Are We on the Same Wavelength? Exploring Inter-Brain Synchrony of Engineering Student Teams When Designing and Building

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ABSTRACT

The collective performance of construction project teams results from individuals sharing ideas and actions, and this collaboration shapes their values toward common goals. Inter-brain synchrony (IBS) is a potential explanation for team performance, which is the coordinated brain activation across individuals. IBS is observed in other disciplines but not adequately studied in engineering and construction project teams. The purpose of the research presented in this paper was to explore the existence of IBS in engineering project teams during design and build activities. The study included 16 undergraduate fourth-year civil engineering students who were paired to form eight dyads. Each team was given the same three tasks varying in time and budget constraints. Team members wore a brain imaging device that measured the change in oxygenated blood in their prefrontal cortex. IBS was observed among all the teams but more prominent in some teams over others. Specific regions of the prefrontal cortex also expressed more IBS than others. The connection between IBS and team cooperation and performance varied. Further exploration is needed to better understand the role of IBS in team dynamics and performance.

INTRODUCTION AND BACKGROUND

The performance of construction project teams is more than the sum of their individual contributions. Their performance is rooted in the exchange of ideas and actions, shaping shared values and goals. A possible theory underlying team performance is inter-brain synchrony, which is the coordinated cerebral activity of two or more persons participating in a social engagement or communication (Crivelli and Balconi 2017, Czeszumski et al. 2020). Inter-brain synchrony strengthens during cooperative efforts, where communication and intuitive understanding of intentions occur (Cui et al. 2012). Particularly during creative problem-solving tasks, when teams cooperate, inter-brain synchrony is observed to positively correlate with performance (Mayseless et al., 2019) and enhance levels of creativity and originality (Lu et al. 2019).

Yet, despite these insights, a significant knowledge gap persists in understanding how inter-brain synchrony operates across various stages of team development (Tuckman & Jensen 1977) and how it contributes to the evolution of construction project teams over time. For example, the intricate dance between architects working together adapting their individual strategies to refine concepts based on the other’s feedback or the positioning of ideas between engineers with technical expertise and field crew with on-the-ground experience when jointly developing a solution for newly discovered challenges during a construction project.

The concept of micro-dynamics, as proposed by Humphrey and Aime (2014), suggests that the subtle interplay that occurs between team members' exchanges carries a cascading weight that can have far-reaching consequences on team cohesion, collaboration, and performance. Exploring this behavior and potential underlying inter-brain synchrony offers an opportunity to decipher the mechanisms driving team dynamics in construction projects. Delving into how these micro-dynamics unfold among team members can help to uncover the hidden drivers of effective teamwork and shed light on the role of inter-brain synchrony in shaping these exchanges. This endeavor also holds the potential to not only enhance the current understanding of team dynamics but also to inform strategies aimed at optimizing it. For example, the adoption of inter-brain synchrony may be useful as a predictor of team success compared to self-assessment measures. Inter-brain synchrony may also be used to analyze future behavioral patterns and cognition capabilities of construction teams, leading to appropriate interventions to bolster cooperation if low inter-brain synchrony is observed.

Coupled dynamics is a framework for understanding both team dynamics and inter-brain synchrony (Hasson and Frith 2016). It argues that interactions are not static, but rather dynamic processes that change quickly and over time, and in this way, aligns with Humphrey and Aime's (2014) concept of micro-dynamics. The coupled dynamics framework suggests a leader-follower relationship created unique neural patterns because of the type of sender-receiver information. This pattern would be distinctly different from the neural patterns when team members synergistically take turns to exchange information. While it is understood the dynamics of these relationships change how information is transmitted between brains (Hasson and Frith 2016), precisely how, in what ways, and what interventions can change it are not well understood.

