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The Underlying neural mechanisms of interpersonal situations on collaborative ability: A hyperscanning study using functional near-infrared spectroscopy

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ABSTRACT

The collaborative ability to coordinate an individual with others is critical to performance of joint actions. Prior studies found that different types of interpersonal situations have more or less impact on the collaborative ability of joint actions, but the results are controversial. To clarify the influence of interpersonal situations on collaborative ability, we adopted the joint Simon task, a choice-reaction task that two people perform together. Functional near-infrared spectroscopy (fNIRS) was used to study the neural mechanisms of interpersonal situations on collaborative ability and task performance under payoffs that fostered competition or cooperation. The fNIRS results showed that significant inter-brain neural synchronization (INS) occurred in the bilateral inferior parietal lobule (IPL) for both situations. Moreover, for the competition situation, the pairs also shown a significant INS in the right IPL. These results imply that the bilateral IPL is involved in cooperation and competition due to involvement of common concern and understanding of intention. The right IPL may be more crucial for competition because of the psychological resources involved in distinguishing self and others. Eventually, the INS in competition was better than in the other situations, correlating with higher performance of the joint task as well.

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KEYWORDS
Joint Simon effect; joint action; interpersonal situation; collaborative ability; fNIRS

1. Introduction

In daily life, people often spend much of their time interacting and communicating with others. Understanding this kind of joint action requires a combination of cognitive science and social science that focuses not only on individual information processing but also on the influence of social factors (Hommel et al., 2009; Ruissen & de Bruijn, 2016). Collaboration depends on the ability to coordinate the behavior of oneself and others in an integrated manner. With strong collaborative ability, each actor can provide reliable information to others iteratively and complement others' predictions when necessary. In contrast, with weak collaborative ability individuals pay most attention to themselves and have difficulty integrating the self with others effectively (Shen et al., 2005).

Interpersonal interaction refers to an individual's simultaneous or sequential actions that will influence the immediate and future performance of the others involved in a situation (Johnson & Johnson, 2005). The influence of interpersonal situations on individuals' behavior and brain activity has been a core issue in social cognition. Prior studies over the past few decades have improved our understanding of the connection between perception and action, that is, how individuals choose task-related information, predict upcoming behavior (Hommel et al., 2001), and integrate predictions of their own and others' behaviors (Wilson & Knoblich, 2005).

However, these studies mostly examined the performance of individuals' cognitive or behavioral tasks independently (Montague et al., 2002; Saito et al., 2010; Tanya & Shulan, 2015), and rarely considered the influence of interpersonal situations and other factors on cognitive processes and performance in a naturalistic environment. Few have investigated the simultaneous neural activity of the brains of two interacting persons, which is needed to provide evidence of the neural mechanisms underlying interpersonal interactions on collaborative ability (Hari & Kujala, 2009).

The interpersonal situation on collaborative ability of joint actions is wherein two or more individuals coordinate their actions in space and time to bring about a change in the environment (Knoblich & Sebanz, 2006). Researchers suggested that interpersonal situations play essential roles in coordinating joint tasks with others and in promoting performance of joint actions (Frith & Wolpert, 2003; Hasson et al., 2012; Tomasello et al., 2005). For instance, cooperation and competition are

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two basic interpersonal situations that would influence the inter-brain correlations on the right inferior frontal gyrus and the performance of joint actions. Liu et al. (2015) found that competitor pairs of persons showed a positive correlation with performance but cooperator pairs did not.

According to the theory of social interdependence, the structure of people's goals in a situation determines the mode of interaction between participants, and the interaction mode determines the outcome of the situation (Johnson & Johnson, 2005). Therefore, cooperation and competition situations may have different effects on collaborative ability and the performance of joint tasks. The joint Simon task has been used to measure the collaborative ability of the joint action and to investigate the underlying mechanisms of how an individual co-represents another's actions and is affected by the other's presence. In a joint Simon task, one participant responds with a keypress to a stimulus of one color, and the other participant responds similarly to a stimulus of another color. The stimuli can appear in a left or right location, which is task-irrelevant. The joint Simon effect (JSE) refers to the finding that each participant responds faster when the stimulus location corresponds spatially to his or her response key compared to when it does not correspond (Sebanz et al., 2003).

JSE is often used to reflect not only collaborative ability but also the extent of integration and discrimination of self and others. The more difficult it is to discriminate self and others, the larger the JSE will be and the larger the collaborative ability will be as well (Weide et al., 2016). The discovery of the JSE shows that a person acting together with another adopts a frame of reference, or task set, that includes the other. According to referential coding theory (Dolk et al., 2014), individuals perceive the similarity between their task actions and those of the co-actor (press left/right button). This may involve the two people sharing a complementary task set that includes a cognitive representation of their own behavior and also simultaneously the behavior of the co-actor (Sebanz et al., 2003). Alternatively, the JSE may reflect more general, nonsocial referential coding processes (Dolk et al., 2013; Klempova & Liepelt, 2016; Xiong & Proctor, 2015). For example, the theory of event coding (TEC; Hommel et al., 2001) also assumes that the behavior representation cognitively consists of all the coding networks of the characteristics of perceived effects, such as perceived position, direction, and speed of action.

The spatial dimension is used as a reference to discriminate between the two representations of actions, like in the standard Simon task in which a single person makes both the left and right responses. The referential coding theory considers that the similarity between perception and the to-be-executed action affects the size of the JSE (Dolk et al., 2011, 2013). This effect of similarity is a consequence of the following: The more similar the actions of two given event representations, the more difficult it is to distinguish characterizations of the events. This difficulty leads to a greater propensity to attend to the obvious and simple event features (such as spatial location) to help distinguish the events, which can lead to a large JSE, and eventually to a large collaborative ability or self-others integration. In summary, the JSE originates from taking the spatial dimension as the reference to reflect the extent to which individuals can integrate the action representation of the co-actor into their own cognitive representation in the joint task.

Prior studies have explored the influence of different types of interpersonal situations (cooperation vs. competition) on joint tasks (Hommel et al., 2009; Ruissen & de Bruijn, 2016). Depending on the interaction model (cooperation or competition), individuals can promote or hinder the achievement of others' goals. Some researchers found that the JSE increased in the cooperative situation but decreased in the competitive situation (Iani et al., 2011). Similarly, co-acting with a participant who is hostile will affect the formation of the joint representation, resulting in disappearance of the JSE. Inversely, a friendly co-actor with cooperative attitude can increase the JSE (Hommel et al., 2009; Ruissen & de Bruijn, 2016). At the behavioral level, interpersonal situations, such as cooperation and competition do have different effects on self-others integration or collaborative ability. However, how this kind of influence takes place is still controversial, and the cortical areas involved are largely unknown (Liu et al., 2017). Therefore, the first purpose of the present study was to further examine how interpersonal situations influence the collaborative ability in a joint task, as indicated by task performance and neural activity.

