Exploring Inter-Brain Electroencephalogram Patterns for Social Cognitive Assessment During Jigsaw Puzzle Solving

Tse-Min Chuang, *Member, IEEE*, Pin-Chao Peng, Yu-Kai Su, *Student Member, IEEE*,
Sin-Huei Lin, and Yi-Li Tseng, *Member, IEEE*

Abstract*—Social interaction enables the smooth progression of our daily lives. Mounting evidence from recent hyperscanning neuroimaging studies indicates that key components of social behavior can be evaluated using inter-brain oscillations and connectivity. However, mapping out inter-brain networks and developing neurocognitive theories that explain how humans co-create and share information during social interaction remains challenging. In this study, we developed a jigsaw puzzle-solving game with hyperscanning electroencephalography (EEG) signals recorded to investigate inter-brain activities during social interactions involving cooperation and competition. Participants were recruited and paired into dyads to participate in the multiplayer jigsaw puzzle game with 32-channel EEG signals recorded. The corresponding event-related potentials (ERPs), brain oscillations, and inter-brain functional connectivity were analyzed. The results showed different ERP morphologies of P3 patterns in competitive and cooperative contexts, and brain oscillations in the low-frequency band may be an indicator of social cognitive activities. Furthermore, increased inter-brain functional connectivity in the delta, theta, alpha, and beta frequency bands was observed in the competition mode compared to the cooperation mode. By presenting comparable and valid hyperscanning EEG results alongside those of previous studies using traditional paradigms, this study demonstrates the potential of utilizing hyperscanning techniques in real-life game-playing scenarios to quantitatively assess social cognitive interactions involving cooperation and competition. Our approach offers a promising platform with potential applications in the flexible assessment of psychiatric disorders related to social functioning.

***Index Terms*—Hyperscanning, inter-brain synchrony, electroencephalography, cooperation, competition.**

I. Introduction

THE investigation of the 'social brain' and its underlying neural mechanisms has garnered increased attention in the past decade [1], [2]. Social interactions and behaviors, such as closeness, cooperation, competition, and team performance, influence various aspects of our lives and personal relationships [3]. Among these interactions, cooperation and competition represent two opposing dynamics during collaborative work [4]. Cooperative interaction is important among agents who intend to produce a common behavioral outcome through joint action, leading to positive social feedback and social organization [1], [5]. On the other hand, competition emphasizes the relevance and salience of social comparison processes between the agents [1]. Previous neuroimaging studies have demonstrated the critical involvement of the prefrontal cortex during cooperative and competitive behaviors [1], [4], [5]. Although these two types of social interaction share some neural correlates related to social cognition, including the frontoparietal network and anterior insula, previous studies have also shown different patterns of network recruitment. Specifically, cooperative actions involve the recruitment of the orbitofrontal cortex, while competition involves the medial prefrontal and inferior parietal cortices [4]. It is worth noting that a most recent study claimed the importance of the prefrontal cortex during cooperation and guiding the behavior appropriately, especially the interaction of the medial prefrontal network and lateral prefrontal areas [6].

In the past five years, hyperscanning electroencephalography (EEG) techniques have emerged as a trend in studying social activities through inter-brain synchrony (IBS) or inter-neuron synchronization (INS) [7], [8], [9]. Among neuroimaging modalities demonstrated for studying social interaction, neurophysiological hyperscanning techniques using EEG provide better temporal resolution during the execution of social cognitive tasks [10], [11], [12], [13], [14], [15], [16]. The high temporal resolution at the millisecond scale enables more precise and diverse types of between-brain analysis during social interactions. Regarding joint attention, Szymanski et al. conducted EEG hyperscanning in 2017 during individual and joint attention, revealing increased local and inter-brain phase synchronization during joint attention, potentially serving as a neural substrate for social facilitation [9]. Pérez et al. also mentioned brain-to-brain entrainment during

Manuscript received 8 September 2023; revised 16 November 2023; accepted 31 December 2023. Date of publication 10 January 2024; date of current version 19 January 2024. This work was supported in part by the Taiwan National Science and Technology Council under Grant 110-2222-E-110-007-MY2 and Grant 112-2222-E-110-021. *(Corresponding author: Yi-Li Tseng.)*

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 (IRB) at the National Taiwan University Hospital, Taiwan under Application No. 202111075RINA.

The authors are with the Department of Electrical Engineering, National Sun Yat-sen University, Kaohsiung 804, Taiwan (e-mail: yilitseng@mail.nsysu.edu.tw).

Digital Object Identifier 10.1109/TNSRE.2024.3352036

conversation in 2017 [17]. In 2018, Balconi et al. discussed the correlation between brain-to-brain coupling and cognitive joint performance [18], [19]. In 2020, Astolfi et al. focused on co-representation and the basis of joint action [20]. In 2020, Barraza et al. claimed the crucial role of inter-brain theta oscillations during competition and cooperation, with stronger theta IBS observed while competing and gamma IBS while cooperating [21]. In 2023, the latest IBS study proposed by Chuang and Hsu demonstrated greater IBS in the frontal brain regions and lower frequency bands during cooperation, whereas stronger IBS involving the posterior brain areas is observed while competing [22]. These studies have indicated that hyperscanning is feasible for studying inter-brain neural underpinnings and have highlighted the significance of inter-brain synchronizations in high-level social-cognitive processing, especially during cooperation and competition [3], [10], [15], [16], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34].

However, mapping out brain networks and neurocognitive theories of how humans co-create and share information during social interaction remains challenging [7], [8]. Increased IBS has been reported in various frequency bands, including delta [22], theta [21], [26], [29], [33], alpha [25], [26], beta [28], and gamma [21], [23], [28], across different cooperation and competition tasks/paradigms. Findings related to the brain regions of IBS and oscillatory frequencies are still diverse, showing inconsistent results during social interactions.

In this study, we developed a game-based dual jigsaw puzzle-solving task to investigate the social cognition of cooperation and competition in a real-life situation. EEG signals were recorded to assess local brain activations and oscillations, as well as inter-brain synchronization. Our aim is to investigate the following hypotheses: 1) the involvement of distinct brain networks during cooperation and competition using brain oscillations and functional connectivity, and 2) the essence of inter-brain connections between collaborators or competitors.

II. MATERIALS AND METHODS

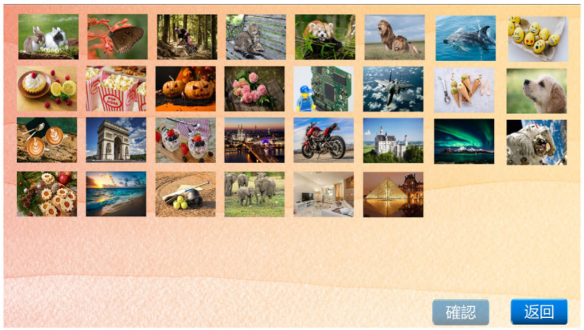
A. Participants

We recruited a total of 58 participants (aged 22.21 ± 2.11; 33 men), specifically 29 pairs of participants for this experiment. Informed written consent was obtained from the legal representatives of all participants before the experiment, following the requirements of the human subject research ethics committee/Institutional Review Board (IRB) at National Taiwan University Hospital, Taiwan (no. 202111075RINA). All participants confirmed that they had no neuropsychiatric disorders, as determined based on the criteria outlined in the American Psychiatric Association's Diagnostic and Statistical Manual of Mental Disorders (DSM-5). Additionally, we assessed the participants' autism spectrum quotient (AQ) [35] and emotional quotient (EQ). All pairs of participants recruited for this study were matched as closely as possible based on their behavior scores.