The objective of the research presented in this paper was to establish the existence of inter-brain synchrony among teams when designing and building and use this insight to help open the way for subsequent studies measuring the coupled dynamics of team performance and brain behavior. Exploring the neural activities and correlations between interacting brains provides new insights into the neural mechanisms shaping behaviors that impact construction team dynamics and project outcomes. To meet the research objective, the study posed three key questions: 1) how does inter-brain synchrony vary among teams and tasks, 2) what brain regions (if any) contribute to inter-brain synchrony, and 3) how does inter-brain synchrony relate to team behavior and performance? The hypothesis was that inter-brain synchrony is observable among teams when both designing and building, gradually increasing as teams work together and is correlated with their performance.

METHOD

Fourth-year undergraduate civil engineering students (n = 16) participated in this initial study. Eight dyads of students were partnered up to complete cooperative design and build activities. The dyads were already acquainted with one another before the experiment, they had collaborated on a different semester-long project.

During Task 1, teams were given a budget as well as a collection of wooden components of various sizes and shapes, each with its own unit cost. Teams had 10 minutes to acquire components and create a towering structure while remaining under the stipulated cost limit using fictional money. The structures were then assessed in terms of total height and cost per inch.

During Task 2, teams were tasked with designing a structure out of 3D printed pieces, with a unit cost per cubic inch of material and a budget set by overall volume. Teams had 15 minutes to develop their pieces using pencil and paper sketches while following a budget, time, and overall design height limits. Unlike Task 1, Task 2 gave teams more leeway in designing their own construction elements.

Task 3 asked the teams to design a pier foundation with minimal resources. Teams were given critical inputs like foundation size, connection types, and load-bearing capabilities, with no time constraints. The differences in restrictions between tasks were designed to explore the impact of limitations on team behavior and the ensuing inter-brain synchronization. The sequencing and timing of the tasks are shown in Figure 1.

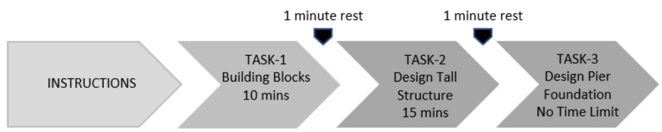

Figure 1: Sequence and timing of design and build tasks

Audio and video recordings of the teams during the task were carried out. Concurrently, the video recordings of the teams engaged in task completion were observed to identify and evaluate behavioral characteristics. Each two-minute video clip was analyzed and scored on a 10-point Likert scale based on three specific behavioral traits: level of participation (ranging from 0 denoting exclusive participation of one person to 10 representing equal participation of both individuals), level of dominance (ranging from 0 denoting one person's control over the team to 10 representing equal contribution), and level of agreement (ranging from 0 reflecting complete disagreement to 10 representing equal contribution). The results across the three behavioral qualities were then averaged to determine the overall collaboration score for each team. The behavioral analysis and scoring were done by two separate raters to assure accuracy. The Inter Class Coefficient (ICC) was used to evaluate the inter-rater reliability and produced a reasonable value of 0.83 (Li et al. 2021, Mayseless et al. 2019).

The teams' final designs for each task were assessed and graded on a 10-point Likert scale. Height, cost, completion time, design uniqueness (compared to the other teams' designs), and design effectiveness were key evaluation parameters for Task 1 and Task 2. Cost per volume, compliance with design specifications, design uniqueness, and design effectiveness were key scoring parameters for Task 3, which had different design requirements than the previous two. The task performance scores for each team were calculated using the average results of all the parameters.

Measurements and Instruments. The NIRSIT functional near-infrared spectroscopy (fNIRS) device from OBELABS was worn by each participant while changes in their oxy-hemoglobin (HbO) levels were recorded. Each dyad and the fNIRS device were connected to separate computers and the start and end times of each task were simultaneously recorded. Figure 2 illustrates and provides an example of the setup.