This examination was accomplished by using functional near-infrared spectroscopy (fNIRS) and hyperscanning techniques to study the neural mechanisms of interpersonal situations on collaborative ability and task performance. The relationship between task performance and inter-brain neural coherence can be assessed by using the techniques to record from both participants simultaneously (Reindl et al., 2019). Cui et al. (2012) used near-infrared spectroscopy to measure the activation of the prefrontal lobes of paired participants in a simultaneous key-press task during cooperation and competition situations. Participants experienced an increase of synchronization in the right superior frontal cortex in the cooperative context but not in the competitive context.

Thus, Cui et al. concluded that inter-brain coherence may be a proxy for performance of cooperative tasks.

Various studies have indicated that spontaneous brain activity plays a crucial role in the coordination of neuronal processing within the brain, and synchronization of the paired participants occurs during the task (Saito et al., 2010). For instance, Yun et al. (2012) explored the brain activity of two subjects simultaneously through the training task on cooperation by using two sets of EEGs, and found a synchronous increase (i.e., body movement synchronization) on participants' frontal parietal activations. Using (functional) near-infrared spectroscopy, researchers have also found that activation in the right inferior frontal gyrus (Liu et al., 2015), the prefrontal lobes (Cui et al., 2012), the right orbitofrontal cortex, the medial prefrontal cortex and the right inferior parietal lobule (Decety et al., 2004) changed in cooperation and competition situations. These results suggest that the frontal parietal network may be the neurophysiological basis for the inter-brain synchronization during interaction. However, the inter-brain neural synchronization (INS) in interpersonal situations of joint actions is largely unknown. Therefore, it is informative to explore to the neural substrates in Interpersonal Situations on the collaborative ability of joint actions (Reindl et al., 2019).

Successful interpersonal interaction also requires an understanding of the intentions, emotions, and behaviors of others in interpersonal interactions (Bernhardt & Singer, 2012; Decety et al., 2004; Hari & Kujala, 2009; Liu et al., 2015). Theory-of-mind (ToM) is thought by some to be the ability to understand the intentions of others (Brunet et al., 2000). In other words, ToM is a skill at reading other people's thoughts through inferential cognitive processing based on schemata in memory, and the responsible brain system is mainly composed of medial prefrontal cortex, temporal pole, and posterior superior temporal sulcus (pSTS) (Behrens et al., 2009, 2008). Therefore, the brain regions involved in ToM may be activated under cooperation and competition rather than independent situations. Specially, under cooperation and competition, the activation of inter-brain synchronization in the right pSTS increases due to the task requirements of common attention and intention understanding (Liu et al., 2017).

Rather than understanding observed actions by mapping them onto abstract concepts, people process them by mapping them onto their own action knowledge as well. So does the mirror neuron system, which is part of the cortical regions that are activated not only when performing an action but also when observing someone else perform the same or similar action (Iacoboni, 2008). This network mainly includes the inferior frontal gyrus (IFG) and the inferior parietal lobule (IPL), enabling individuals to understand the behaviors and intentions of others through embedded simulation. According to this view, both theory of mind and the mirror neuron system are key to interpersonal interaction (Iacoboni & Dapretto, 2006; Keysers & Gazzola, 2007; Keysers & Mckay, 2011; Simpson & Ferrari, 2013). The above two neural networks and previous neurophysiological studies provide a reference to set the regions of interest (ROIs) and experimental parameters in the present study. Consequently, we focused on ROIs in the bilateral posterior superior temporal sulcus (pSTS), inferior frontal gyrus (IFG), and inferior parietal lobule (IPL).

To summarize, we adopted the joint Simon task to investigate the collaborative ability of integrating self and others, which can provide a sufficient neurophysiological basis for our understanding of self-others integration and discrimination and the underlying mechanisms of interpersonal situations on collaborative ability by using hyperscanning functional near-infrared spectroscopy. This method is different from most previous studies on joint actions in which participants knew whether the next step requires their own reaction. In the present study, participants had no forewarning of whether they should make a response because of the randomized reaction sequence, which is like that of many real-life circumstances and, in that sense, of high ecological validity. As a collaborative joint task, it was expected that shared representations of other people's tasks would occur in the presence of others in the joint Simon task, even if coordination between the two were not required. Therefore, it was hypothesized that participants would respond faster when the go signal was in the spatially compatible location (go/compatible) rather than in the incompatible location (go/incompatible) and that the activation and the INS of the right pSTS, bilateral IFG and IPL would also be different under conditions in which the participant was to respond or not respond.

Second, it was hypothesized that increased activation of the right pSTS, bilateral IFG and IPL would occur in cooperative situations. When individuals cooperate with others, the integration and collaborative ability between themselves is enhanced, whereas in the context of competition, individuals focus on their own tasks, which will weaken or even cause the disappearance of collaborative ability between them. Third, it was hypothesized that both cooperative and competition situations would show increased INS in the bilateral IPL due to task demands of joint attention and intention understanding, while the right IPL may be more crucial for competition because of the psychological resources involved in distinguishing self and others.

2. Method

2.1 Participants

Seventy-two undergraduate students were recruited (54 females, aged 19.96 ±1.74 years) and paired in same-gender dyads. Pairs of participants were strangers who were allocated randomly and evenly to one of three different interpersonal situations (independence, cooperation, or competition). All participants were right-handed, with normal or corrected vision, no mental illness, and no history of brain injury. The study was approved by the research ethics board at Shaanxi Normal University; all participants signed consent forms and agreed to participate in this study. After the experiment, participants were paid 30 RMB as a reward.

2.2 Materials and design

2.2.1 The inclusion of other in the self (IOS) scale

The IOS Scale is a seven-level isometric scale measuring the degree of intimacy of relationship. Participants were asked to choose the one among seven pictures that best described the relationship between themselves and the co-actor (see Figure 1). The larger the number assigned a particular picture, the closer (more similar) the two people were judged by themselves to be acting together. Previous research has indicated that the IOS has good reliability and validity (Aron et al., 1992; Mendl et al., 2018).

2.2.2 The joint Simon task

The Joint Simon task was compiled with the E-Prime 3.0 software. Similar to the classic Simon task, in the present study, the stimuli were red and green squares (3 * 3 cm) that randomly appeared on the left or right of the screen (see Figure 2). The participant sitting on the left side was instructed to respond only to the red square by pressing the "Z" button with the left-index finger. The participant sitting on the right side was instructed to respond only to the green square by pressing the "3" button with the right-index finger.

In the joint Simon task, a trial is compatible when the stimulus location corresponds with the location on the responding participant's side. The trial is incompatible when the stimulus is on the opposite side from that of the responding participant. Regardless of the stimulus location, each participant was to respond to a non-location stimulus feature, one of the two colors in which the stimulus could occur (go trials) and not responding to the other possible color (no-go trials). This resulted in four experimental conditions: go/compatible, go/incompatible, no-go/compatible, and no-go /incompatible (named GC, GI, NC, and NI, respectively).