B. Experimental Design: Dual Jigsaw Puzzle Solving Task

A dual jigsaw puzzle-solving task was developed using the Unity 2021.2.13f1 game engine. The task consists of three modes: a collaboration mode, a competitive mode, and a single-player mode. Prior to the experiment, two participants were paired together to complete a jigsaw puzzle. Initially, participants were asked to complete a questionnaire to select their preferred pictures from a set of thirty options. The pictures chosen by both participants served as the jigsaw puzzle images for the experiment. Before entering the game screen, both participants were required to select a unique icon as their mouse cursor picture and color. This measure aimed to prevent confusion or distractions when moving the puzzle pieces (Fig. 1).

A. Jigsaw puzzle: Picture menu



B. Jigsaw puzzle: Mouse menu

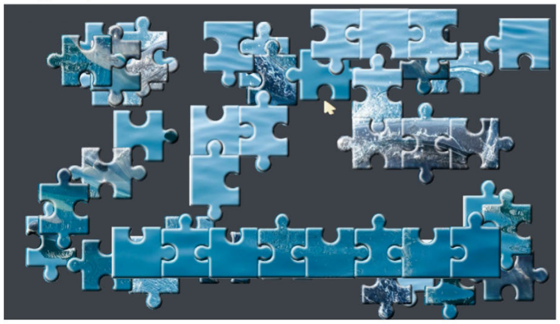
Fig. 1. Game interfaces of the jigsaw puzzle, including (A) the option menu of the multiplayer mode for users to select their favorite pictures, and (B) the option menu of the multiplayer mode for users to select their represented icons and colors.

The first mode is the collaboration mode, where both players work together to solve a 48-piece jigsaw puzzle within a specified time limit. The second mode is the competition mode, where the two players take turns solving the puzzle. The player who successfully fits more pieces wins a gift card. The third mode is the single-player mode, where each player solves a jigsaw puzzle individually. The primary game interface for both the single and multiplayer modes is depicted in Fig. 2A. When a player correctly places a jigsaw puzzle piece, a resting screen randomly appears for a duration of 1.4 to 1.6 seconds. This resting screen features a black background with a cross in the middle, as shown in Fig. 2B. Additionally, a hint sound is played to indicate the accuracy of the placement, with a high-pitched sound indicating correct placements and a low-pitched sound indicating incorrect placements. This stimulus is simultaneously received by both participants. The complete experimental paradigm is illustrated in Fig. 3.

C. EEG Recording and Signal Processing

The EEG signals were recorded using two Neuroscan Grael EEG amplifiers (Grael, Compumedics Ltd., Australia) at a sampling rate of 1024Hz with 32 scalp electrode EEG caps.

A. Jigsaw puzzle: Game interface



B. Jigsaw puzzle: Resting

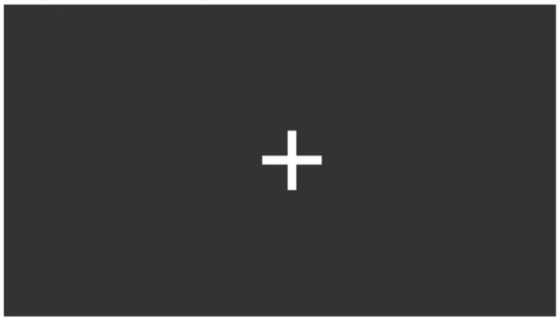
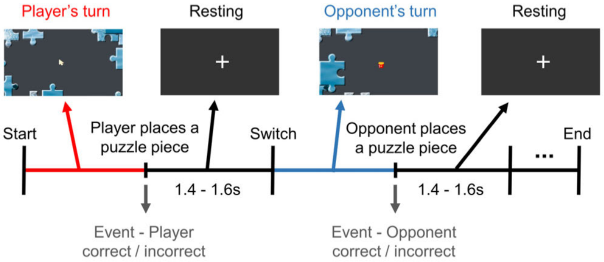


Fig. 2. (A) The main game interface of single/multiplayer modes, and (B) the resting screen when players place the jigsaw puzzle pieces.

A. Double-player mode



B. Single-player mode

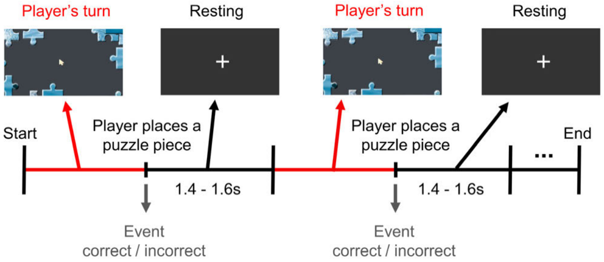


Fig. 3. (A) The complete stimulus processes for the double-player mode, and (B) the stimulus process for the single-player mode.

Silver/silver chloride electrodes were positioned according to the international standard 10-20 system. All signals were online referenced to the M1 and M2 electrodes of the bilateral mastoid. The channel impedances were maintained below 5 kΩ. Data analysis was performed using MATLAB R2022a (The MathWorks, Inc., Natick, MA, USA).

The EEG data was preprocessed using the EEGLAB toolbox and a standard preprocessing pipeline [36], [37]. Firstly, the data went through a high-pass filter at 0.5 Hz. After filtering, channels with signal amplitudes exceeding 4 standard deviations and signal correlations below 0.8 were removed due to poor behavior. Subsequently, Artifact Subspace Reconstruction (ASR) utilizing Independent Component Analysis (ICA) was employed to distinguish artifacts from brain signals. In our data, the removal of eye movement artifacts had a significant impact. The parameter "k" was set to 20 to achieve optimal results [37]. ASR was performed on the data after the removal of bad channels, followed by reconstruction through interpolation. Before proceeding with the separation of the original signals, epoching was conducted on the continuous signal, and baseline subtraction was performed to reduce mutual information [38]. The epoch time was set to 0 seconds when the sound indicating a correct or incorrect response was played, with a 0.2-second forward cut and a 1-second backward cut. Trials with amplitudes exceeding 500 μV or exceeding 6 standard deviations compared to trials in the same channel, or 2 standard deviations compared to trials across all channels, were excluded. Channels near Fp1 and Fp2, which are susceptible to eye blinks, were excluded to prevent excessive trial removal. Component separation can significantly assist in artifact removal and facilitate subsequent source analysis. The Adaptive Mixture of Independent Component Analyzers (AMICA), which yielded the best results for blind source separation, was used for component separation and underwent 2000 iterations [39], [40]. Components associated with more than 90% eye artifacts or more than 60% muscle artifacts were removed [41]. After completing all the processes, the original channels were reconstructed.

D. Event-Related Potentials and Time-Frequency Analysis

To investigate the brain signals associated with the event, the mean of all trials for each channel was calculated under experimental conditions. The Anderson-Darling test was initially applied to assess the normality of the data [67]. A comparison between the results from different experimental conditions was performed using a paired t-test. Time points with a significance level of $p < 0.05$ were identified and extracted for further statistical analysis of event-related potentials (ERP) components. Significant ranges with continuous time periods of less than 50 ms were excluded from further significance analysis. The topographic mappings of the ERP were conducted, and electrodes with the largest ERP components were selected for subsequent statistical analysis. This analysis involved paired t-tests between conditions, encompassing correctness versus incorrectness conditions in single-player mode and cooperation and competition conditions in double-player mode.

