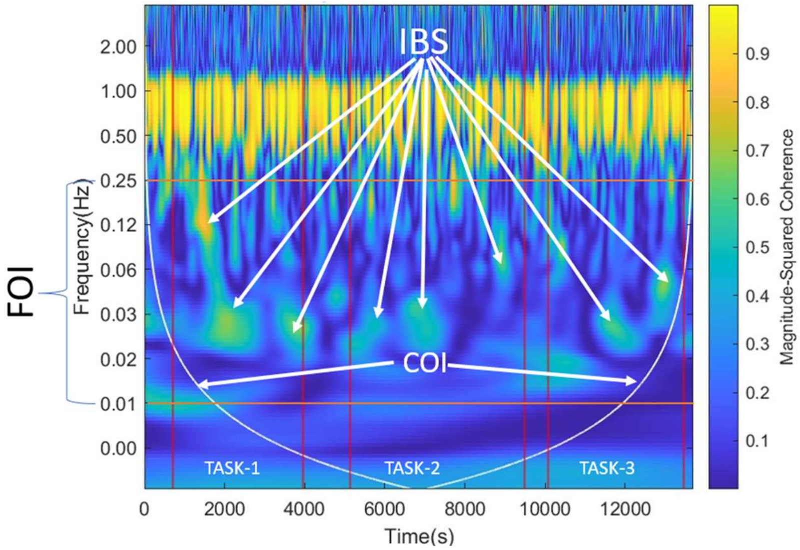

Figure 4: Overall coherence plot

Results

To address research question 1, "what patterns of inter-brain synchrony are observable among engineering student teams?" WTC analysis on the two HbO time series from each dyad showed the occurrence of inter-brain synchrony during a team task, however, inter-brain synchrony patterns varied between groups and tasks. Figure 5 below shows the average coherence plot for each task across all groups. The occurrence patterns in the inter-brain synchrony vary with time and intensity between each task.

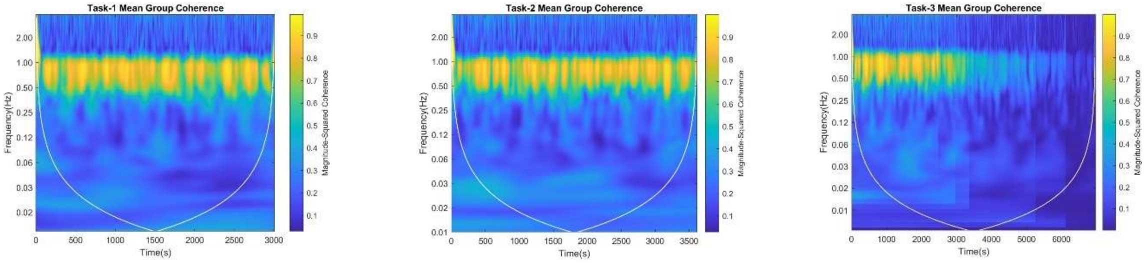

Figure 5: Average coherence plot for each task across all groups

The mean inter-brain synchrony values for the three tasks are shown in Figure 6(a), where a slight variability in the median values can be observed. To verify an increase in IBS values between the three tasks, the difference of mean IBS values was calculated between the three tasks as shown in Figure 6(b). While IBS is present, there was no observed difference from each subsequent task.

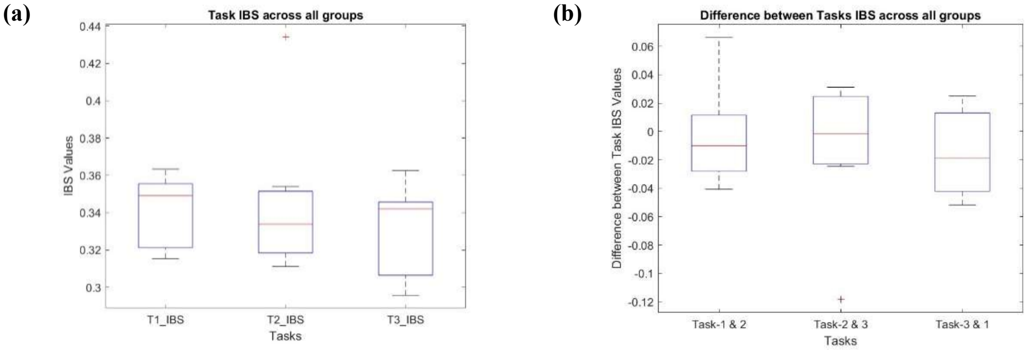

Figure 6: (a) Mean IBS values for the three tasks. (b) Difference between mean IBS of three tasks

