Inter-Brain Synchrony Pattern Investigation on Triadic Board Game Play-Based Social Interaction: An fNIRS Study

Jinwoo Park, Jaeyoung Shin, Jaehoon Lee, and Jichai Jeong, *Senior Member, IEEE*

***Abstract*— Recent advances in functional neuroimaging techniques, including methodologies such as fNIRS, have enabled the evaluation of inter-brain synchrony (IBS) induced by interpersonal interactions. However, the social interactions assumed in existing dyadic hyperscanning studies do not sufficiently emulate polyadic social interactions in the real world. Therefore, we devised an experimental paradigm that incorporates the Korean folk board game "Yut-nori" to reproduce social interactions that emulate social activities in the real world. We recruited 72 participants aged 25.2 ± 3.9 years (mean ± standard deviation) and divided them into 24 triads to play Yut-nori, following the standard or modified rules. The participants either competed against an opponent (standard rule) or cooperated with an opponent (modified rule) to achieve a goal efficiently. Three different fNIRS devices were employed to record cortical hemodynamic activations in the prefrontal cortex both individually and simultaneously. Wavelet transform coherence (WTC) analyses were performed to assess prefrontal IBS within a frequency range of 0.05–0.2 Hz. Consequently, we observed that cooperative interactions increased prefrontal IBS across overall frequency bands of interest. In addition, we also found that different purposes for cooperation generated different spectral characteristics of IBS depending on the frequency bands. Moreover, IBS in the frontopolar cortex (FPC) reflected the influence of verbal interactions. The findings of our study suggest that future hyperscanning studies should consider polyadic social interactions to reveal the properties of IBS in real-world interactions.**

***Index Terms*— Brain imaging, functional near-infrared spectroscopy, hyperscanning, inter-brain synchrony, triad.**

Manuscript received 21 February 2023; revised 17 June 2023; accepted 3 July 2023. Date of publication 6 July 2023; date of current version 12 July 2023. This work was supported in part by the Institute of Information and Communications Technology Planning and Evaluation (IITP) grant funded by the Korean Government [Ministry of Science and ICT (MSIT)] under Grant 2017-0-00451, in part by the Development of Brain Computer Interface (BCI) based Brain and Cognitive Computing Technology for Recognizing User's Intentions using Deep Learning, and in part by Brain Korea 21 (BK21) Four Project of the National Research Foundation of Korea. *(Corresponding authors: Jaeyoung Shin; Jaehoon Lee; Jichai Jeong.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board of Korea University under Grant KUIRB-2022-0177-01.

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Digital Object Identifier 10.1109/TNSRE.2023.3292844

I. Introduction

SOCIAL interactions are referred to as cognitive activity among people and are integral to daily life and social achievements [1], [2]. Moreover, previous studies in various fields have investigated social interactions [3], [4], [5]. Modern advances in neuroimaging techniques have enabled the exploration of social interactions in terms of inter-brain synchrony (IBS) [6], [7], [8] using hyperscanning, which is a neuroimaging approach that integrates simultaneous brain signals from two or more participants to investigate their social interactions. In particular, the use of electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), which are the usual methods of neuroimaging, has inspired growing interest in hyperscanning in the field of modern neuroscience [9], [10], [11], [12], [13], [14].

Unfortunately, several drawbacks constrain conventional neuroimaging modalities from being applied in the field of hyperscanning. For instance, the poor spatial resolution of EEG compared to other brain imaging methodologies renders it challenging to pinpoint where IBS occurs. Additionally, susceptibility to motion artifacts is inherent in EEG, which can present challenges when processing and interpreting measurement results if the participants' body movements are involved [15], [16]. With regard to fMRI, high costs are incurred when setting up multiple fMRI systems in a well-shielded room. Moreover, fMRI severely restricts participants' movements during system operation, limiting the number of available hyperscanning tasks [17]. A promising alternative to overcome these limitations is to use functional near-infrared spectroscopy (fNIRS). Compared with EEG, fNIRS offers superior spatial resolution [18] and robustness against motion artifacts [19]. Furthermore, the relatively straightforward working principle of fNIRS allows its applications to be manufactured in compact form factors with low costs [20].

Previous investigations on fNIRS-based hyperscanning have covered neural synchrony induced by several different types of activities, such as musical coordination [21], [22], behavioral synchrony [23], [24], [25], problem-solving [26], [27], and verbal communication [28], [29]. These findings have inspired researchers' perspectives on social interactions between two people. Furthermore, advances in hyperscanning research techniques have made it possible to examine IBS triggered by polyadic cognitive interactions between three or more people [28], [30], [31], [32], [33], [34], [35], [36], [37], [38]. Given the prevalence of polyadic engagements in real-world social interactions, the polyadic hyperscanning may enhance the fidelity of simulated social interactions to real-world scenarios. We aimed to investigate the dynamics of IBS in a triadic context by assuming different styles of cooperation within social interaction scenarios. Also, we sought to compute IBS and examine its patterns under differentiated cooperation methods as well as communication styles. In formulating the study, two major hypotheses were postulated. First, different styles of cooperation within social interaction scenarios would influence the pattern of IBS. Second, the mode of communication employed, including both verbal and non-verbal cues, would have an impact on the observed patterns of IBS. To empirically examine these hypotheses, we emulate complex yet controlled triadic interactions through the traditional Korean board game "Yut-nori" using either standard or modified rules. Moreover, we explore how IBS is observed differently under polyadic interactive situations.

II. Methods

A. Participants

We recruited 72 participants (36 males and 36 females) aged 25.2 ± 3.9 years (mean ± standard deviation) and grouped them into gender-separated triads (12 male triads and 12 female triads). None of the triad members knew each other prior to the experiments. Moreover, all participants reported having sufficient sleep and abstaining from alcohol consumption before the experiments. After receiving a thorough briefing on the experimental procedure, the participants provided written consent. The experimental procedures of this study were approved by the Institutional Review Board of Korea University (KUIRB-2022-0177-01).