To analyze the time-frequency patterns of each frequency band across different conditions, wavelet transformation was applied to the data within the frequency range of 1 to 30 Hz and the time range of -0.2 to 1 seconds. The Event-Related Spectral Perturbation (ERSP) was calculated using the EEGLAB toolbox [68]. Event-related synchronization (ERS) and event-related desynchronization (ERD) were indicated by increases and decreases in the power of different frequency bands, respectively, relative to the pre-stimulus baseline. The ERSP values for all subjects within the same condition were averaged. Before conducting statistical comparisons between the two conditions, we conducted a normal distribution test and generated topographic mappings for all electrodes. Finally, a paired t-test was performed to assess the significance of differences between the two conditions at brain regions, time intervals, and frequency bands with the largest ERS activations.

E. Inter-Brain Functional Connectivity

The inter-brain functional connectivity between pairs of participants was compared using the inter-brain phase lag index (PLI) [42]. For a pair of channels between participants, the PLI can be calculated as follows:

$$PLI = \frac{1}{N}\left|\sum_{k=1}^{N} \operatorname{sgn}\left(Im\left[e^{j\theta(t,k)}\right]\right)\right|, \tag{1}$$

where N represents the number of trials, $\theta(t,k)$ denotes the phase differences between a pair of channels, and t represents the time range. The imaginary part (Im) is extracted before calculating the sign (sgn) of the result.

To evaluate the statistical significance of IBS, also known as inter-brain functional connectivity, we randomly shuffled the labels for the two conditions, cooperation and competition, and calculated PLI values from the label-shuffled signals. Using a permutation test, we assessed the significance of inter-brain and cross-channel connections between label-shuffled PLI pairs of channels in dyads with the Wilcoxon signed-rank test. This test compared the original PLI value with a distribution of label-shuffled PLI values over 1000 iterations. If the original PLI value exhibited a significant difference ($p < 0.05$) compared to the randomly shuffled distribution, it was considered indicative of a significant connection between the corresponding pair of channels within a pair of participants.

The analysis covered both collaboration and competition modes, resulting in two distinct conditions: when a player or partner matched a piece in the collaboration mode, and when a player or partner matched a piece in the competition mode.

III. RESULTS

A. Behavioral Results

The AQ and EQ scores of all participants fell within the normal range, with an AQ score lower than 32 and an EQ score higher than 30 (AQ: 20.75 ± 6.30; EQ: 42.32 ± 11.65). In the single-player mode of the game, the numbers of correct and incorrect matches were 45.86 ± 1.68 and 67.72 ± 37.93, respectively ($p < 0.001$). The total time spent completing the puzzle was 807.31 ± 312.37 seconds. For the cooperative and competition modes, the total numbers of correct matches by participants themselves were 22.87 ± 4.15 and 22.93 ± 2.64, respectively, and there was no significant difference between the two modes ($p = 0.921$). However, the total numbers of incorrect matches by participants themselves in the cooperative and competition modes were 20.70 ± 10.01 and 9.34 ± 6.85, respectively, and a significant difference existed between the two modes ($p < 0.001$). The overall time spent completing the puzzle in the competition mode was 831.86 ± 251.43 seconds, slightly slower than that in the cooperative mode (768.07 ± 204.80 seconds), but the difference was not significant ($p = 0.076$).

B. ERP Results

The ERPs in the single and multiple player modes are presented in Fig. 4 and 5. In the single-player mode, significant differences between correctness and incorrectness were observed when the player attempted to match a puzzle piece. As depicted in Fig. 4A, substantial distinctions were evident in both the topography (left segment of Fig. 4A) and ERP components (middle segment of Fig. 4A) within the fronto-central regions, indicating a feedback-related negativity (FRN) during an incorrect outcome. The statistical findings indicate significant differences within the 450 to 550 ms range at the FCz ($p < 0.001$) and Cz ($p < 0.001$) electrodes. Additionally, a reduction in the P3 component (300–400 ms) was observed in the parietal region at the CPz ($p < 0.001$) and Pz ($p < 0.001$) electrodes when the player failed to match a puzzle piece compared to the correct outcome.

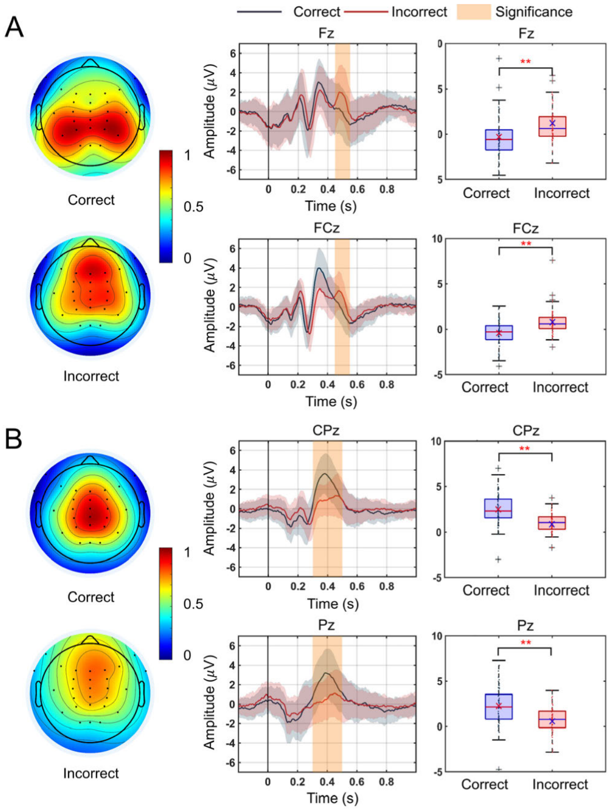


Fig. 4. Topographic mappings (left segment) and event-related potentials (middle segment) of the single-player mode in the jigsaw puzzle game, along with the corresponding statistical results (right segment) within the following time intervals: (A) 450–550 ms at the Fz and FCz electrodes, and (B) 300–400 ms (the P3 component) at the CPz and Pz electrodes.

The topographic mappings and ERPs in the cooperation and competition modes are displayed in Fig. 5. When the player observed their opponent correctly matching a puzzle piece (Fig. 5A), a significant difference was observed between 425 and 450 ms. The ERPs of the cooperation mode exhibited a larger peak at the FCz electrode ($p = 0.005$) and the Cz electrode ($p = 0.001$) compared to the ERPs of the competition mode. Additionally, a delayed decay of the P3 component at the midline electrodes was observed (Fig. 5B; FCz: $p = 0.001$; Cz: $p < 0.001$; CPz: $p = 0.008$) in the cooperation mode compared to the competition mode when the player successfully matched a puzzle piece.

C. ERSP Results

Average ERSPs were presented in Fig. 6 for both the single-player and multiple-player modes in the jigsaw puzzle game.