2.2.3 Manipulation of three interpersonal situations

Three different interpersonal situations were designed by setting the instructions of different scoring rules. For all responses, 4 points were added for each correct trial and 2 points were subtracted for each incorrect trial. In the independent situation, each participant received a final score earned on her/his own. The rules for cooperative and competitive situations were similar to those of Task 3 in the study of Mendl et al. (2018). In the cooperation situation, the final score was the average of the sum of the two participants' scores (half of the total). In the competition situation, an incorrect response was punished with a loss of 2 points, which would be credited to the other participant. Whoever earned the most points received the total sum of points earned by both participants, and there was no reward for the lower scores.

Except for the scoring rules, the experimental tasks and procedures of the three interpersonal situations were the same. The independent situation was taken

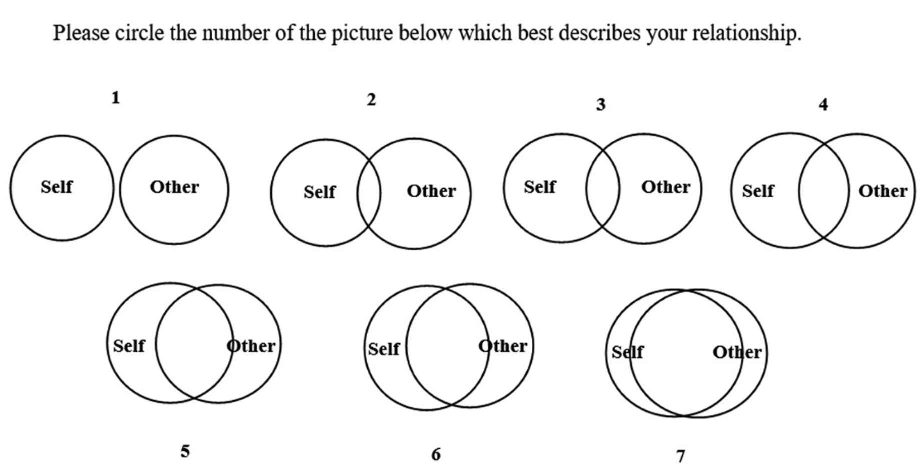

Figure 1. The inclusion of other in the self scale.

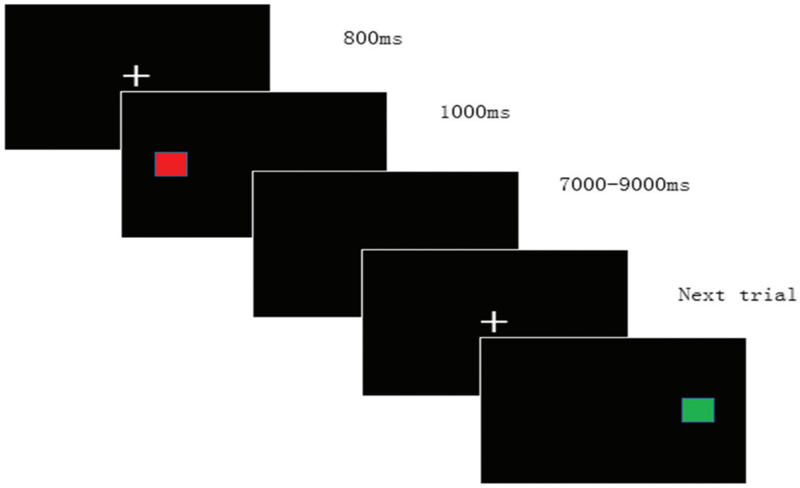

Figure 2. Experimental procedure for one trial. First, the central fixation was presented for 800 ms. Then a red or green stimulus randomly appeared on the left or right side of the screen, and the stimulus disappeared immediately when a button was pressed or automatically if the stimulus had been displayed for 1000 ms. Lastly, entering 7–9 s random blank black screen, and proceed to the next trial.

as the control condition. The experiment was to investigate the differences of integration of self and others and differences of brain activation in the joint actions under different interpersonal situations.

2.2.4 Four experimental conditions

In the joint Simon task, regardless of the stimulus location, participants were told to respond to the stimulus of one color (go) and inhibit responding to the other color stimulus(no-go), which resulted in the four experimental conditions mentioned before: GC, GI, NC, and NI.

The whole experiment had three identical runs, with each run containing 48 trials, of which there were 12 trials for each experimental condition (i.e., GC). The order of red and green stimuli was random in each run. The formal experiment contained 144 trials.

The experiment adopted a slow event-related design (Slow ER Design). Because the stimulus presentation changes the proportion of blood oxygen concentration in the brain, it takes several seconds for the blood oxygen concentration to be restored to the baseline level. Therefore, an empty screen of 7–9 s was randomly presented between each trial to allow return to baseline.

2.3 Experimental procedure

The experiment was performed in a quiet room. Participants sat side by side in front of a computer monitor, with their heads about 60-cm away from the monitor. Participants were fitted with near-infrared acquisition headgear. After signal debugging, they were ready to start the experiment. Participant pairs received training at the task before the formal experiment, until they sufficiently understood the task and played without errors. The behavioral and NIRS data were recorded throughout the formal experiment.

After entering formal experiment, first, a black screen was displayed for 20 s before the start of the experiment to connect the near-infrared equipment. Then, the participants were presented with a written instruction on the screen: "Welcome to the experiment! When the experiment begins, a "+" fixation point will appear in the center of the screen. For the student sitting on the left side, you are to respond only to the red square by pressing the "Z" button with your left-index finger. For the student sitting on the right side, you are to respond only to the green square by pressing the "3" button with your right-index finger. After you understand the above instructions, press "Q" to turn to the next page. "

Second, the participants were presented the instructions for one of the three interpersonal situations' scoring rules. Participants were required to press the "Q" to start the experiment after they understood the rule.

As the formal experiment started, a fixation point appeared in the center of the screen for 800 ms. Then, a red or green stimulus randomly appeared to the left or right of the central fixation point. The participants were to respond within 1000 ms; otherwise, the stimulus would disappear. After the response was recorded or the stimulus disappeared automatically, a black blank screen was displayed for a 7–9 s random period. Then, the next trial started: a fixation point appeared again in the center of the screen for 800 ms, and a red or green stimulus randomly appeared (see Figure 2), to which a response was made. After 48 trials (including 24 red stimuli and 24 green stimuli) finished, a run ended.

Then, the participant pair completed runs 2 and 3. In addition, a resting session was assigned between each run of approximately 120 s. After completing the three runs, the near-infrared acquisition headgears of participants were taken off, and the participants completed the IOS.