B. Data Acquisition

We employed three fNIRS devices (NIRSIT LITE, OBELAB, Seoul, Korea) to monitor cortical hemodynamic activations, *i.e.*, concentration changes of oxygenated hemoglobin (ΔHbO) and reduced hemoglobin (ΔHbR), in the prefrontal cortex (PFC). Each fNIRS device employed 5 sources and 7 light detectors, forming a total of 15 fNIRS channels. Fig. 1 presents the source and detector arrangement and the channel configuration. Each channel comprised a pair of adjacent sources and detectors that were spaced 3 cm apart. Channel 8 was located at the AFz position according to the international 10–10 system [39]. The device was designed to map its channels to corresponding Montreal Neurological Institute (MNI) coordinates [40], [41]. TABLE I provides the MNI coordinates and corresponding PFC sub-regions for each fNIRS channel. All channels, except for channel 8, are assigned to either the left/right dorsolateral prefrontal cortex (L/R DLPFC) or the left/right frontopolar PFC (L/R FPC). We excluded channel 8 from the analysis because it does not belong to either the left or right FPC. We used three computers to compose the system: one primary and two secondary. The primary PC generated and sent marker signals to the secondary PCs using a wireless local access network (WLAN) user datagram protocol (UDP) to synchronize the fNIRS signals. The complete experimental system was configured with three separately-linked pairs of a computer and an fNIRS device to manage the fNIRS devices. The three fNIRS devices recorded the participant's fNIRS signals individually at a sample rate of 8.138 Hz and sent the signals to the corresponding linked computer via the Bluetooth Low Energy (BLE) 5.0 protocol. It was confirmed that the synchronization timing errors between PCs were consistently less than 10 ms. A descriptive illustration is provided in Fig. 2.

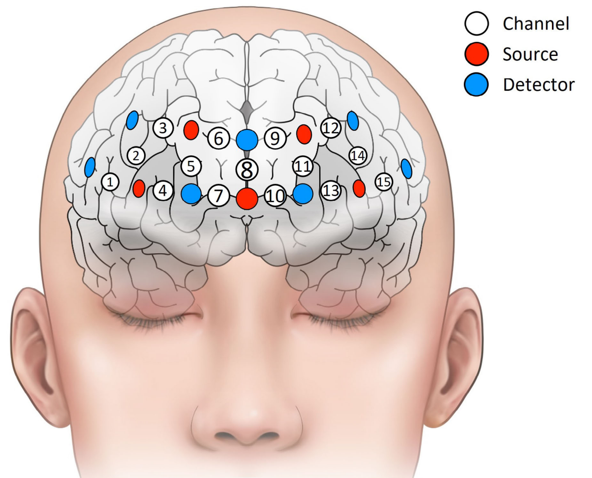

Fig. 1. fNIRS channel configuration. The red and blue circles represent light sources and detectors, respectively. Each fNIRS channel is formed by a pair of adjacent sources and detectors. Numbers 1–15 indicate the fNIRS channel locations. Channel 8 is located at the AFz position according to the 10–10 system.

C. Experimental Paradigm

Each triad played Yut-nori, a turn-based strategic Korean folk board game. Usually, two or more teams compete in the game; therefore, in this study, two members formed a team (duo team), while the remaining member became the opponent (solo team). In the game, players throw four wooden sticks named 'Yut' and advance their markers based on the Yut's outcome. The team that advances all their markers to the final goal wins the game. Please refer to the URL for more detailed rules of Yut-nori [42]. The rules of the experimental tasks were systematically adjusted to allow for varying goals of cooperation. Thus, the game was played in two different ways: Mode 1, following the standard rules, and Mode 2, following modified rules. In Mode 1, the two teams competed against each other to advance their markers to the final goal more efficiently than the opponent. In Mode 2, the two teams aimed to cooperate without interfering the opponent, striving to finish the game together in the fewest number of turns. Hence, in Mode 1, the members of the duo

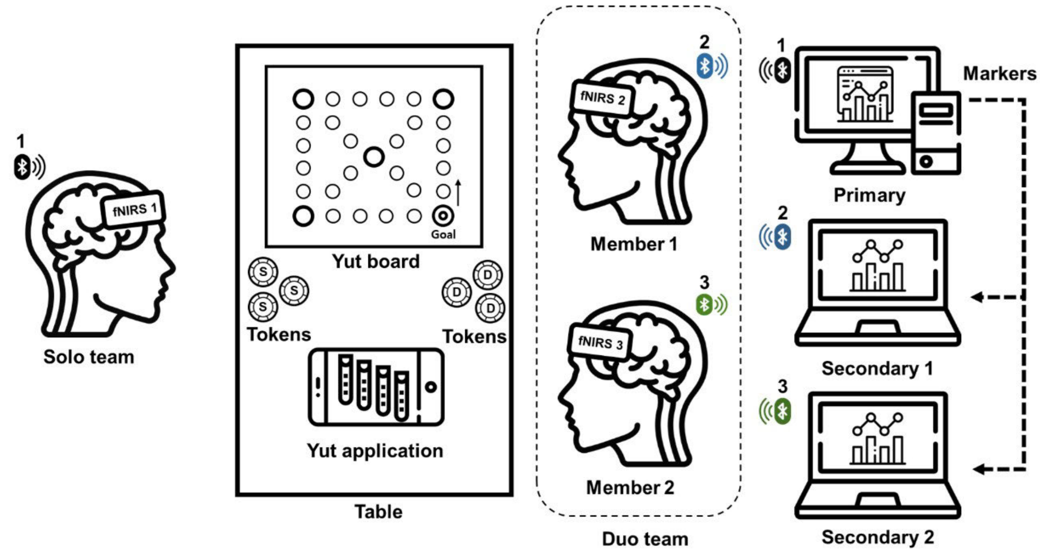

Fig. 2. Experimental setup for hyperscanning. A "solo team" and a "duo team" played a turn-based strategic board game named "Yut-nori." An fNIRS device was linked to an individual computer. The recorded fNIRS signals were transmitted to the corresponding computer via the BLE 5.0. In addition, a primary computer sent markers to secondary computers to synchronize the recorded fNIRS signals.