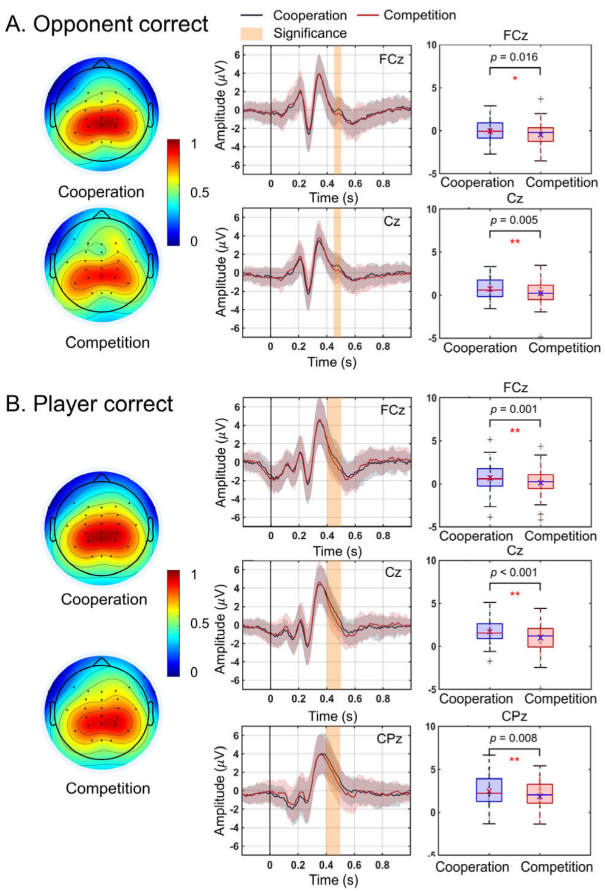


Fig. 5. Topographic mappings (left segment) and event-related potentials (middle segment) of the cooperation and competition modes in the jigsaw puzzle game, accompanied by the corresponding statistical results (right segment) within the following time intervals: (A) Opponent correct: 425–450 ms at the FCz and Cz electrodes, and (B) Player correct: 400–450 ms at the FCz, Cz, and CPz electrodes.

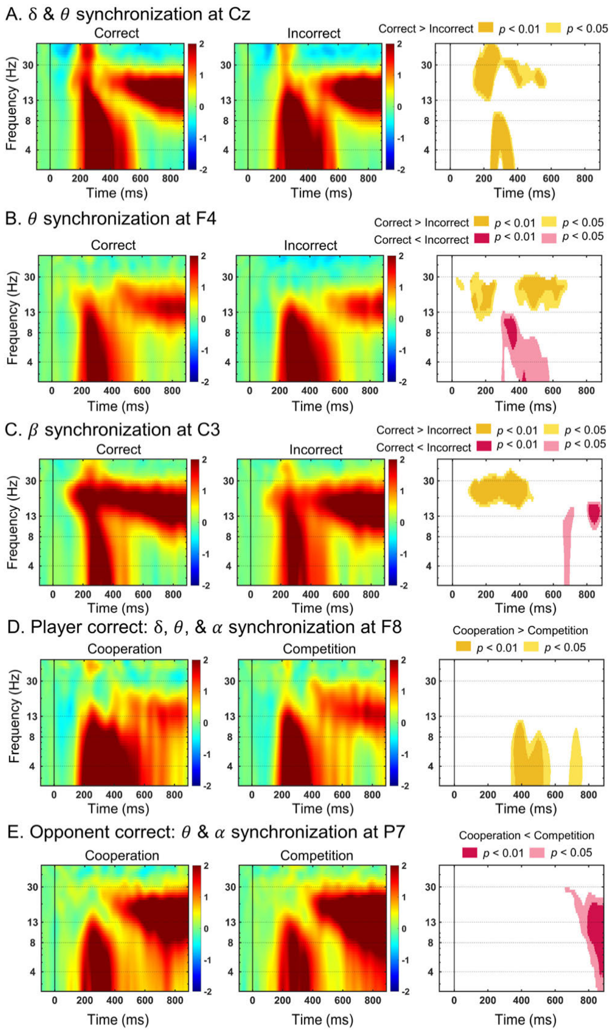


Fig. 6. Average event-related spectral perturbations (ERSPs) for the single-player (A-C) and multiple-player (D-E) modes in the jigsaw puzzle game, along with significantly active time intervals and their corresponding brain regions presented in the right column.

In the single-player mode, a significant difference between correct and incorrect puzzle-solving matches was observed in the delta (1-4 Hz), theta (4-7 Hz), and beta (13-30 Hz) frequency bands in the centroparietal regions (Fig. 6A-C). In the multiple-player mode, a significant difference between cooperation and competition modes was observed in the delta, theta, and alpha (8-12 Hz) frequency bands in the right frontal regions when the player themselves matched a puzzle piece (Fig. 6D). Additionally, brain oscillations of theta and alpha frequency bands in the parietal regions were observed to increase in the later stages of the competition mode when the players observed a correct outcome from their opponents (Fig. 6E). Significantly active time intervals and their corresponding brain regions are presented in the right column of Fig. 6. Topographic mappings of brain oscillations in different frequency bands and the corresponding statistical results are also shown in Fig. 7. In the early stages (200–400 ms) of the single-player mode, delta and theta oscillations were observed to be larger in the correct conditions compared to the incorrect ones, with the most significant difference at the Cz electrode (Fig. 7A; $p = 0.004$). Additionally, beta synchronization between 200 and 600 ms at the C3 electrode exhibited a significant difference (Fig. 7C; $p = 0.004$), which may be related to beta suppression. In contrast, a more pronounced increase in theta synchronization in the frontocentral regions was observed in the incorrect condition during the middle stage (400–600 ms) of the trial (Fig. 7B; $p = 0.031$), which may be related to the FRN component.

Significant differences in brain oscillations between social interactions of cooperation and competition were measured. When the player correctly matched a puzzle piece themselves, more pronounced increases in delta, theta, and alpha oscillations were observed in the frontocentral regions during cooperation compared to the competition conditions. The largest difference was observed at the F8 electrode between 300 and 500 ms ($p = 0.007$). In contrast, more pronounced increases in theta and alpha oscillations were observed in the competition mode when the player observed the correctness of their opponents, mainly at the P7 electrode between 600 and 900 ms, especially right before the beginning of the next turn for the player themselves.

D. Inter-Brain Connectivity

The brain regions and time intervals with increased brain oscillations in specific frequency bands were selected for further IBS analysis. As depicted in Fig. 6, brain oscillations in the delta, theta, and alpha frequency bands were observed between 200 and 400 ms in all conditions, both in the

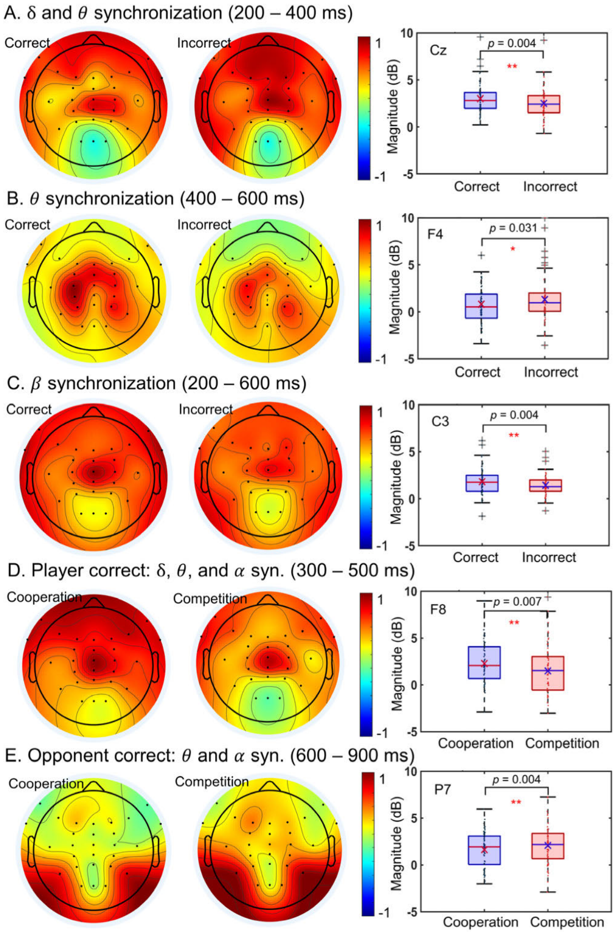


Fig. 7. Topographic mappings (left segment) and statistical results of event-related spectral perturbation (ERSPs; right segment) within the following time intervals: (A) Single player: 200–400 ms (delta and theta bands) at Cz, (B) Single player: 400–600 ms (theta band) at F4, (C) Single player: 200–600 ms (beta band) at C3, (D) Player correct: 300–500 ms at F8, and (E) Opponent correct: 600–900 ms at P7 electrodes.

single-player and multiple-player modes. Additionally, Fig. 6 also shows increases in beta oscillations between 500 and 900 ms. The magnitude of IBS was calculated using PLI from different frequency bands within the aforementioned time intervals (Fig. 8).