On the z-transformed IBS increase values from the 36 ROI pairs, one sample t-test was carried out to find ROI pairs that showed significant IBS increase. Two main regions on the left hemisphere of the brain, in the ventrolateral PFC (L-VLPFC) and dorsolateral PFC (L-DLPFC) were found to be significant ($p<0.05$) with pairings of L-VLPFC & L-VLPFC, L-VLPFC & L-DLPFC and L-DLPFC & L-DLPFC (Figure 7(a)).

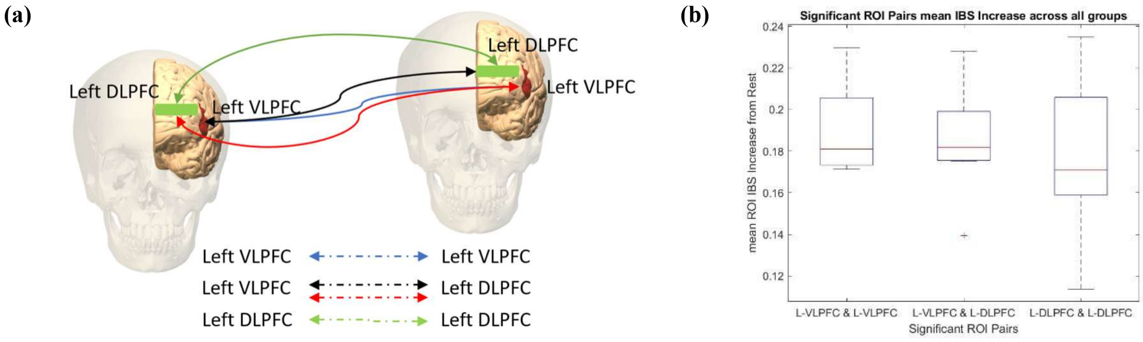

Figure 7: (a) Significant ROI pairing. (b) Values of mean ROI IBS Increase

Figure 7(b) shows the mean IBS increase from the resting state of the three significant ROI pairs, and there was no observed difference in the median values of the ROI pairs.

To address our second research question, what is the relationship between inter-brain synchrony and team collaboration, correlation analysis was carried out at two levels. First, the mean task IBS values were correlated with the respective task performance scores and separately with the task cooperation scores. Second, the mean IBS increase values of the significant ROI pairs were correlated with each task performance score and separately with each task cooperation score.

IBS values were positively correlated with task performance and cooperation scores for Task-1, highlighted in Figure 8, but negatively correlated with performance and cooperation in Task-2 and Task-3. Figure 8 shows the correlation between Task-1 cooperation scores and task IBS values for the two ROI pair IBS values. Task-1 is presented in the figure because of its focus on design and build that depended on the teams' cooperation capabilities and because of the positive correlation. Task-2 and Task-3 were open-ended and likely required different team dynamics and strategies observed in the change in IBS. Teams were not building but instead sketching and planning. The negative correlation of the IBS values with Task-2 and Task-3 cooperation scores suggests that inter-brain synchrony varies by task type.

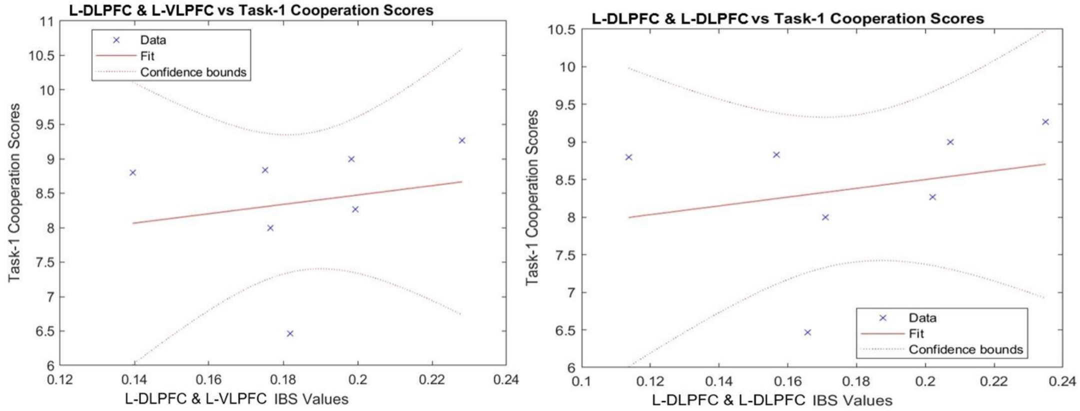

Figure 8: Correlation between Task IBS Values and Task-1 Cooperation Scores for two ROI Pairs