TABLE I
TARGET MNI COORDINATES AND CORRESPONDING PFC SUB-REGIONS FOR FNIRS CHANNELS

Channel	X	Y	Z	PFC Sub-region
1	54.67	44.00	0.00	R DLPFC
2	48.00	52.67	12.67	R DLPFC
3	36.33	58.33	24.67	R FPC
4	39.00	64.67	0.00	R FPC
5	26.33	69.67	12.67	R FPC
6	13.67	69.00	24.67	R FPC
7	14.33	73.00	0.33	R FPC
8	0.33	68.00	24.00	N/A
9	–13.00	68.00	24.00	L FPC
10	–14.33	73.00	0.00	L FPC
11	–26.00	68.00	12.00	L FPC
12	–35.67	57.67	23.67	L FPC
13	–38.00	63.00	0.00	L FPC
14	–45.67	51.67	12.33	L DLPFC
15	–52.33	43.67	–0.33	L DLPFC

team had to cooperate while competing against the solo team. In Mode 2, both teams as well as the members of the duo team had to cooperate mutually to achieve the common goal efficiently. Fig. 3 graphically illustrates the team configurations and interaction methodologies in Modes 1 and 2. The games were repeated twice for all possible team organizations and modes (3 possible team organizations × 2 modes × 2 repetitions; a total of 12 games per triad). To avoid bias, the order of experimental conditions was randomized across the 12 repetitions of the experiment. The participants were instructed not to make unnecessary body movements and used a smartphone application simulating 'Yut' instead of physically throwing 'Yut' to minimize potential motion artifacts. During the use of the smartphone application, participants were explicitly instructed to avoid sudden head movements that could introduce significant motion artifacts. Moreover, they were strictly prohibited from communicating with the opponent team to fair ensure competition but encouraged to actively communicate with their own team members to promote cooperation.

D. Signal Processing and IBS

We specifically processed the time courses of ΔHbO to analyze inter-brain synchrony (IBS) since it is known that ΔHbO effectively reflects inter-brain synchrony induced by social interactions [26], [43]. We also analyzed ΔHbO-based IBS levels in both the time and frequency domains using wavelet transform coherence (WTC) [44]. Before computing the WTC, we applied temporal derivative distribution repair

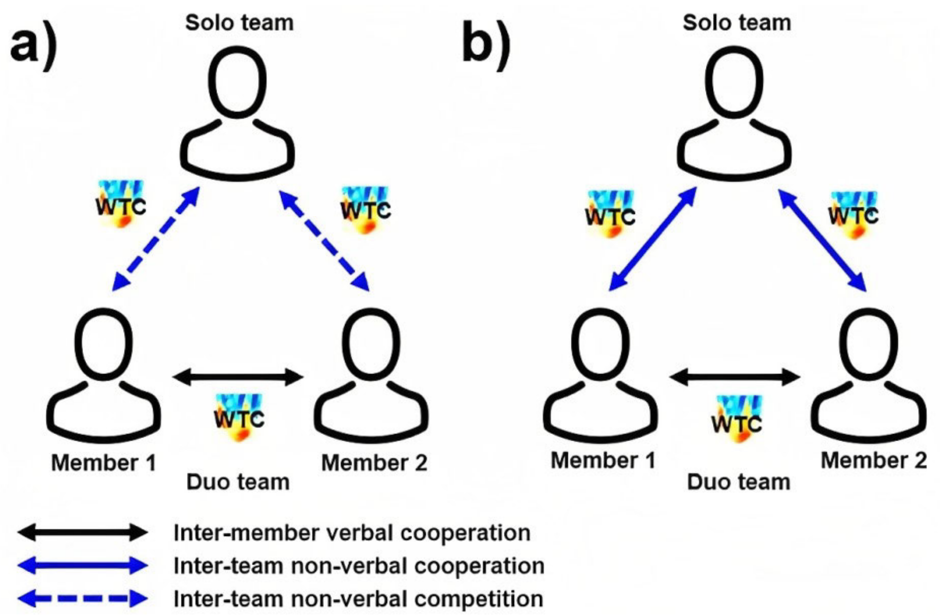

Fig. 3. Illustration of two game modes for hyperscanning. In Mode 1, both teams competed to win the game. Inter-member verbal communication was allowed to beat the opponent, although inter-team communication was strictly prohibited. In Mode 2, both teams cooperated in trying to finish the game with the minimum number of turns, and team members were allowed to actively communicate verbally; however, inter-team verbal communication was not allowed.