2.4 fNIRS data acquisition

A 96-channel NIRS system (ETG-7100, Hitachi Medical Co., LTD., Japan) was used to simultaneously record the two cortical hemisphere's hemodynamic activities, including concentration changes of oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total hemoglobin. The absorption of near-infrared light (wavelengths: 695 and 830 nm) was measured at a sampling rate of 10 Hz. Two 4 × 4 optode probes set (eight emitters and eight detectors, 3 cm optode separation) were bilaterally placed on the fronto-tempo-parietal regions for each participant, forming 24 channels for each hemisphere. The middle channels in the lowest line (Ch2 and 26) were located, respectively, at the T3 and T4 positions according to the international 10–20 system. Specifically, positions of all the NIRS channels were measured by a 3D electromagnetic tracking device. Finally, the estimated mean locations of the NIRS channels were obtained using anatomical information based on Brodmann's areas.

As regions of interest, we mainly focused on the channels approximately covering the bilateral inferior frontal gyrus (IFG: left: Ch7, Ch14; right: Ch28, Ch35), posterior superior temporal sulcus (pSTS: left: Ch5, Ch6, Ch9; right: Ch29, Ch30, Ch33) and inferior parietal lobule (IPL: left: Ch11, Ch12, Ch15, Ch18, Ch19, Ch22; right: Ch37, Ch38, Ch41, Ch44, Ch45, Ch48). Figure 3 illustrates positions of the NIRS channels for one participant.

2.5 Data analysis

Matlab 2013b toolbox and Excel 2010 were used to preprocess the fNIRS data. To avoid influences from the error performance, fNIRS data obtained from trials that contained errors were excluded. The significance level was set at $p < 0.05$. All statistical analyses of behavioral data and the processed fNIRS data were carried out using SPSS 20.0.

2.5.1 behavioral data statistical analysis

For the behavioral data statistical analysis, mean reaction time (*RT*) for correct responses and percentage correct (PC) were computed for each participant; incorrect responses were all errors of commission. Trials with *RT* beyond ±2.5 *SDs* were excluded from the subsequent analysis (2.1% of trials). Then, we analyzed the mean *RT* and PC by a 2 (compatibility: compatible, incompatible) × 3 (Interpersonal Situations: independence vs. cooperation vs. competition) analysis of variance (ANOVA). Interpersonal situations and compatibility were between- and within-subject factors, respectively, on go trials.

2.5.2 fNIRS data statistical analysis

For the fNIRS data, only the HbO was analyzed since oxygenated hemoglobin is the most sensitive parameter of regional cerebral blood flow and provides a robust correlation with the BOLD signal of fMRI (Cui et al., 2012;). A function of data-filt was used to reduce the noise of the fNIRS data in Matlab. The individuals' fNIRS data were analyzed independently for each ROI. First, baseline correction was applied using the average of the 2-s black-screen period before each run-set to remove any longitudinal signal drift. After baseline correction, all fNIRS data were converted to *z*-scores relative to the preceding 2-s baseline. The NIRS data were further averaged across 12 trails of each type of condition (GC, GI, NC, and NI) separately for each run. This average value of NIRS data is the activation value of each run. The final data used to access intra-brain activation were the averaged values of the activation values of 3 runs. For more thorough explanations of data preprocessing as well as illustrative examples, please see Liu et al. (2015) and Oi et al. (2013).

Finally, we analyzed intra-brain activation and inter-brain neural synchronization (INS) with the processed fNIRS data. Three steps were included when we accessed INS to analyze the inter-brain correlation by ANOVA. First, we independently analyzed the relationship between the two fNIRS time series (preprocessed fNIRS time series and the processed fNIRS time series) of each participant pair over 48 trials during the joint task. For analyzing pairs of participants in one run, the *z*-scores were averaged every 10 s, forming 144 points. Then, they were further averaged across three runs of each type of situation (independent, cooperation, and competition) separately. Pearson product-moment correlation analysis was conducted between the two participants in each dyad, and the ROI channels in each experimental condition.

Second, to reduce the effect of physiological artifacts, such as breathing and cardiac activity on INS, we

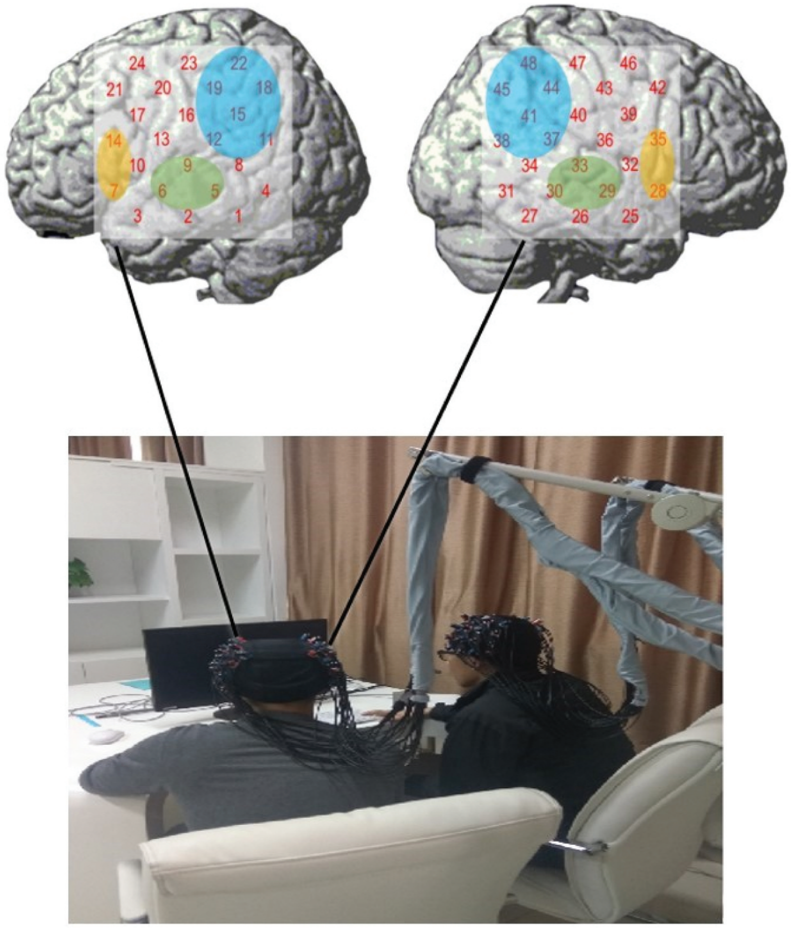

Figure 3. Positions of the NIRS channels. The channel setting of ROI placed on one participant's left and right hemispheres. The green, yellow, and blue overlays cover the bilateral pSTS, IFG and IPL, respectively. pSTS: posterior superior temporal sulcus; IFG: inferior frontal gyrus; IPL: inferior parietal lobule.

performed a phase-scrambling permutation test, and mainly focused on the channels that showed a higher INS value than the scrambled time series. Preprocessed fNIRS time series of each pair were randomly phase scrambled, and relations between the two scrambled time series were analyzed using the same Pearson correlation analysis, forming a series of pseudo data. Then, differences between the correlation coefficients of preprocessed fNIRS data and the scrambled fNIRS time series were assessed by *t*-test with Bootstrap (1000 times) for each ROI channel. Significantly higher ordered time series INS values than the scrambled series was an indicator of the cortical areas showing task-related synchronization.