The results of IBS after shuffling indicated that the quantity of IBS in the competition mode is significantly greater than that in the cooperation mode across all frequency bands. As shown in Fig. 8A and 8B, long-range IBS was observed in low- frequency bands (delta and theta waves), particularly in the inter-brain connections between frontal and parietooccipital regions whenever a player made a correct move during competition. In contrast, the connection patterns between local brain regions of the two participants were observed in the alpha (200–400 ms) and beta (500–900 ms) frequency bands, especially in the connections within frontal, centroparietal, and occipital regions (Fig. 8C and 8D). These results demonstrate increased IBS during competition in a turn-taking manner.

IV. DISCUSSIONS

A. Diverse ERP Morphological Patterns of P3 in Competitive and Cooperative Contexts

In the present study, we incorporated behavioral and EEG measures to investigate social interactions involving

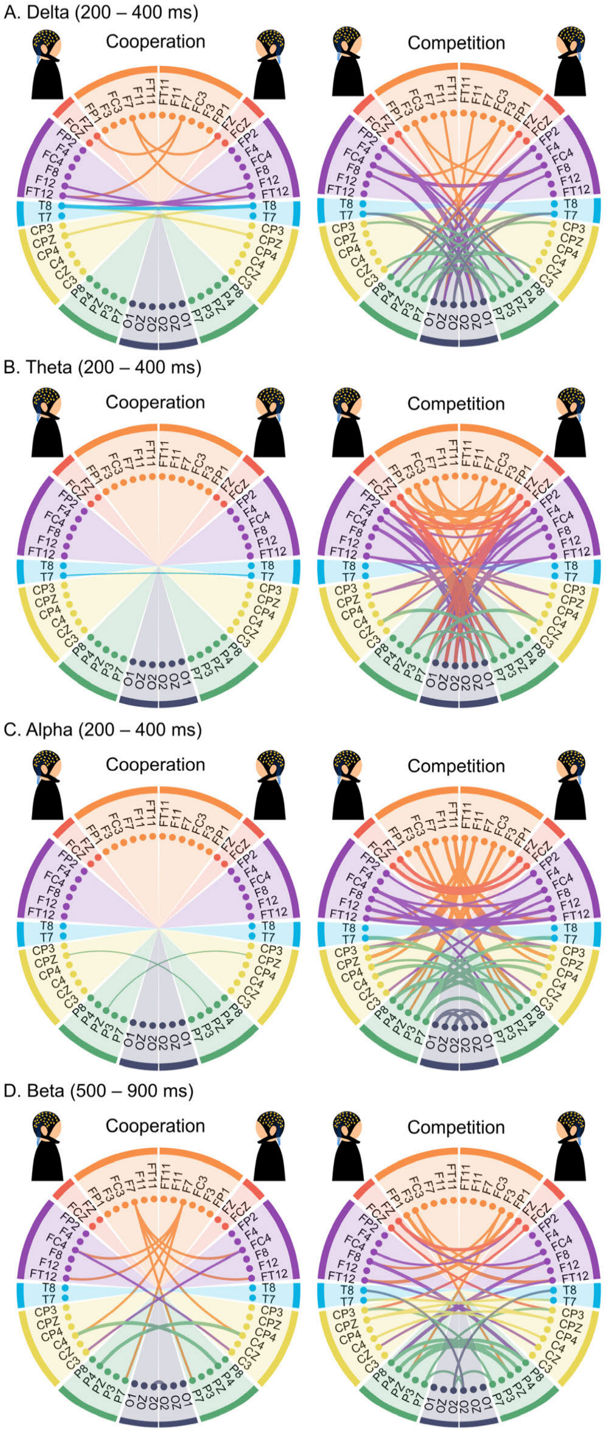


Fig. 8. The significance of inter-brain synchrony (IBS) was assessed after label shuffling within the time intervals of 200 to 400 ms for the (A) delta, (B) theta, and (C) alpha frequency bands, as well as 500 to 900 ms for the (D) beta frequency band. The level of IBS in the competition mode was found to be significantly greater than that in the cooperation mode across all frequency bands.

competition and cooperation. The validity of the novel game-based paradigm proposed in this study is supported by the ERP results observed during the single-player mode. An obvious FRN is observed in the frontocentral regions approximately 200 to 300 ms after the feedback onset when players fail to match a puzzle piece [43]. In contrast, a typical N2-P3 complex is observed in the single-player mode when players successfully match a puzzle piece. We further compared the ERP results in the dual-players modes, and consistent findings of divergent morphologies in P3 patterns were observed between the competitive and cooperative contexts. Specifically, a delayed decay of the P3 complex has been found in the cooperation mode compared to the competition mode. In the cooperation mode, when the player themselves matched a puzzle piece, a significant delayed decay of P3 was observed between 400 and 600 ms. Similarly, a different morphology of P3, followed by a small peak at around 500 ms, is reported in the current study in the cooperation mode when players observed their partner matching one puzzle piece. These results may indicate a more complex cognitive process during cooperation than during competition [44]. A recent study on competition and cooperation also showed that an opponent's defection elicited a smaller P3a but a larger P3b when participants wrongly believed that their opponent would cooperate [45]. These findings provide evidence supporting the importance of the P3 component in studying social activities.

B. Low-Frequency Synchronization as an Indicator of Social Cognitive Activities

In line with previous research on paradigms related to error feedback, our results from the single-player mode demonstrated similar findings. This included delta and theta synchronization related to P3 during correct conditions, as well as theta synchronization related to FRN in incorrect conditions. Specifically, delta and theta synchronization related to P3 were mainly observed in the centroparietal regions between 200 and 400 ms during the correct condition in the single-player mode. This synchronization has been suggested to be associated with P3, focused attention, and selective attention. In the single-player mode, when players failed to match a puzzle piece, we observed FRN-related theta synchronization in the midline frontocentral regions between 400 and 600 ms. This finding is suggested to represent error feedback signals for optimizing future behavior [43].

Our results also revealed distinct patterns of beta synchronization between the correct and incorrect conditions. We observed greater beta synchronization in the central regions between 200 and 600 ms during the correct-matching condition compared to the incorrect one. Previous studies have already mentioned the phenomenon of beta rebound after motion-related suppression. It's worth noting that error detection in the post-movement stage may attenuate the level of beta rebound [46], [47], [48], [49], [50]. In summary, our ERS findings from the single-player mode align with those observed in traditional cognitive paradigms proposed in previous studies.