(TDDR) and low-pass filter (LPF) to minimize the potential effects of motion artifacts [45]. For the low-pass filtering, we employed a fifth-order type 2 Chebyshev filter. To ensure minimal impact on the frequency domain of 0.1 to 0.3 Hz, the stopband edge frequency was set to 0.7 Hz, and the stopband attenuation was adjusted to 50 dB. The continuous wavelet transform of a time series, $x_{k,n}$, on channel k for a length of N is computed by

$$W_{k,n}^{X}(s) = \sqrt{\frac{\Delta t}{s}} \sum_{n'=1}^{N} x_{k,n'} \psi_0 \left[\left(n' - n\right) \frac{\Delta t}{s} \right] \quad (1)$$

where s, n, ψ_0, and Δt are the wavelet scale, time index, wavelet time function, and uniform time step, respectively. We adopted the following Morlet wavelet:

$$\psi_0(\eta) = \pi^{-\frac{1}{4}} e^{j\omega_0 \eta} e^{-\frac{1}{2}\eta^2} \quad (2)$$

where ω_0 and η represent dimensionless frequency and dimensionless time, respectively. The cross-wavelet transform of the two time series on channel k, $x_{k,n}$ and $y_{k,n}$ is given by

$$W_{k,n}^{XY}(s) = W_{k,n}^{X}(s)\, W_{k,n}^{Y*}(s) \quad (3)$$

where the asterisk ($*$) represents the complex conjugation. We defined the WTC of the two time series ($x_{k,n}$ and $y_{k,n}$) as follows:

$$\mathrm{WTC}_{k,n}(s) = \frac{\left|\left\langle s^{-1} W_{k,n}^{XY}(s)\right\rangle\right|^2}{\left|\left\langle s^{-1} W_{k,n}^{X}(s)\right\rangle\right|^2 \left|\left\langle s^{-1} W_{k,n}^{Y}(s)\right\rangle\right|^2} \quad (4)$$

where n represents the time index, $|\cdot|$ denotes the absolute value, and $\langle\cdot\rangle$ represents the smoothing operation in time and scale [46]. To avoid edge-effects at the beginning and termination of each task session [44], we considered the cone of influence (COI) for each task session and excluded the data within the COI from further analyses. As described previously [47], the COI for the Morlet wavelet is determined by

$$COI(n, s) = \left\{ n' \left| n - n' \right| \leq \sqrt{2}\, s \right\} \quad (5)$$

where n represents the time index, and s denotes the wavelet scale. Note that our definition of WTC is based on the magnitude-squared coherence (MSC).

E. Averaged WTC

The degree of IBS was quantified using the temporal averaged WTC (aWTC) over the duration of the task. The aWTC was computed within the frequency range of 0.1–0.3 Hz (B), as previous studies have demonstrated significant inter-brain synchronization (IBS) within this frequency band. Therefore, the aWTC on channel k in the frequency band of interest is given by

$$\mathrm{aWTC}_k(B) = E\left[\mathrm{WTC}_{k,n}(s)\,|_{n \in t_{task}, s \in B}\right]$$
$$s.t.\,(n, s) \notin COI \quad (6)$$

where n represents the time index, s denotes the wavelet scale, and t_{task} is the task period. After computing $\mathrm{aWTC}_k(B)$ for all channels, we derived locally averaged $\mathrm{aWTC}_k(B)$ to identify local changes in IBS. The IBS values at the left prefrontal PFC (L FPC) were computed by averaging $\mathrm{aWTC}_9(B)$, $\mathrm{aWTC}_{10}(B)$, $\mathrm{aWTC}_{11}(B)$, $\mathrm{aWTC}_{12}(B)$, and $\mathrm{aWTC}_{13}(B)$. The IBS values at the right frontopolar PFC (R FPC) were computed by averaging $\mathrm{aWTC}_3(B)$, $\mathrm{aWTC}_4(B)$, $\mathrm{aWTC}_5(B)$, $\mathrm{aWTC}_6(B)$, and $\mathrm{aWTC}_7(B)$. The IBS values at the left frontopolar PFC (L FPC) were computed by averaging $\mathrm{aWTC}_{14}(B)$ and $\mathrm{aWTC}_{15}(B)$.The IBS values at the right frontopolar PFC (R FPC) were computed by averaging $\mathrm{aWTC}_1(B)$ and $\mathrm{aWTC}_2(B)$.

TABLE II

BEHAVIORAL RESULTS OF 'YUT-NORI' GAMES PLAYED FOLLOWING THE STANDARD RULE (MODE 1) AND THE MODIFIED RULE (MODE 2). THE VALUES ARE EXPRESSED AS THE MEAN ± STANDARD DEVIATION

	Mode 1	Mode 2	Sig.
Number of Yut casting (A)	38.1 ± 9.8 times	29.9 ± 6.4 times	***
Elapsed playing time (B)	260.1 ± 88.0 s	187.0 ± 54.4 s	***
Elapsed time per Yut casting (A/B)	13.7 ± 3.1 s	12.7 ± 3.0 s	

***, p < 0.01.

F. Statistical Analyses

We employed the t-test as well as ANOVA test to verify the statistical significance of the experimental findings. The independent samples t-test was employed to perform statistical comparisons between two groups, whereas the one-way ANOVA test was utilized for comparisons among multiple groups. For multiple comparison, false discovery rate post-hoc analyses were additionally applied [48].

III. RESULTS

A. Behavioral Results

The behavioral data of the Yut-nori games in Modes 1 and 2 are summarized in TABLE II. On average, Yut casting occurred 38.1 ± 9.8 times and 29.9 ± 6.4 times to conclude the game in Modes 1 and 2, respectively. The total duration of gameplay per game was 260.1 ± 88.0 and 187.0 ± 54.4 seconds in Modes 1 and 2, respectively. In Mode 1 and Mode 2, the average time spent on a single Yut casting was 13.7 ± 3.1 seconds and 12.7 ± 3.0 seconds, respectively. Notably, there was a substantial disparity in the mean number of Yut castings to conclude the game between Mode 1 and Mode 2, as well as a notable discrepancy in the duration required to conclude the game. However, there was no discernible difference in the time spent on a single Yut casting.

B. aWTC Results

Fig. 4(a)–(c) present examples of $WTC_{11,n}(s)$ for the 21st triad during the task session in Mode 2. The red boxes indicate $WTC_{11,n}(s)$ in the frequency band of interest (0.1–0.3 Hz). Here, IBS by WTC was quantified by an MSC value ranging from 0 to 1. Strong IBS (MSC values close to 1) and weak IBS (MSC values close to 0) are visualized in red and blue, respectively. In Fig. 4(a), inter-member IBS induced by cooperation was strongly revealed in the frequency range of 0.1−0.3 Hz. In contrast, Fig. 4(b) and (c) exhibit relatively low inter-team IBS induced by competition in the same frequency range.