Thirdly, we analyzed INS of the three situations by using the repeated-measures ANOVA, focusing on ROI channels of INS that showed a significant difference between preprocessed NIRS data and pseudo data. The situation-averaged INS for each experimental condition (i.e., GC) in each ROI was also analyzed by ANOVA.

3. Results

3.1 Behavioral performance

To assess the validity of the interpersonal situation manipulation, a one-way ANOVA with Interpersonal Situations (i.e., independence, cooperation, or competition dyads) was performed on the mean value of the IOS scale in the preliminary test. The results showed a significant effect of Situations, $F\,(2,71) = 5.47$, $p = .006$, $\eta_p^2 = .14$, with the ratings being lower for the competitive situation (M = 3.33, SD = 1.03) than the cooperative situation (M = 4.42, SD = 1.15), and mid-way for the independent situation (M = 3.92, SD = 1.15). Further, post-hoc tests (LSD) showed the mean value of the cooperation condition was significantly larger than that of the competition condition (p = 0.002), and the difference of the mean values between the independent condition and the competitive condition was marginally significant (p = 0.08). There was no significant difference in the mean value between the independent group and the cooperative group (p = 0.132) (see Figure 4). The results indicate that compared with completing a competitive task, after completing a collaborative task, the relationship between partners became closer regardless of whether the collaborative task explicitly required cooperation between partners.

Results of RT showed a significant main effect of compatibility, F (1,69) = 87.5, $p < .001$, $\eta_p^2 = .56$: compatible responses (M = 338 ms) were significantly faster than incompatible responses (M = 352 ms), indicating a JSE. The size of JSE is equal to the mean RT of incompatible trials minus the mean RT of compatible trials in each interpersonal situation (see Table 1). The incompatible RT was significantly larger than the compatible RT in each of three interpersonal situations. The main effect of Situation was not significant, F (2,69) = 2.44, p = .095, $\eta_p^2 = .07$, but the interaction of Situation and compatibility was significant, F (2,69) = 4.15, p = .02, $\eta_p^2 = .11$. Simple effect analysis further revealed that the JSE for the independent situation (15 ms) and the cooperative situation (18 ms) did not differ significantly, F (2,69) = .69, p = .523, but each was significantly larger than the JSE for the competitive situation (8 ms), Fs (2,69) = 5.32 and 8.57, ps = .038 and .008, respectively (see Table 1 & Figure 5).

The same analysis was conducted on PC, for which the results showed that neither the main effect of compatibility nor that of Situation was significant, Fs (1,69) = 1.01 and 2.29, ps = .318 and .109, η_p^2s = .02 and .07. The interaction between compatibility and Situation was close to the .05 criterion, F (2,69) = 2.87, p = .064, η_p^2 = .08. Simple effect tests demonstrated a significant JSE in the competitive situation, F (1,69) = 6.19, p = .015,η_p^2 = .08, but not in the independent and cooperation situations, ps. > .05.

Table 1. Mean reaction time and percentage correct as a function of compatibility and interpersonal situation, and joint simon effect ($M\pm SD$).

interpersonal situation		Compatible	Incompatible	JSE
Cooperation	RT (ms)	346 ± 35	364 ± 37	18***
	PC (%)	99.87 ± .59	99.74 ± .82	
Competition	RT (ms)	328 ± 30	336 ± 33	8**
	PC (%)	99.88 ± .5	98.73 ± 2.2	
Independent	RT (ms)	341 ± 46	356 ± 43	15***
	PC (%)	98.50 ± 3.6	98.84 ± 2.0	

Note:*$p < .05$, **$p < .01$, ***$p < .001$

3.2 fNIRS results

3.2.1 Intra-brain activation

To investigate the differences of brain activation in the three situations, we took situation as a between-subject variable and conducted a three-way repeated measure ANOVA analysis, 2 (Compatibility: compatible vs. incompatible) × 2 (Respond: go vs. no-go) × 3 (Situation: independence vs. cooperation vs. competition) in the ROI channels (i.e., bilateral IFG, pSTS and the IPL), independently.

Results indicated significant main effects of compatibility in the left IFG (Ch7), the bilateral IPL (Ch12, Ch37, and Ch48) and the right pSTS (Ch30). Further, a simple main effect test revealed significantly higher intra-brain activation in the left IFG, the bilateral IPL and the right pSTS for the incompatible than compatible condition. A main effect of respond demonstrated higher activation in the bilateral IPL (Ch11, Ch18, Ch22, Ch38, and Ch48) during go trials than no-go trials, reflecting that the go response required more cerebral blood flow. Importantly, a main effect of situation demonstrated significant higher activation in the right IPL (Ch38) for the competitive situation than for the cooperative situation (p = .045) and independent situation (p = .01), but no significant

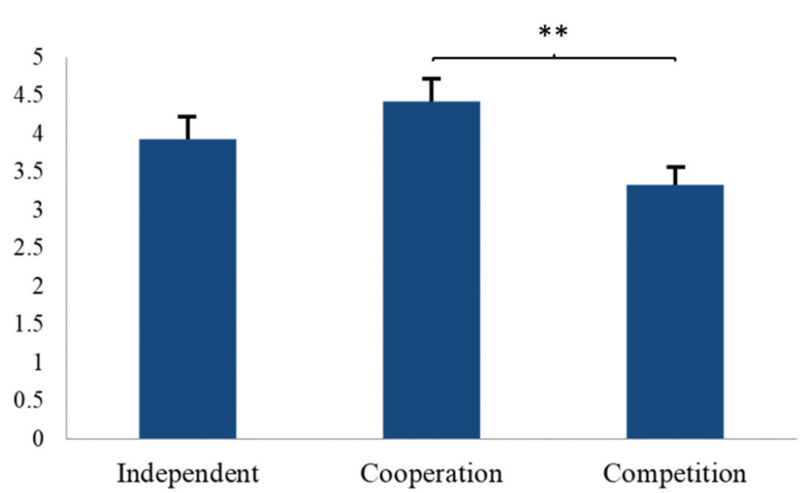

Figure 4. Mean value of the IOS score in three interpersonal situation groups (independent, cooperation and competition). Error bars indicate standard errors of the mean. **$p < .01$.