Executive functions of the brain are mainly associated to the prefrontal cortex (PFC) and hence it was the main area of interest. There were 24 laser sources producing light at 780 nm and 850 nm wavelengths in the fNIRS device. The device enabled measurements through various source-detector spacing configurations at distances of 1.5 cm, 2.12 cm, 3.00 cm, and 3.35 cm, resulting in a total of 204 measurement channels. Of these, the 3 cm spacing offered 48 measurement channels. The 3 cm spacing is the most used and ideal for measuring the change in neurocognition within the cortex (Shin et al. 2017, Yu et al. 2020). The 48 channels of the fNIRS divided the PFC into eight Regions of Interest (ROIs), four on either side of the brain as shown in Figure 3.

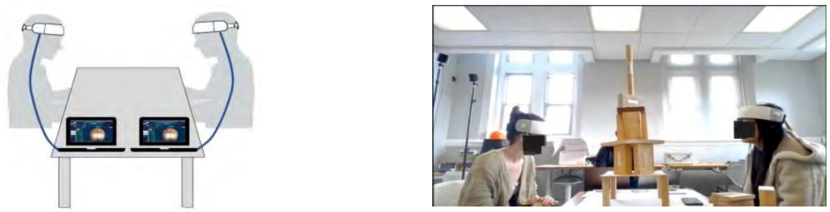

Figure 2: Experimental set for hyper-scanning during collaborative design task

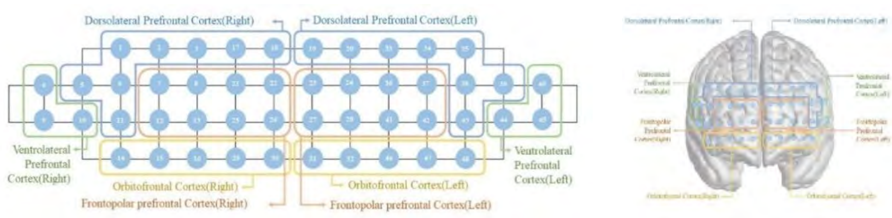

Figure 3: Placement of sensors on 3 cm channel configuration along the regions of the prefrontal cortex. (courtesy: OBELABS, S.Korea)

The raw data obtained from the fNIRS software was preprocessed (Tak and Ye 2014). This included converting raw light density to Optical Density, then correcting for movements using the Temporal Derivative Distribution Repair method (Fishburn et al. 2019) and filtering out physiological artifacts such as heartbeat and blood pressure. Data were then converted to Hemoglobin (Hb) signals using the Modified Beer-Lamberts Law. The global physiological noise (Mayer wave noise from blood pressure) was then regressed out using the median values of the short-distance channels at 1.5 cm (Sato et al. 2016).

Coherence computation using Wavelet Transform Coherence (WTC). Coherence between neural signals received from the dyads was analyzed using the Wavelet Transform Coherence (WTC) method. WTC analysis on the two oxygenated hemoglobin (HbO) time series from the dyads was computed using MATLAB's 'wcoherence' function with a sampling frequency of 10.2 Hz (Cui et al. 2012). WTC analysis of the HbO values from the dyads within a task duration provided the Task inter-brain synchrony values, similarly, WTC analysis on HbO values between two tasks provides the baseline. Due to excessive noise, data from dyad 1 were excluded from the analysis resulting in seven dyads participating in the study.

What is Inter-brain synchrony and how to interpret it? Inter-brain synchronization (IBS) is the degree of neural coherence displayed by team members during collaborative or creative tasks, as measured by wavelet transform coherence (WTC) analysis. This approach involves generating a two-dimensional coherence heat map by applying WTC to the HbO time series signals of seven teams, resulting in a visual depiction of the time series' localized phase-locked interactions across multiple frequencies and time points (Mayseless et al. 2019).

Figure 4 shows a sample coherence plot that depicts the analysis of a dyad throughout the experiment, with the cone of influence denoted by a white line. The cone of influence determines

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where wavelets stretch across the signal in the wavelet power spectrum, possibly generating distortions in the time-frequency plane, and so denotes the region prone to edge effects that may compromise result accuracy. Because of these aberrations, coherence values beyond this threshold may be unreliable. Refer to Chang and Glover (2010) and Grinsted et al. (2004) for a more detailed explanation of WTC.