Fig. 5(a) and (b) display the grand averaged inter-member IBS and inter-team IBS (across all participants and their corresponding experimental trials), respectively, during a task period in Mode 1 in different parts of the PFC varying according to the frequency. Overall, the IBS results tended to become stronger as the frequency increased and then peaked in the frequency range between 0.1 and 0.3 Hz, regardless of the method of interaction (*i.e.*, cooperation or competition), and then fell. The steeply increasing inter-member IBS over 0.3 Hz in both hand sides of FPC (Fig. 5(a)) would be meaningless due to IBS contaminations by physiological noises [49]. The laterality of IBS magnitude was not clearly or consistently observed.

The grand averaged inter-member and inter-team IBSs during a task period in Mode 2 are provided in Fig. 6(a) and (b), respectively. Compared to Fig. 5(a) and (b), inter-member IBS became stronger in the left FPC in Fig. 6(a), and inter-team IBS peaks were sharper in the frequency range 0.1–0.3 Hz in Fig. 6(b). Moreover, inter-team IBS magnitude rebound at relatively high frequencies (>0.3 Hz) was not observed in the right DLPFC. Finally, consistent laterality of IBS magnitude was also not observed.

IV. DISCUSSION

In the majority of situations, social interaction, such as cooperation, is not inherently pursued as a standalone objective but is rather undertaken to fulfill a multitude of purposes [50], [51]. However, it is not well understood how IBS changes when the purpose of social interaction varies. In this study, Yut-nori games were played to emulate polyadic interactions through different social interactions between participants. Within the framework of our experimental design, our objective was to examine the impact of two factors, namely the purpose of cooperation and the presence of verbal communication, on IBS.

A. Behavioral Patterns of Mode 1 and Mode 2

Participants completed the Mode 2 task significantly faster than the Mode 1 task ($p < 0.01$) with a significantly smaller number of Yut castings ($p < 0.01$). This may be attributed the observation that, during the Mode 1 task, participants actively disrupted and impeded the progress of the opposing team, whereas in the Mode 2 task, participants substantially facilitated the other team's advancement, resulting in enhanced efficiency. However, no statistically significant difference was detected in the mean duration spent on a single Yut casting. This implies that there is no significant difference in behavioral patterns that make up the gameplay in Mode 1 and Mode 2. Prior fNIRS hyperscanning investigations involving repeated task performance have consistently revealed that the

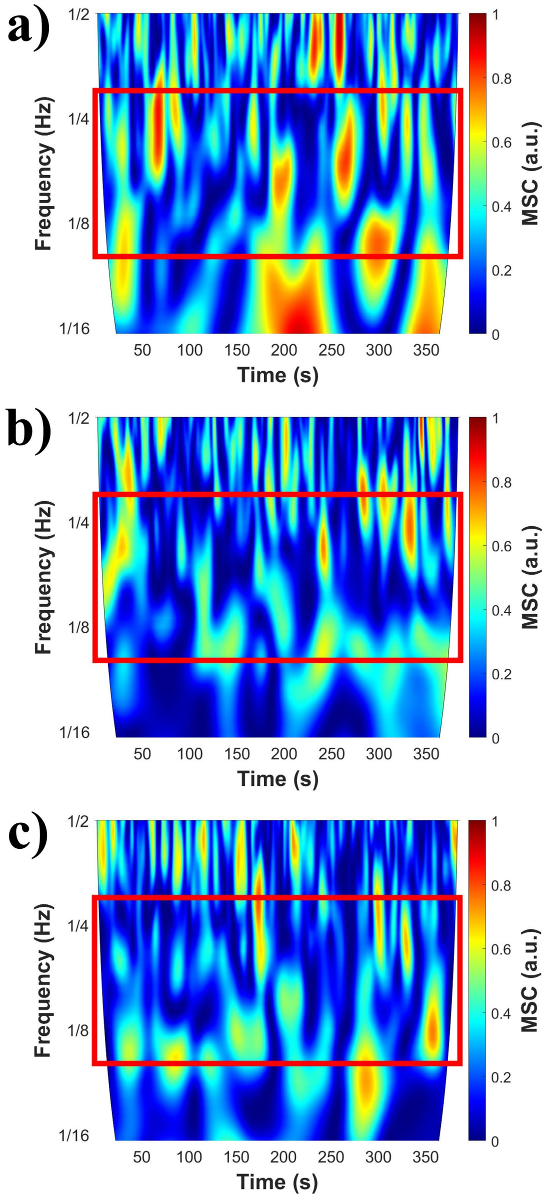

Fig. 4. WTC analysis results on Ch. 11 for the 21st triad during task period in Mode 2. (a) Inter-member IBS and (b) inter-team IBS between Member 1 and the opponent. (c) Inter-team IBS between Member 2 and the opponent. Strong IBS induced by cooperation was observed between 0.1 and 0.3 Hz in panel (a) but not in panels (b) and (c). Data within COI was excluded.

occurrence of IBS is not contingent upon the frequency of behavior repetition [28], [52]. Furthermore, a parallel line of research utilizing fNIRS hyperscanning with tasks of varying durations has reported the presence of IBS within a shared frequency range, unaffected by the task's inconsistent temporal duration [53]. Therefore, we hypothesized that IBS induced by identical cognitive interaction would be observed in the same frequency band, even if the task duration varied.