Discussion

This pilot study aimed to establish that inter-brain synchrony (IBS) exists when engineering students work together as a team. IBS was observed among teams but varied between teams and tasks. The most evident IBS was observed in the left ventrolateral prefrontal cortex (VLPFC) and the left dorsolateral prefrontal cortex (DLPFC). Broadly, the left prefrontal cortex is described as serving as the central hub of inductive reasoning (Babcock and Vallesi, 2015). In addition, the left VLPFC and the left DLPFC are often associated with cognitive processes such as problem-solving, working memory, and decision-making. In addition, the regulated processing of goal-relevant item information is thought to occur in the VLPFC areas, and the encoding of the relational information in the left DLPFC (Blumenfeld et al., 2011).

One possible explanation for the positive correlation between the cooperation scores of Task-1 involving ROIs of L-VLPFC & L-DLPFC and L-DLPFC & L-DLPFC, as shown in Figure 8, could be the involvement of the left DLPFC in problem-solving and coordinated verbal exchange through the left ventrolateral prefrontal cortex (L-VLPFC), which is responsible for semantic processing and emotion regulation. These results about the left VLPFC and DLPFC align with Hu et al. (2017) that showed that a coordination activity led to significant inter-brain synchrony in the left middle frontal area. Another study showed greater team cooperation behavior and increased IBS between the left and right dorsolateral prefrontal cortex (Lu and Hao, 2019). Increased IBS in the pars triangularis Broca's region (ventrolateral PFC) symbolizes the cognitive function of turn-based cooperation, which involves verbal communication to share intentionality and make shared decisions (Reindl et al., 2018; Zhou et al., 2022).

The negative correlation of ROI IBS in Task-2 and Task-3 needs further exploration. The negative correlation could be due to factors such as divergent versus convergent thinking, task difficulty, individual differences, or other environmental factors such as drawing and sketching rather than physically building. The idea of distraction, which posits that some peer interactions may impair optimal performance, provides a plausible explanation for this finding. Particularly, stronger attentional temptation, which diverts attention from the tasks at hand and lowers task performance (Baron et al., 1978; Roseth et al., 2008). Gvirts and Permlutter (2020) classified aspects of interactions that facilitate IBS into a) the type of social activity, b) the setting of interaction, and c) the nature of interacting partners. Like these classifications, the factors that could facilitate IBS during task performance could be i) the type of task (convergent or divergent), ii) the setting of the task (drawings/writing or building) and iii) the nature of dyads (same sex or opposite sex, individual's creativity index) (Zhou et al., 2022). These differences need to be investigated further. Understanding the factors influencing inter-brain synchrony among engineering teams is essential for developing strategies to improve team performance and communication.

Implications and Further Studies

While this initial sample size is small, team cooperation, measured by the behavioral patterns amongst team members, and inter-brain synchrony appear related. Future studies along the same line, with a larger sample size, could be carried out to make statistical conclusions on the effects of IBS on teams' behavior and performance. This pilot study demonstrated the use of neuroimaging to analyze behavioral patterns, decision processes, and conflict management within engineering teams, which could be a step in building better-performing engineering teams.

The average oxygenated hemoglobin across the prefrontal cortex and regions of interest was used to measure inter-brain synchrony. Subsequently, future analysis will be carried out by temporal segmentation of the IBS, calculated using WTC, across the entire task duration for each dyad using a sliding window approach. Such a method could provide insight into the state of progression of IBS during the entire task duration in conjunction with the behavior of the team members. Future research could begin to test interventions that accelerate inter-brain synchrony—for example, measuring the effects of team training, adding diversity within groups, adding a leadership role or moderator in a team, or remote teams, and measuring the impact on inter-brain synchrony.

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