On the coherence plot, the occurrence of tasks on the time-frequency domain is marked by red lines, and the frequency range where tasks occur (0.01 – 0.125 Hz) is called the frequency band of interest (FOI). FOI allows for the exclusion of frequencies associated with cardiac and respiratory signals (above 0.2 Hz) and low-frequency fluctuations that are below 0.01 Hz fluctuations (Balters et al. 2023, Molavi and Dumont 2012). Areas of highest coherence are displayed as yellow while areas of lowest coherence are in white and quantified on a correlation scale of 0 to 1. WTC analysis was also carried out for each task using the HbO values associated with the task from each person in the dyad. The extent of coherence for each task is augmented by plotting task-level coherence, which also makes it possible to visualize synchrony periods between dyads.

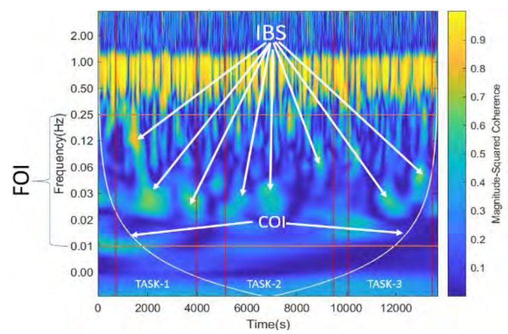

Figure 4: Overall coherence plot; frequency band of interest (FOI) shown on the y-axis, inter-brain synchrony (IBS) and cone of influence (COI) shown with white arrows.

Wavelet Transform Coherence for Cerebral Regions of Interest (ROI). The wavelet transform coherence was computed for each possible pair of regions of interest (ROIs) in the converted time series of HbO signals, within the frequency range of interest between 0.01 Hz and 0.125 Hz. With eight ROIs available, there were a total of 64 possible ROI combinations (8 ROIs x 8 ROIs). Subsequently, the coherence values corresponding to the same ROI pairing were averaged. For instance, the coherence value between ROI2 of participant 1 and ROI3 of participant 2 was averaged with the value between ROI2 of participant 2 and ROI3 of participant 1 that yielded 36 ROI pairings for further analysis (Balters et al. 2023, Li et al. 2021, Mayseless et al. 2019). Next, the coherence values of the paired ROIs were subtracted from the resting state coherence (baseline), to assess the magnitude of coherence change. Coherence values are computed as correlation values and need to be transformed into Fisher z-statistics (Chang and Glover 2010, Cui et al. 2012) prior to conducting any statistical analyses. To identify ROI pairs exhibiting a significant increase in IBS values, a one-sample t-test was conducted on the inter-brain synchrony values for all 36 ROI pairings.

Periodic Inter-brain Synchrony (pIBS). On each of the three significant ROI pairs from the one sample t-test, wavelet transform cohere (WTC) analysis was carried out for every 2-minute epoch for each task. The HbO values corresponding to the channels of each ROI were aggregated for each task and for each participant of the dyad and were further divided into 2-minute periods resulting in 5 segments for Task-1 and 7 segments for Task-2. The number of segments for Task-3 varied according to the task completion time for each team. Inter-brain synchrony (IBS) values were computed for each corresponding segment from either participant of the dyad for each task.

RESULTS

To address how inter-brain synchrony (IBS) varies among student teams and tasks, WTC analysis was performed on the two-time series of HbO signals from each dyad. This revealed the occurrence of IBS during each task, with distinct patterns and intensities observed across different 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.