B. Polyadic Social Interactions

Previous studies have reported that IBS induced by cooperative interactions can be observed in the PFC, especially DLPFC area [23], [54], [55]. Figures 5 and 6 unveil disparities in IBS within the frequency range of 0.1–0.3 Hz. It is noteworthy that this frequency range has been extensively explored in other studies, revealing alterations in IBS patterns attributed to social interaction [54], [56], [57]. In light of these observations, we undertook a comprehensive re-analysis focusing on the aforementioned frequency range (0.1–0.3 Hz) in order to thoroughly investigate the impact of continuous IBS fluctuations. Fig. 7 shows inter-team IBS induced by non-verbal cooperation and competition in the frequency bands of 0.1–0.3 Hz at dorsolateral regions of the PFC. The blue bars depict IBS resulting from competitive interactions, while the red bars represent IBS arising from cooperative interaction. On average, the degree of IBS exhibited during the co-operative task surpassed that observed during the competitive task. Specifically, the left DLPFC exhibited significantly higher IBS during the cooperative task compared to the competitive task ($p = 0.016$). These results are consistent with previous findings reporting that the cooperative social interaction induces higher IBS than competitive social interaction on DLPFC area.

According to our investigation, we determined that the effects of triadic interactions, such as those in the Yut-nori game, can result in different IBS patterns because they entail two types of social interactions. Hence, we suggest using polyadic interactions like the Yut-nori game as a task to emulate IBS induced by real-world social interactions.

C. Effects of Ultimate Purpose of Cooperation on IBS

It has been widely recognized that IBS is observed during cooperative tasks between dyad members [58], [59], [60], [61]. However, the differences in IBS patterns based on the method or ultimate purpose of cooperation remain relatively unknown. To investigate this aspect, we compared the differences in inter-member IBS observed during competition and cooperation with the opponent team. Fig. 8 illustrates the grand averaged IBS according to the ultimate purpose of cooperation, focusing on four different parts of the PFC. The grand averages were investigated in the frequency bands of 0.2–0.3 Hz, and the error bars indicate the standard error of the mean. As stated previously, according to the standard and modified rules, duo team members were expected to cooperate with each other to compete with the opponent (in Mode 1) or to cooperate with the opponent to finish the game in the fewest number of turns (in Mode 2), respectively. In contrast to other regions, a significant difference in IBS was observed in the right DLPFC region based on the ultimate purposes of cooperation ($p = 0.035$). In the right DLPFC region, higher averaged IBS was observed during cooperation for cooperation compared to cooperation for competition. These observations suggest that even for the same task with the same target, different IBS patterns can emerge depending on the purpose of cooperation. Of note, this trend was not observed in the investigation of the 0.1–0.3 Hz frequency range.

D. Effects of Verbalness on IBS

Verbalness plays a crucial role in social interactions, and verbal interactions are known to be the primary

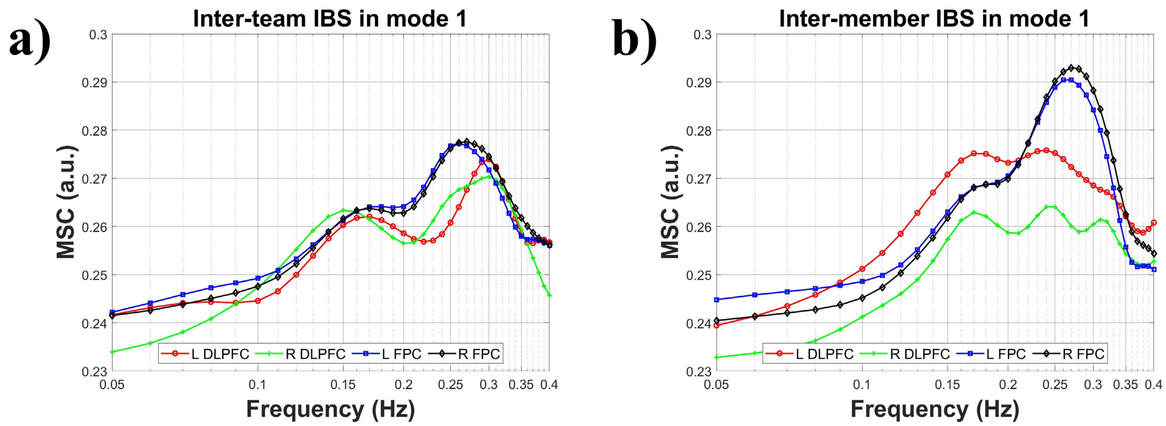

Fig. 5. Grand averages across all participants of (a) inter-member and (b) inter-team IBS for different brain regions of the prefrontal cortex according to the frequency during a task period in Mode 1. The x-axis is presented on a logarithmic scale.

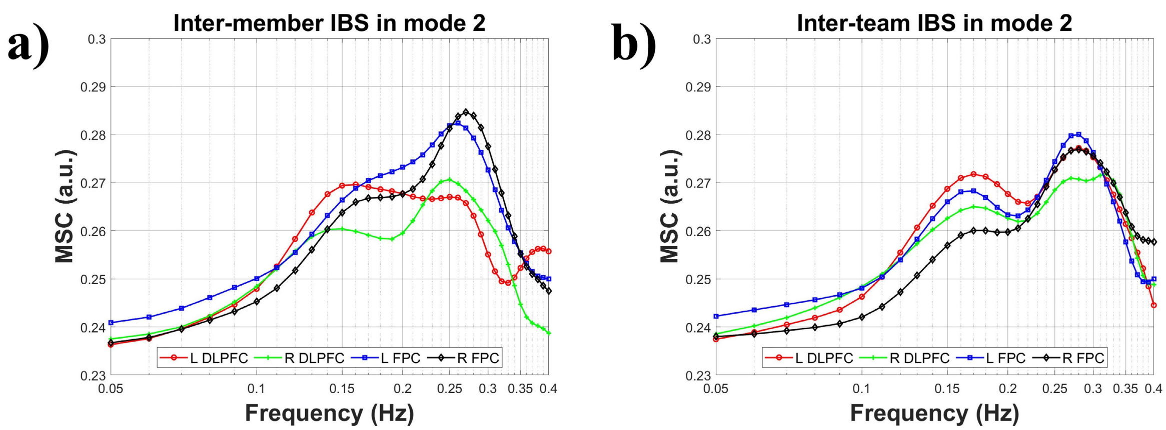

Fig. 6. Grand averaged (a) inter-member IBS and (b) inter-team IBS across all participants for different brain regions of the prefrontal cortex according to the frequency during a task period in Mode 2. The x-axis is presented on a logarithmic scale.