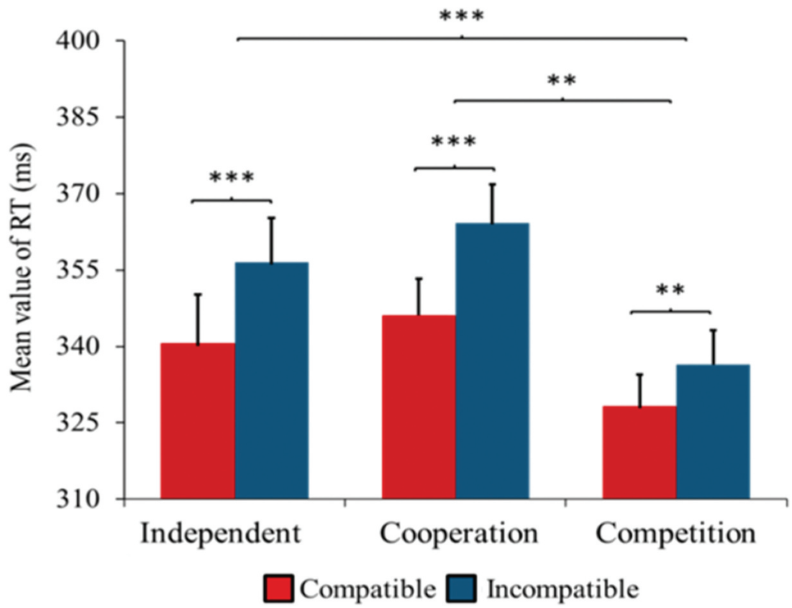

Figure 5. Mean value of response time (*RT*) under compatible and incompatible conditions in three interpersonal situation groups (independent, cooperation and competition). Error bar represents standard error. $^{**}p < .01$, $^{***}p < .001$.

difference between the latter two situations (p = .537). Also, the left IPL (Ch11) showed a significant three-way interaction effect. Simple effect analysis showed higher go response activation increase during the incompatible condition than the no-go response only in independent situation (p = .037), with the other situations not showing any significant difference, *ps.* > .05. All the intra-brain activation survived after FDR (False discovery rate) correction ($p < .05$) (see Table 2).

3.2.2 Inter-brain neural synchronization

The INS of the three situations was analyzed by using the repeated-measures ANOVA, 2 (Compatibility: compatible vs. incompatible) × 2 (Respond: go vs. no-go) × 3 (Situation: independence vs. cooperation vs. competition) in the ROI channels independently. The result showed a significant main effect of Situation only in the right IPL (Ch48), F (2,69) = 4.305, p = .022, η_p^2 = .207 (see Figure 6A, Figure 6B). A sample of the time course of the inter-brain correlations of pairs under the Ch48 in three interpersonal situations was also shown (see Figure 6A). Further, post-hoc tests indicated that the competitive situation showed significantly higher INS than the independent situation (p = .007) and numerically higher INS than the cooperative situation (p = .065). This result is consistent with the fact that the competitive situation showed the shortest RT, suggesting that the right IPL may be more critical for the competition situation (see Figure 6C), whereas greater INS in competition situation leads to the higher task performance (the RT was shorter than the other situations).

The result also showed a significant three-way interaction effect only in the left IPL (Ch11) (p = .046) (see Figure 7A), simple effect analysis demonstrated significantly higher INS during competitive situation under the go/compatible condition than independent situation (p

Table 2. Result of significant effect in the analysis of three-way repeated measure ANOVA analysis.

	ROI	Channel	F	p	η_p^2
Compatibility $_{(1,69)}$	L-IFG	7	4.764	.03	.024
	L-IPL	12	8.985	.003	.04
	R-IPL	37	10.535	.001	.047
		48	4.673	.032	.023
	R-pSTS	30	4.262	.04	.02
Respond $_{(1,69)}$	L-IPL	11	5.771	.017	.026
		18	13.098	< .001	.062
		22	6.304	.013	.029
	R-IPL	38	9.245	.003	.046
		48	6.763	.01	.031
Group $_{(2,69)}$	R-IPL	38	3.739	.025	.036
Group × Respond × Compatibility $_{(2,69)}$	L-IPL	11	5.706	.004	.054

Note: IFG, inferior frontal gyrus; IPL, inferior parietal lobule; pSTS, posterior superior temporal sulcus. All p-values survived after FDR correction, data above are the raw.