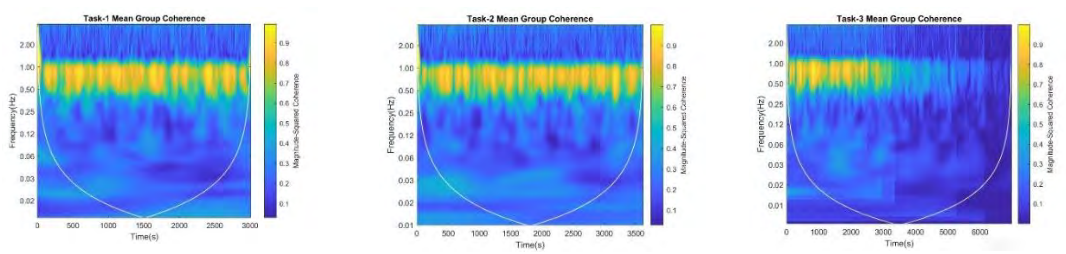

Figure 5: Average coherence plot for each task across all groups

Figure 6a shows the mean values of IBS for the three tasks, which indicates a slight variability in the median values. The difference in mean IBS values was calculated to assess whether there was an increase in IBS between the three tasks (Figure 6b). Despite the presence of IBS, no significant differences were observed between each subsequent task, suggesting comparable levels of inter-brain synchrony across the three tasks.

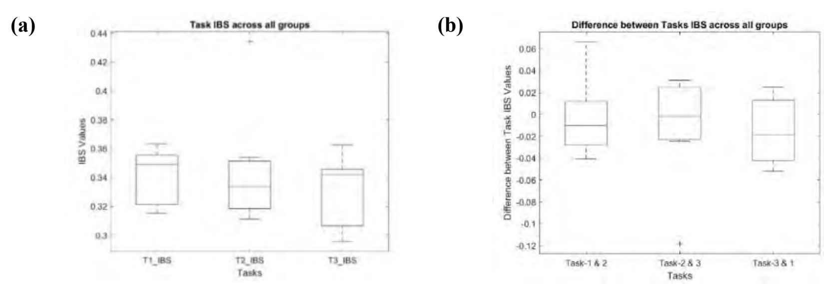

Figure 6: (a) Mean inter-brain synchrony and (b) differences between mean inter-brain synchrony for the three tasks.

To address the second research question on which regions of the brain contribute to IBS, one sample t-tests were carried out on the z-transformed IBS increase values from the 36 ROI pairs. The ventrolateral PFC (L-VLPFC) and dorsolateral PFC (L-DLPFC) were found to be two significant regions ($p<0.05$) on the left hemisphere of the brain with pairings of L-VLPFC and L-VLPFC, L-VLPFC and L-DLPFC and L-DLPFC and L-DLPFC (Figure 7a). The three significant ROI pairings' mean elevated IBS are displayed in Figure 7b.

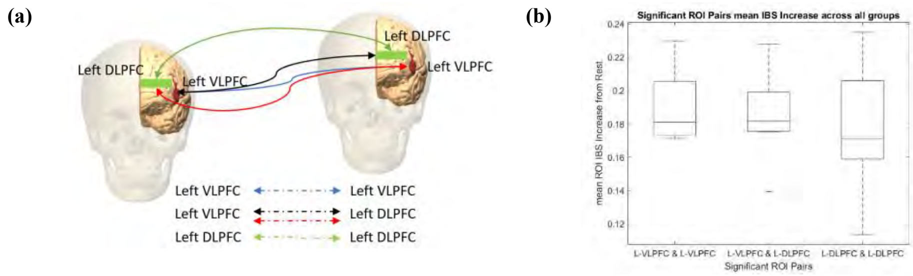

Figure 7: (a) Significant region of interest pairing and (b) values of the mean region of interest inter-brain synchrony increase.

Periodic IBS (pIBS). WTC analysis was carried out on every 2-minute segment of HbO values of each significant ROI pair from each dyad for every task that resulted in an IBS matrix for every 2-minute period of the task duration, which was then averaged. As a result, at the group level, for each ROI pair there are 35 mean IBS values for Task-1, 49 mean IBS values for Task-2 and 53 mean IBS values for Task-3. One-way ANOVA on the mean Periodic IBS (pIBS) values was calculated for all significant ROI pairs across the three tasks. The mean pIBS values of ROI pair L-DLPFC and L-DLPFC were not statistically significant, while the mean IBS values for ROI pairs L-VLPFC and L-VLPFC and L-VLPFC and L-DLPFC were found to be statistically significant. The results of the statistical tests are presented in Figure 8.