Building on these consistent findings from the single-player mode, we conducted further comparisons of brain oscillations during multiple player modes, including cooperation and competition. Theta oscillations have been shown to play a crucial role during social interactions in both cooperation and competition. In the cooperation mode, we observed larger delta and theta synchronization between 300 and 500 ms in the frontal regions when a player successfully matched a puzzle piece. In comparison to the competition mode, this increased low-frequency synchronization may suggest a greater involvement of focused and selective attention related to the P3 component in cooperative situations [51].

Conversely, increased theta synchronization was observed between 600 and 1000 ms at the FC4, C4, and P7 electrodes in the competition mode when an opponent successfully matched a puzzle piece. The larger theta synchronization right before the next trial in the competition mode, compared to cooperation, may suggest an increased intention to move or a preparation for movement in the competitive context.

C. Increased Inter-Brain Synchronization During Competition

Our findings have revealed an increased level of IBS in the competition mode when compared to the cooperative context, particularly in terms of long-range IBS between frontal and parietooccipital regions in low-frequency bands, as well as local IBS in high-frequency bands. Table I provides a comparison of tasks and modalities from recent hyperscanning studies related to social assessment. The majority of prior studies focusing on cooperative tasks consistently reported elevated IBS across a wide range of frequency bands in EEG and functional near-infrared spectroscopy (fNIRS) measurements [3], [16], [26], [27], [28], [29], [30], [34], [52]. The diversity of tasks/games developed and the choice of imaging modality for assessing social cognition have contributed to varying findings of IBS in specific brain regions and frequency bands in previous research, as summarized in Table I.

Relatively few studies have explored increased IBS in competitive compared to the cooperative contexts [21], [22], [32]. In line with the latest EEG studies demonstrating cooperation and competition using different paradigms, our results also reveal a greater IBS in the frontal brain regions and lower frequency bands during cooperation. In contrast, stronger IBS involving the posterior brain areas is observed while competing [21], [22]. These findings suggest that IBS in delta and theta frequency bands is highly correlated with social activities.

The previous results of high-frequency IBS, including alpha, beta, and gamma, are relatively diverse [3], [21], [22], [23], [24], [32], [34]. Although our results in Fig. 8 demonstrated greater IBS in most frequency bands, including delta, theta, alpha, and beta oscillations, several recent studies, encompassing both cooperation and competition modes, have reported no findings in alpha and beta IBS [21], [22]. Nevertheless, some studies using cooperative tasks have found that alpha, beta, or even gamma IBS has been observed during joint action or cooperation [3], [21], [23], [24], [34]. Further investigation is needed to verify the role of alpha and beta IBS during competition.

With the maturation of hyperscanning techniques, more studies have been devoted to exploring the mechanisms of social interaction using IBS. Further investigation is warranted to facilitate future applications in assessing mental health and social cognitive functions. In comparison to previous studies, our research introduces a novel approach by utilizing a turn-taking puzzle-solving game that encompasses single-player, cooperative, and competitive modes. The game is designed with real-life scenarios, making it suitable for future applications in mental training. The validity of the physiological indices is proven by comparing the results with those of previous ERP, ERSP, and IBS studies.

TABLE I

PREVIOUS STUDIES OF INTER-BRAIN SYNCHRONY (IBS) FOR SOCIAL COGNITIVE ASSESSMENT (IFG: INFERIOR FRONTAL GYRUS; TPJ: TEMPOROPARIETAL JUNCTION; DLPFC: DORSOLATERAL PREFRONTAL CORTEX)

Study	Tasks	Modality	Findings
Liu (2015) [15]	Turn-taking game	fNIRS	Competitor–builder pairs show IBS in right IFG
Pan (2017) [30]	Cooperation in lovers	fNIRS	Lover dyads demonstrated increased IBS in right superior frontal cortex
Balconi (2018) [31]	Ineffective joint strategies	fNIRS	Decreased IBS in post-feedback condition for the dyad
Jahng (2017) [25]	Prisoner's dilemma game	EEG	IBS of right temporal-parietal cortical region
Xue (2018) [10]	Realistic presented problem	fNIRS	IBS in rDLPFC and rTPJ of two less-creative members
Hu (2018) [26]	Interactive decision making	EEG	Larger centrofrontal theta-band and centroparietal alpha-band IBS in tasks set for high cooperation
Lu (2019) [27]	Group creative performance	fNIRS	IBS in the r-DLPFC, r-TPJ, prefrontal and posterior temporal regions during cooperation
Wang (2019) [16]	Pain-induced cooperation in females	fNIRS	IBS in right prefrontal and right parietal cortex
Dodel (2020) [28]	Team coordination	EEG	IBS of beta and gamma rhythms during critical phases of task performance where subjects exchange information
Barraza (2020) [21]	Dual visual cue-target task	EEG	IBS in theta band while competing, and IBS in gamma band while cooperating
Shiraishi (2021) [29]	Cooperative finger tapping	EEG	IBS in theta oscillations between the frontal region in the leader and the right temporo-parietal region in the follower
Richard (2021) [23]	Discussion of social issues	EEG	IBS in gamma frequency range when subject pairs agreed on the social issues
Dikker (2021) [24]	Face-to-face interactions	EEG	IBS in low alpha and beta oscillations during joint action
Liu (2021) [34]	Motion-sensing tennis game	EEG	Cooperation elicited positive single-channel IBS at the delta and theta bands in extensive brain regions, while competition was associated with negative occipital IBS at the alpha and beta bands
Wikstrom (2022) [3]	Collaborative coordination task	EEG	IBS in the alpha, beta, and gamma frequency bands in pairs who work together
Park (2022) [53]	Cooperative and competitive *N*-back	fNIRS	IBS levels increased in the cooperation mode according to the task difficulty level
Zhang (2023) [32]	Competitive tasks	fNIRS	Increased IBS in elder couples between the middle temporal cortex and the TPJ across task processes
Park (2023) [52]	Triadic board game	fNIRS	Cooperative interactions increased prefrontal IBS
Chuang (2023) [22]	Shared attention tasks	EEG	Low frequency IBS: Frontal IBS while cooperating and posterior IBS while competing
Proposed study	Cooperative and competitive puzzle solving	EEG	Long-range IBS between frontal and parietooccipital regions in low-frequency bands, as well as local IBS in high-frequency bands during competition

V. CONCLUSION

Our study introduced a novel approach by developing a jigsaw puzzle-solving game and employing hyperscanning EEG signals to investigate inter-brain dynamics during cooperative and competitive social interactions. The findings revealed distinct patterns of P3 activity in these contrasting contexts, shedding light on the potential role of low-frequency brain oscillations and heightened inter-brain functional connectivity as markers of social cognitive processes. This research underscores the feasibility of using hyperscanning techniques for the quantitative assessment of social cognitive interactions. Furthermore, our innovative social interaction game could serve as a valuable tool for monitoring and analyzing inter-brain activities in scenarios closely resembling real-life social situations. These findings hold promise for versatile applications, particularly in evaluating psychiatric disorders related to social interactions.

REFERENCES

[1] M. Balconi and M. E. Vanutelli, “Functional EEG connectivity during competition,” *BMC Neurosci.*, vol. 19, no. 1, p. 63, Oct. 2018, doi: 10.1186/s12868-018-0464-6.

[2] J. Toppi et al., “Investigating cooperative behavior in ecological settings: An EEG hyperscanning study,” *PLoS ONE*, vol. 11, no. 4, Apr. 2016, Art. no. e0154236, doi: 10.1371/journal.pone.0154236.