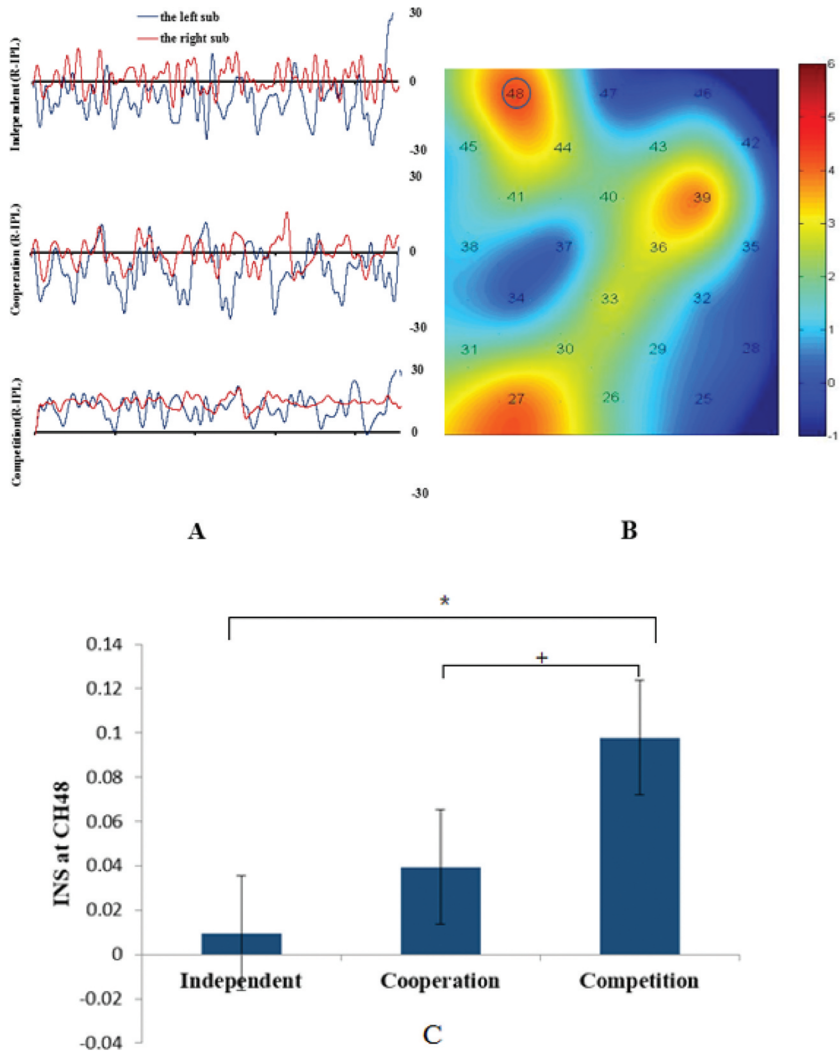

Figure 6. Comparison of three interpersonal situations (independent, cooperation and the competition). A) The graphs show the time course of the inter-brain correlations under the Ch48, from three pairs of samples in three interpersonal situations. All three samples of subjects' NIRS data were *z*-score of HbO after preprocessed. B) The ANOVA heat map of inter-brain neural synchronization (INS) values. The color bars show the *F*-values. The right IPL (Ch48) shows the significant main effect result of Group ($p < .05$). C) The amplitude of INS at CH48 under three different interpersonal situations. Note that a significant main effect of Group in the right IPL (Ch48). And the competition group showed significantly higher INS than the independent group (*, $p = .007$), at the same time, the competition group showed marginal significantly higher INS than the cooperation group (+, $p = .065$).

= .033), and the overall performance of the rest of the two situations was comparable, both *ps.* > .05 (see Figure 7B). However, there was no difference in the INS(Ch11) of the three groups under the no-go condition (see Figure 7C).

Also, the results of Pearson product-moment correlation analysis showed significant relationships between the two NIRS time series of the pairs (i.e., the INS indexed by the intra-brain activation) in each experimental condition.

3.2.3 The INS-behavior relation

A Pearson correlation was conducted to clarify the relationship between brain synchronization and joint action performance in this study. The results showed that INS in the competitive situation was negatively correlated with RT in the left IPL (CH11) ($r = -.61$, $p = .037$, see Figure 8A) and in the right IPL (CH48) ($r = -.57$, $p = .051$, see Figure 8B).

4. General discussion

The present study investigated neural mechanisms, including intra- and inter-brain processing, underlying the joint actions in different Interpersonal Situations, namely, independence, cooperation, and competition. The fNIRS hyper-scanning technique was employed to verify the influence of three different Interpersonal

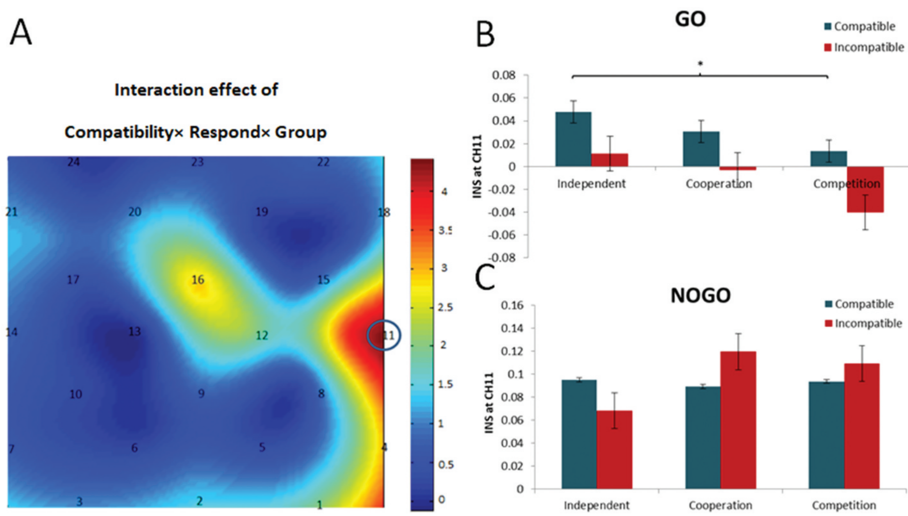

Figure 7. INS in the left inferior parietal lobule (L-IPL). A) The results of the repeated-measures ANOVA of the interaction effect of Compatibility ×Respond ×Group on INS. B) The amplitude of INS in the Left IPL (CH11) in different levels of Group and Compatibility under g condition. The simple effect analysis demonstrated significantly higher INS during competition group under the go/ compatible condition than independent group (p = .033). C) The amplitude of INS at CH11 in different levels of Group and Compatibility under no-go condition. *p < .05.

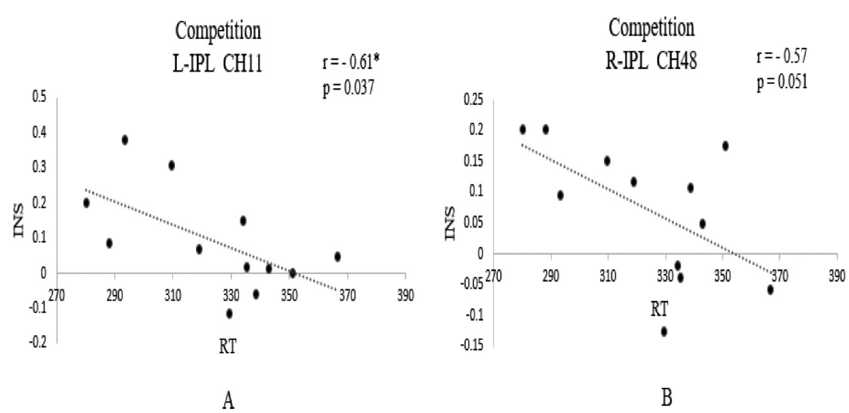

Figure 8. Pearson correlation diagram between brain synchronization and joint action performance. A) The correlation between INS and RT in the left IPL (CH11) in the competition group ($r = -.61$, $p = .037$); B) The correlation between INS and RT in the right IPL (CH48) in the competition group ($r = -.57$, $p = .051$).

Situations on the joint actions via simultaneously recording two brains' fronto-tempo-parietal regions.

When completing a joint task with others, shared representation of actions or goals can promote the performance of the task. Previous studies have found that social factors such as Interpersonal Situations or emotion can affect co-representation. Although recent hyper-scanning studies have started to examine social cognition and performance in naturalistic contexts of social interactions, it is still unknown how the different interpersonal situations influence the co-representation and collaborative performance between each participant in a joint task. Thus, the present study was designed to contribute to the hyper-scanning literature by revealing neural bases of the underlying mechanism of interpersonal situations on co-representation of two individuals in the joint Simon task.

As expected, all interpersonal situations in our experiment showed a significant JSE, and the JSE in the competitive situation was smaller than that in the cooperative and independent situations, but there was no significant difference of the JSE between the cooperative and independent situations. This result verified the theory of social interdependence and was consistent with the research that the JSE is evident in all situations, but lower in a competitive situation than that in the other two (Ruys & Aarts, 2010). That is to say, interpersonal situation determines the way of interaction between individuals, which in turn lead to different outcome in each situation (Johnson & Johnson, 2005).