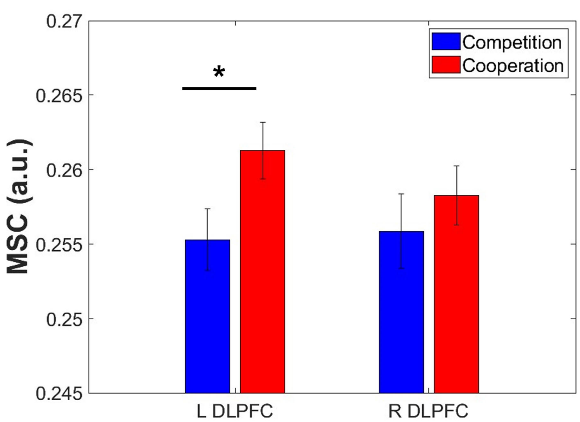

Fig. 7. Inter-team IBS associated with competition (blue) and cooperation (red) in frequency bands of 0.1–0.3 Hz at dorsolateral regions of the PFC. The error bars indicate the standard error of the mean. L and R refer to left and right sides, respectively. In both left and right DLPFC regions, higher average IBS values were observed during the cooperative task compared to the competitive task.

mechanism for inducing IBS in the PFC. Accordingly, several studies have examined this phenomenon [62], [63], [64]. In our experiments, the two members of the duo team engaged in verbal communication to cooperate, while the solo and duo teams cooperated or competed without verbal communication. We examined how IBS was observed differently by comparing the differences in IBS induced by verbal or non-verbal cooperation. Previous fNIRS-based hyperscanning studies have reported that the FPC reflects IBS induced by verbal interaction [28], [65]. Therefore, we focused on the magnitudes of IBS observed in the FPC. Fig. 9(a) and (b) present the magnitudes of IBS according to task mode and pair type in the left and right FPC, respectively. In the left FPC, the average IBS during tasks involving verbal communication was higher than that during tasks without verbal communication. Additionally, IBS induced by verbal cooperation was significantly higher than that induced by non-verbal cooperation in the right FPC ($p = 0.045$). These observations are consistent with previous investigations suggesting that verbal interactions elicit IBS in the FPC. Notably, the left FPC and right FPC exhibited distinct patterns of IBS across identical verbal interactions: the left FPC showed higher IBS during verbal interaction compared to non-verbal interaction, while the right FPC exhibited the highest IBS during verbal collaboration and the lowest IBS during non-verbal collaboration. Based on these observations, we can propose two hypotheses. First, the left FPC tends to reflect IBS induced by verbal interaction. Second, the IBS observed in the right FPC reflects the effect of the type of cooperative task as well as verbal interaction.

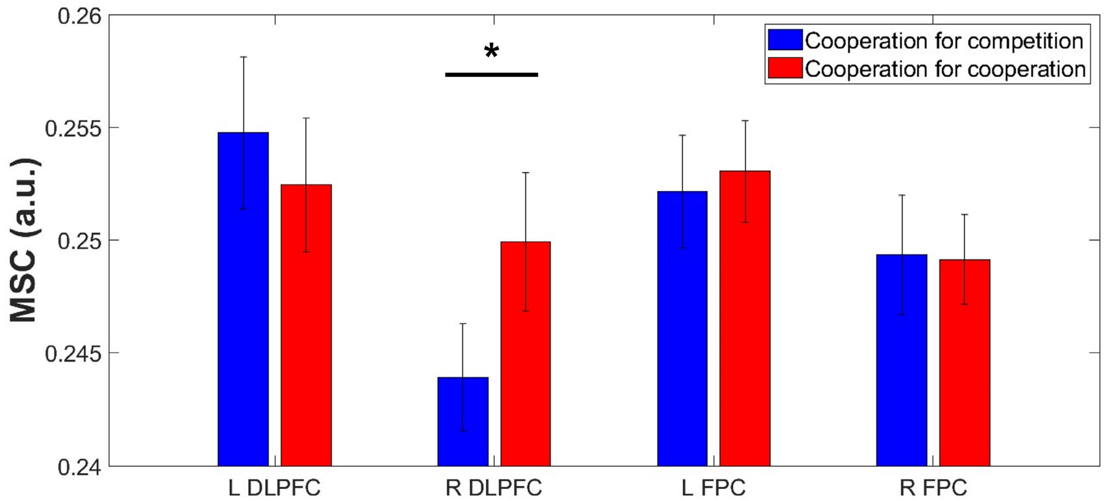

Fig. 8. Inter-member IBS observed at four different parts of the PFC in the frequency bands of 0.2–0.3 Hz. Inter-member IBS was induced by cooperation for different ultimate purposes; cooperation for competition (blue) and cooperation for cooperation (red). The error bars indicate the standard error of the mean. In the right DLPFC region, a significant IBS difference was observed according to the different ultimate purposes.