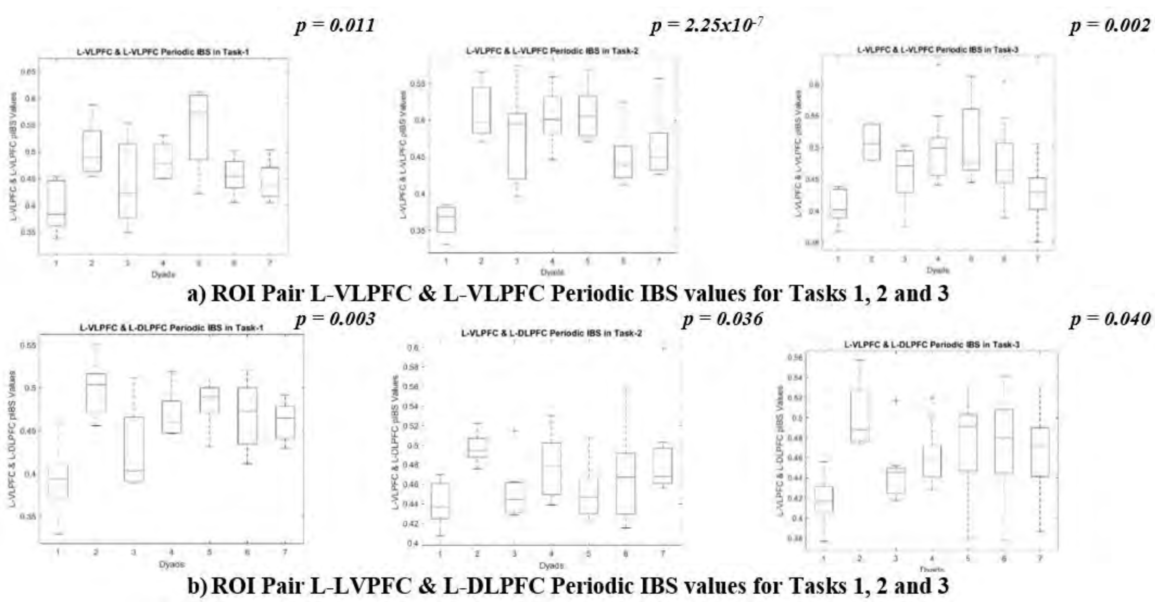

Figure 8: a) Mean periodic inter-brain synchrony values of left ventrolateral prefrontal cortex (L-VLPFC) & L-VLPFC in Task-1 and Task-2, b) Mean periodic inter-brain synchrony values L-VLPFC & left dorsolateral prefrontal cortex (L-DLPFC) in Task-1 and Task-2

Correlation analysis was carried out at two levels to address the third research question on the relationship between inter-brain synchrony and team behavior. The mean task IBS values and corresponding task performance scores were first correlated. Then, the mean Periodic IBS (pIBS) values of the significant ROI pairs were correlated with respective periodic task cooperation scores, i.e., team behavioral scores for every 2 minutes of the task.

The task IBS values were negatively correlated with all task performance scores and the periodic IBS scores were also negatively correlated with the team cooperation scores for all tasks. Figure 8a shows, a time series plot of the mean Periodic IBS (pIBS) values for the two significant ROI pairs during Task-1 and Task-2, while Figure 8b shows the mean Team Cooperation Scores during Task-1 and Task-2. These two plots inferred that the mean pIBS values did not increase from Task-1 to Task-2. It stayed the same. The mean Team Cooperation Scores decreased from Task-1 to Task-2; so did the mean Task Performance Scores seen in Figure 9c.