[3] V. Wikström et al., “Inter-brain synchronization occurs without physical co-presence during cooperative online gaming,” *Neuropsychologia*, vol. 174, Sep. 2022, Art. no. 108316, doi: 10.1016/j.neuropsychologia.2022.108316.

[4] J. Decety, P. L. Jackson, J. A. Sommerville, T. Chaminade, and A. N. Meltzoff, “The neural bases of cooperation and competition: An fMRI investigation,” *NeuroImage*, vol. 23, no. 2, pp. 744–751, Oct. 2004, doi: 10.1016/j.neuroimage.2004.05.025.

[5] M. Balconi, M. E. Vanutelli, and L. Gatti, “Functional brain connectivity when cooperation fails,” *Brain Cognition*, vol. 123, pp. 65–73, Jun. 2018, doi: 10.1016/j.bandc.2018.02.009.

[6] Y. Zoh, S. W. C. Chang, and M. J. Crockett, “The prefrontal cortex and (uniquely) human cooperation: A comparative perspective,” *Neuropsychopharmacology*, vol. 47, no. 1, pp. 119–133, Jan. 2022, doi: 10.1038/s41386-021-01092-5.

[7] T. Wheatley, A. Boncz, I. Toni, and A. Stolk, “Beyond the isolated brain: The promise and challenge of interacting minds,” *Neuron*, vol. 103, no. 2, pp. 186–188, Jul. 2019.

[8] E. Redcay and L. Schilbach, “Using second-person neuroscience to elucidate the mechanisms of social interaction,” *Nature Rev. Neurosci.*, vol. 20, no. 8, pp. 495–505, Aug. 2019.

[9] C. Szymanski et al., “Teams on the same wavelength perform better: Inter-brain phase synchronization constitutes a neural substrate for social facilitation,” *NeuroImage*, vol. 152, pp. 425–436, May 2017, doi: 10.1016/j.neuroimage.2017.03.013.

[10] H. Xue, K. Lu, and N. Hao, “Cooperation makes two less-creative individuals turn into a highly-creative pair,” *NeuroImage*, vol. 172, pp. 527–537, May 2018.

[11] M. Balconi, L. Pezard, J.-L. Nandrino, and M. E. Vanutelli, “Two is better than one: The effects of strategic cooperation on intra- and inter-brain connectivity by fNIRS,” *PLoS ONE*, vol. 12, no. 11, Nov. 2017, Art. no. e0187652, doi: 10.1371/journal.pone.0187652.

[12] X. Lei and P.-L.-P. Rau, “Emotional responses to performance feedback in an educational game during cooperation and competition with a robot: Evidence from fNIRS,” *Comput. Hum. Behav.*, vol. 138, Jan. 2023, Art. no. 107496, doi: 10.1016/j.chb.2022.107496.

[13] R. Li, N. Mayseless, S. Balters, and A. L. Reiss, “Dynamic inter-brain synchrony in real-life inter-personal cooperation: A functional near-infrared spectroscopy hyperscanning study,” *NeuroImage*, vol. 238, Sep. 2021, Art. no. 118263, doi: 10.1016/j.neuroimage.2021.118263.

[14] Y. Li, R. Chen, O. Turel, T. Feng, C.-Z. Zhu, and Q. He, “Dyad sex composition effect on inter-brain synchronization in face-to-face cooperation,” *Brain Imag. Behav.*, vol. 15, no. 3, pp. 1667–1675, Jun. 2021, doi: 10.1007/s11682-020-00361-z.

[15] T. Liu, H. Saito, and M. Oi, "Role of the right inferior frontal gyrus in turn-based cooperation and competition: A near-infrared spectroscopy study," *Brain Cognition*, vol. 99, pp. 17–23, Oct. 2015, doi: 10.1016/j.bandc.2015.07.001.

[16] C. Wang, T. Zhang, Z. Shan, J. Liu, D. Yuan, and X. Li, "Dynamic interpersonal neural synchronization underlying pain-induced cooperation in females," *Hum. Brain Mapping*, vol. 40, no. 11, pp. 3222–3232, Aug. 2019, doi: 10.1002/hbm.24592.

[17] A. Pérez, M. Carreiras, and J. A. Duñabeitia, "Brain-to-brain entrainment: EEG interbrain synchronization while speaking and listening," *Sci. Rep.*, vol. 7, no. 1, pp. 1–12, Jun. 2017.

[18] M. Balconi, L. Gatti, and M. E. Vanutelli, "EEG functional connectivity and brain-to-brain coupling in failing cognitive strategies," *Consciousness Cognition*, vol. 60, pp. 86–97, Apr. 2018.

[19] M. Balconi, L. Gatti, and M. E. Vanutelli, "Cooperate or not cooperate EEG, autonomic, and behavioral correlates of ineffective joint strategies," *Brain Behav.*, vol. 8, no. 2, Feb. 2018, Art. no. e00902.

[20] L. Astolfi, J. Toppi, A. Ciaramidaro, P. Vogel, C. M. Freitag, and M. Siniatchkin, "Raising the bar: Can dual scanning improve our understanding of joint action?" *NeuroImage*, vol. 216, Aug. 2020, Art. no. 116813.

[21] P. Barraza, A. Pérez, and E. Rodríguez, "Brain-to-brain coupling in the gamma-band as a marker of shared intentionality," *Frontiers Hum. Neurosci.*, vol. 14, p. 295, Jul. 2020, doi: 10.3389/fnhum.2020.00295.

[22] C. Chuang and H. Hsu, "Pseudo-mutual gazing enhances interbrain synchrony during remote joint attention tasking," *Brain Behav.*, vol. 13, no. 10, Oct. 2023, Art. no. e3181, doi: 10.1002/brb3.3181.

[23] C. Richard et al., "Elevated inter-brain coherence between subjects with concordant stances during discussion of social issues," *Frontiers Hum. Neurosci.*, vol. 15, May 2021, Art. no. 611886, doi: 10.3389/fnhum.2021.611886.

[24] S. Dikker et al., "Crowdsourcing neuroscience: Inter-brain coupling during face-to-face interactions outside the laboratory," *NeuroImage*, vol. 227, Feb. 2021, Art. no. 117436, doi: 10.1016/j.neuroimage.2020.117436.

[25] J. Jahng, J. D. Kralik, D.-U. Hwang, and J. Jeong, "Neural dynamics of two players when using nonverbal cues to gauge intentions to cooperate during the Prisoner's dilemma game," *NeuroImage*, vol. 157, pp. 263–274, Aug. 2017, doi: 10.1016/j.neuroimage.2017.06.024.

[26] Y. Hu, Y. Pan, X. Shi, Q. Cai, X. Li, and X. Cheng, "Inter-brain synchrony and cooperation context in interactive decision making," *Biol. Psychol.*, vol. 133, pp. 54–62, Mar. 2018, doi: 10.1016/j.biopsycho.2017.12.005.

[27] K. Lu, H. Xue, T. Nozawa, and N. Hao, "Cooperation makes a group be more creative," *Cerebral Cortex*, vol. 29, no. 8, pp. 3457–3470, Jul. 2019, doi: 10.1093/cercor/bhy215.

[28] S. Dodel, E. Tognoli, and J. A. S. Kelso, "Degeneracy and complexity in neuro-behavioral correlates of team coordination," *Frontiers Hum. Neurosci.*, vol. 14, p. 328, Sep. 2020, doi: 10.3389/fnhum.2020.00328.