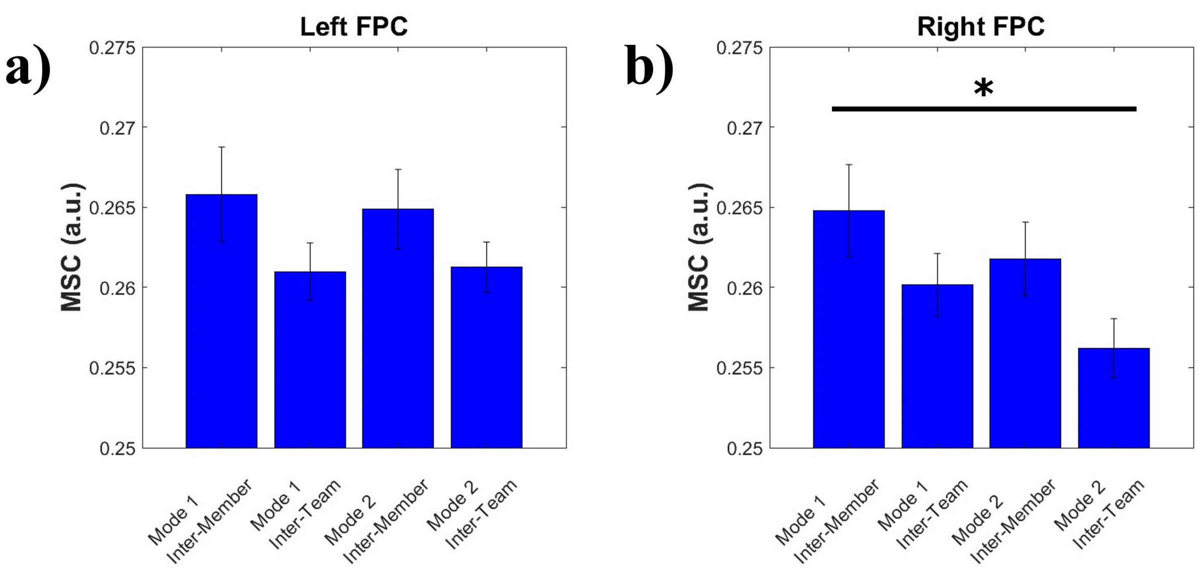

Fig. 9. Magnitudes of IBS according to task mode and pair type in the FPC area; left FPC and right FPC. The error bars indicate the standard error of the mean. For both tasks, the members of the same team verbally communicated with each other, and members of the other team did not verbally communicate with each other. In the left FPC, IBS during tasks involving verbal communication was higher on average compared to IBS during tasks without verbal communication. In the right FPC, a significant IBS difference was observed between the Mode 1 inter-member task and the Mode 2 inter-team task.

E. Neural Mechanisms of IBS

The exploration of how the brain is engaged in social interactions has long been a focal point in cognitive neuroscience. Hyperscanning research has demonstrated the presence of brain coherence patterns, leading to multiple attempts to identify the underlying neurological basis of IBS [66], [67], [68]. The "mutual prediction" theory, among the various hypotheses proposed to explain the neurocognitive mechanisms of IBS, has emerged as a compelling model to elucidate our findings [69], [70]. The fundamental premise of the mutual prediction theory posits that individuals engaged in social interactions possess the ability to regulate their own cognitive processes while concurrently anticipating the cognitive processes of their interaction partner, resulting in a mutual alignment of brain activation. Our findings can be interpreted within the framework of this theory.

In our experimental design, the members of opposing teams competitively played Yut-nori in Mode 1, while they cooperatively played Yut-nori in Mode 2. Given the stochastic nature of the Yut-nori game, which involves random throws of Yut during each turn, an effective strategy in Mode 1 involves impeding the opponent's game progress through possible moves at every turn. Conversely, in Mode 2, a strategy that facilitates progress by anticipating the opponent's potential next move at each turn proves more effective. The analysis results presented in Fig. 7 can be interpreted in this light. Given the established involvement of the left DLPFC in contextual prioritization [71], the participants were more likely to engage in cognitive processes that prioritize their own actions while concurrently predicting their opponents' actions in Mode 2. It is plausible to hypothesize that this behavior elicited activation in the left dorsolateral prefrontal cortex (DLPFC), potentially contributing to the manifestation of IBS. The analysis results depicted in Fig. 8 can be interpreted in a similar manner. Based on the involvement of the right DLPFC in the assessment of action sequences [72], it may be hypothesized that participants in the duo team would demonstrate an enhanced inclination towards action assessments and predictions about action assessments in Mode 2, compared to Mode 1. This provides a rationale for the significant differences in IBS when the ultimate purpose of cooperation shifts between modes.

The involvement of the FPC in linguistic processing provides a basis for understanding the induction of IBS in the FPC through verbal activity, as observed in prior hyperscanning studies. The findings presented in Fig. 9(a) support the proposition that the left FPC tends to exhibit higher average levels of IBS during verbal tasks compared to non-verbal tasks, thus aligning with the proposed hypothesis. Conversely, the results presented in Fig. 9(b) do not reveal a corresponding pattern within the right FPC. In addition to verbal activity, the right FPC has been extensively studied for its involvement in various cognitive functions associated with Yut-nori tasks, including decision-making [73], directed exploration [74], and short-term recognition [75]. These cognitive functions are intricately intertwined during the execution of playful tasks. Thus, it is plausible to hypothesize that the significant disparity observed between Mode 1 inter-member IBS and Mode 2 inter-team IBS in the right FPC can be attributed to the simultaneous engagement of multiple cognitive functions in this region.

V. Conclusion

This research provided valuable insights into the mechanisms of neural synchronization. Our findings indicate that the neural mechanisms underlying cooperative interactions exhibit similarities between dyadic and triadic interactions. However, we can also infer that these neural mechanisms can operate differently depending on two factors: the purpose of cooperation and the presence of verbal communication. We endeavored to elucidate the neural mechanisms that give rise to neural synchronization by examining the patterns of IBS observed during social interactions involving complex cognitive activities. Therefore, we suggest that future fNIRS-based hyperscanning studies should consider the distribution and manifestation of cognitive activities within the context of social interactions.

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