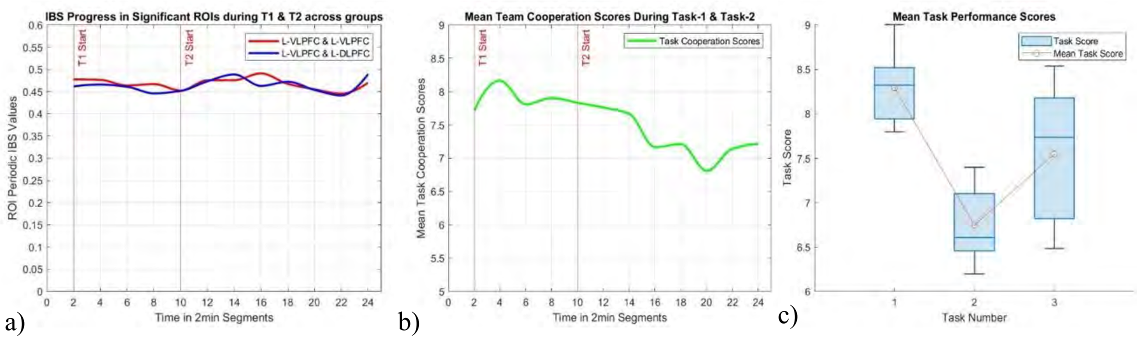

Figure 9: a) Mean Periodic IBS Progress in Significant ROIs during Task-1 and Task-2, b) Mean Team Cooperation Scores during Task-1 and Task-2, c) Mean Task Performance Scores for Task-1, Task-2, and Task-3

DISCUSSION AND IMPLICATIONS

This pilot research intended to demonstrate inter-brain synchronization (IBS) among engineering students during collaborative design and build tasks. While IBS was found across teams, its intensity varied depending on the task and team. This is consistent with Hasson & Frith’s (2016) framework for coupled dynamics, in which interactions are dynamic processes that can change quickly and this variability is observed in levels and intensity of IBS. Nonetheless, IBS was observed in the left ventrolateral prefrontal cortex (VLPFC) and left dorsolateral prefrontal cortex (DLPFC). Figure 8 depicts the range in mean pIBS values for the top two significant ROI pairings, which might indicate the importance of these areas in group interactions when designing and building. The left prefrontal cortex is involved with inductive thinking (Babcock and Vallesi 2015), whereas the left dorsolateral prefrontal cortex (DLPFC) and ventral lateral prefrontal cortex (VLPFC) are often associated with a variety of cognitive activities such as decision-making, working memory, and problem-solving. The left DLPFC is often associated with relational information encoding, whereas the VLPFC regions handle goal-relevant item information (Blumenfeld et al. 2011). The activation and synchronicity found in these areas during the tasks appear to be in line with previous studies on their cognitive functions.

The mean pIBS values were reasonably steady across Tasks 1 and 2 (Figure 9a), showing persistent inter-brain synchrony during interactions. However, despite continued inter-brain synchronization, there was a notable drop in team collaboration and task performance from Task 1 to Task 2 (Figure 9b and 9c), indicating a shift in behavioral tendencies.

Additional investigation is required to further explore the negative correlation between IBS and team cooperation. Divergent and convergent thought processes, task difficulty, individual variations among team members, or contextual variables like drawing and sketching activities rather than physically building could likely contribute to this negative correlation. Gaining a deeper understanding of the underlying factors that influence inter-brain synchrony within project teams is crucial for devising strategies aimed at enhancing team performance and communication.

Despite a small initial sample size, a relationship between inter-brain synchrony and team cooperation seems to exist as indicated by behavioral patterns among team members. Further studies with a larger sample size could provide statistically significant inferences on the relationship between IBS and team performance. While demonstrating the potential of neuroimaging for studying behavioral patterns and decision-making in engineering teams, this pilot study suggests that future research could investigate interventions aimed at improving inter-brain synchrony, such as team training, diversity inclusion, leadership roles, and remote team dynamics. These metrics might be crucial in improving the performance of engineering and construction teams.

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