[29] M. Shiraishi and S. Shimada, "Inter-brain synchronization during a cooperative task reflects the sense of joint agency," *Neuropsychologia*, vol. 154, Apr. 2021, Art. no. 107770, doi: 10.1016/j.neuropsychologia.2021.107770.

[30] Y. Pan, X. Cheng, Z. Zhang, X. Li, and Y. Hu, "Cooperation in lovers: An fNIRS-based hyperscanning study," *Hum. Brain Mapping*, vol. 38, no. 2, pp. 831–841, Feb. 2017, doi: 10.1002/hbm.23421.

[31] M. Balconi, L. Gatti, and M. E. Vanutelli, "When cooperation goes wrong: Brain and behavioural correlates of ineffective joint strategies in dyads," *Int. J. Neurosci.*, vol. 128, no. 2, pp. 155–166, Feb. 2018, doi: 10.1080/00207454.2017.1379519.

[32] Q. Zhang, Z. Liu, H. Qian, Y. Hu, and X. Gao, "Interpersonal competition in elderly couples: A functional near-infrared spectroscopy hyperscanning study," *Brain Sci.*, vol. 13, no. 4, p. 600, Mar. 2023, doi: 10.3390/brainsci13040600.

[33] T. Liu, G. Saito, C. Lin, and H. Saito, "Inter-brain network underlying turn-based cooperation and competition: A hyperscanning study using near-infrared spectroscopy," *Sci. Rep.*, vol. 7, no. 1, p. 8684, Aug. 2017, doi: 10.1038/s41598-017-09226-w.

[34] H. Liu, C. Zhao, F. Wang, and D. Zhang, "Inter-brain amplitude correlation differentiates cooperation from competition in a motion-sensing sports game," *Social Cognit. Affect. Neurosci.*, vol. 16, no. 6, pp. 552–564, May 2021, doi: 10.1093/scan/nsab031.

[35] W. Y.-P. Lau et al., "Psychometric properties of the Chinese version of the autism spectrum quotient (AQ)," *Res. Develop. Disabilities*, vol. 34, no. 1, pp. 294–305, Jan. 2013, doi: 10.1016/j.ridd.2012.08.005.

[36] M. Iwata. *Makoto's Preprocessing Pipeline*. Swart Center Computational Neuroscioence. Accessed: Apr. 2023. [Online]. Available: https://sccn.ucsd.edu/wiki/Makoto's_preprocessing_pipeline

[37] C.-Y. Chang, S.-H. Hsu, L. Pion-Tonachini, and T.-P. Jung, "Evaluation of artifact subspace reconstruction for automatic artifact components removal in multi-channel EEG recordings," *IEEE Trans. Biomed. Eng.*, vol. 67, no. 4, pp. 1114–1121, Apr. 2020, doi: 10.1109/TBME.2019.2930186.

[38] Z. Zakeri, S. Assecondi, A. P. Bagshaw, and T. N. Arvanitis, "Influence of signal preprocessing on ICA-based EEG decomposition," in *XIII Mediterranean Conference on Medical and Biological Engineering and Computing 2013: MEDICON 2013, 25–28 September 2013, Seville, Spain*. Springer, 2014, pp. 734–737.

[39] J. A. Palmer, K. Kreutz-Delgado, and S. Makeig, "AMICA: An adaptive mixture of independent component analyzers with shared components," Swartz Center Comput. Neurosci., Univ. California San Diego, San Diego, CA, USA, Tech. Rep., 2012.

[40] C. Stergiadis, V.-D. Kostaridou, and M. A. Klados, "Which BSS method separates better the EEG signals? A comparison of five different algorithms," *Biomed. Signal Process. Control*, vol. 72, Feb. 2022, Art. no. 103292.

[41] A. Delorme, "EEG is better left alone," *Sci. Rep.*, vol. 13, no. 1, p. 2372, Feb. 2023, doi: 10.1038/s41598-023-27528-0.

[42] C. J. Stam, G. Nolte, and A. Daffertshofer, "Phase lag index: Assessment of functional connectivity from multi channel EEG and MEG with diminished bias from common sources," *Hum. Brain Mapping*, vol. 28, no. 11, pp. 1178–1193, Nov. 2007, doi: 10.1002/hbm.20346.

[43] Y. Wang, H. Cheung, L. T. S. Yee, and C.-Y. Tse, "Feedback-related negativity (FRN) and theta oscillations: Different feedback signals for non-conform and conform decisions," *Biol. Psychol.*, vol. 153, May 2020, Art. no. 107880, doi: 10.1016/j.biopsycho.2020.107880.

[44] J. Polich, "Updating p300: An integrative theory of P3a and P3b," *Clin. Neurophysiol.*, vol. 118, no. 10, pp. 2128–2148, Oct. 2007, doi: 10.1016/j.clinph.2007.04.019.

[45] D. Zhang, Y. Lin, Y. Jing, C. Feng, and R. Gu, "The dynamics of belief updating in human cooperation: Findings from inter-brain ERP hyperscanning," *NeuroImage*, vol. 198, pp. 1–12, Sep. 2019, doi: 10.1016/j.neuroimage.2019.05.029.

[46] F. Torrecillos, J. Alayrangues, B. E. Kilavik, and N. Malfait, "Distinct modulations in sensorimotor postmovement and foreperiod β-band activities related to error salience processing and sensorimotor adaptation," *J. Neurosci.*, vol. 35, no. 37, pp. 12753–12765, Sep. 2015, doi: 10.1523/JNEUROSCI.1090-15.2015.

[47] H. Tan et al., "Human subthalamic nucleus in movement error detection and its evaluation during visuomotor adaptation," *J. Neurosci.*, vol. 34, no. 50, pp. 16744–16754, Dec. 2014, doi: 10.1523/JNEUROSCI.3414-14.2014.

[48] H. Tan, N. Jenkinson, and P. Brown, "Dynamic neural correlates of motor error monitoring and adaptation during trial-to-trial learning," *J. Neurosci.*, vol. 34, no. 16, pp. 5678–5688, Apr. 2014, doi: 10.1523/JNEUROSCI.4739-13.2014.

[49] J. Alayrangues, F. Torrecillos, A. Jahani, and N. Malfait, "Error-related modulations of the sensorimotor post-movement and foreperiod beta-band activities arise from distinct neural substrates and do not reflect efferent signal processing," *NeuroImage*, vol. 184, pp. 10–24, Jan. 2019, doi: 10.1016/j.neuroimage.2018.09.013.

[50] J. Barone and H. E. Rossiter, "Understanding the role of sensorimotor beta oscillations," *Frontiers Syst. Neurosci.*, vol. 15, May 2021, Art. no. 655886, doi: 10.3389/fnsys.2021.655886.

[51] S. Karakaş, "A review of theta oscillation and its functional correlates," *Int. J. Psychophysiol.*, vol. 157, pp. 82–99, Nov. 2020, doi: 10.1016/j.ijpsycho.2020.04.008.

[52] J. Park, J. Shin, J. Lee, and J. Jeong, "Inter-brain synchrony pattern investigation on triadic board game play-based social interaction: An fNIRS study," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 31, pp. 2923–2932, 2023, doi: 10.1109/TNSRE.2023.3292844.

[53] J. Park, J. Shin, and J. Jeong, "Inter-brain synchrony levels according to task execution modes and difficulty levels: An fNIRS/GSR study," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 30, pp. 194–204, 2022, doi: 10.1109/TNSRE.2022.3144168.