Past research has found the JSE to be greater in a cooperative situation than in an independent one (Iani et al., 2011). The mean JSE was 3 ms longer for the cooperation situation than for the independent situation in the present study, but this difference was far from being statistically significant. One plausible explanation is that even strangers have a tendency to cooperate with others even in the independent situation, leaving little room for an increase in JSE when instructions emphasize cooperation. Another reason is that the difference between the cooperative and independent groups was not manipulated sufficiently, because the results of IOS are not significant for the two groups as well. But, the competition instruction is for the loser to give up all points that she or he earned, which makes the individual focus on their own task performance. In other words, only in a competitive situation does the consequence of performance alter the strategy of individual behavior in our task. The result is consistent with the previous study that in the competitive situation of a joint task, improving one's own performance to the limit rather than focusing consideration on the other' s performance seems to be the appropriate strategy (Poortvliet & Darnon, 2010). That is, when people want to beat the coactor, they will attend more to their own actions to maximize the reward.

The main finding concerns the neural mechanisms of the influence of interpersonal situations on co-representation in a joint task. Firstly, for the intra-brain analysis, the main effect of spatial compatibility was significant on the bilateral IPL, the left IFG and the right pSTS, which is indicative of ToMs being used to understand the intentions of others in different interpersonal situations (Behrens et al., 2009, 2008). As a result, the incongruent trials yielded significantly higher activation than the congruent trials in these brain regions, which indicates that when the locations of the stimulus and the response or participant were incompatible, the brain regions mentioned above devoted more resources to the response conflict.

The main effect of spatial compatibility also showed that the left IPL only had a higher activation under incompatible conditions in the competitive situation rather than in the independent and cooperative situations. The possible reason may be that participants paid more attention to respond on the compatible trials in the independent and the cooperative groups, while the competitive group focused more on the incompatible trials and speeded up the response to them. This result was consistent with the behavioral result that the RT of incompatible trials of the competing group was shorter than that of the independent and cooperative groups.

Prior studies have demonstrated that the IPL could function as joint attention (Park et al., 2012), and information integration (Lorenz et al., 2015). The result of this research also indicated that the main effect of response was significant on both sides of IPL, showed the activation of the go condition was significantly higher than that of the no-go condition, indicating stronger activation in these cortices when it was the participants' turn to execute their own response. Meanwhile, the IPL is a part of the mirror neuron system, which plays a role in an individual understanding the actions and intentions of others via simulation (Iacoboni, 2008; Iacoboni & Dapretto, 2006; Keysers & Mckay, 2011; Simpson & Ferrari, 2013). This suggests that participants manipulated actions mentally while planning the action, and that was associated with both left and right IPL.

Previous neuroscience studies have reported that the right IFG is associated with intention understanding and empathy. The results of the present study imply that the supportive move by the cooperator may increase the partner's activation in the right IFG, even if the cooperator does not actively trace the partner's move due to the surface cooperation with the partner. In contrast, the competitor may need to actively trace the partner's move to disturb the partner's goal, as if the competitor has an empathetic view of the partner.

Consistent with our hypothesis, the main effect of interpersonal situation in the right IPL was significantly higher for the competitive situation than for the independent and cooperative situations. Besides, the shortest RT and the greatest intra-brain activation were both observed in the competitive situation, showing that the shorter RT relied on the higher brain synchronization of IPL. These results indicated that INS occurred in different Interpersonal Situations on collaborative ability of joint action, especially higher in the competitive situation, which implying that the participants devoted more attention resources to maximize their reward in the competitive situation with faster responses. In fact, participants paid more attention to the tasks and themselves instead of the co-representation of self and other in this situation, and aroused higher INS in the process, as a result, they achieved better performance in competitive situation.

It is worth noting that the left IPL showed a significant three-way interaction effect, and simple effect tests indicated that the increase in go response activation relative to no-go response activation in the incompatible condition was greatest for the independent situation. This result provides evidence that more cognitive resources were concentrated on the individual's own reactions in independent situations. However, as compared to the independent situation, the nonsignificant results of both the competition and cooperation situations suggests that in the two situations, the participants paid similar amounts of attention to themselves and their partner during the task.

Secondly, significantly increased INS channels of the bilateral IPL were found in cooperative, competitive, and independent situations, which indicates that they are commonly involved in the joint task. For the main effect of situation, a higher task-related significant INS of competition situation was found in the right IPL rather than independent and cooperation situation, which means that the right IPL may be crucial in the competitive situation and is a part of brain network referring to the role of self-other discrimination. This result suggests that the competition situation devoted greater cognition resources related to the function of the right IPL than did the cooperation and independent situations. Noticeably, the better INS in competition situation is associated with better task performance, and the RT was shortest. The possible reason may as follow: individuals faced the greatest risk of losing money in competitive situation, so they used more cognitive resource to concentrate on the task and themselves, so the level of brain activation is higher and the reaction is faster compared to others situations. However, in both independent and cooperative situations, individuals only need to focus on go trials to get the reward, so they devoted fewer cognitive resources to distinguish between themselves and others. As the right IPL related to cognitive functions, such as self-other discrimination, the INS between the activation of the right IPL and react time of independent situation was not significantly different from the cooperation situation.

Also, the result of three-way interaction revealed significantly higher INS in the left IPL of competition situation. More specifically, we distinguished INS from four experiment conditions (GC, GI, NC, and NI) in three situations, separately. The increased higher INS of the competition situation was under the GC condition, in which participants were to respond to the compatible stimulus that appeared on the ipsilateral side. Considered along with the function of the IPL, these results demonstrate participants in competition situation paid more active cognition resources to distinguish self and others.

A question in social cognition and social neuroscience is how to improve collaborative ability and task performance. The parietal lobe is thought to associate with multisensory integration, which is a site for the formation of forward and feedback internal models of action control (Della-Maggiore & V, 2004; Desmurget & Grafton, 2000). Focusing on the ROI channels that displayed significant task-related INS compared to the scrambled time series, the right IPL is closely associated with cognitive functions such as theory of mind and self-other discrimination on comparing different interpersonal situations. This is consistent with the behavioral result that participants in competitive situations took the shortest time to respond to the stimulus, which also corresponding to the highest intra-brain activities in dyads of competitive situation. Studies have shown that the fronto-parietal networks including the IPL play an important role in cognitive and emotional processing. In particular, the right IPL is thought to play a crucial role in distinguishing self from others (Lamm et al., 2007; Schulte-Rüther et al., 2007). For example, in an fMRI study, Lamm et al. (2007) found that when considering one's own feelings and emotions, the activation degree of the left IPL was higher, while that of the right IPL was higher when considering others. They think that the IPL can distinguish the self from others. Therefore, higher competitive INS was shown during the go/compatible condition than the cooperation and the independent in the left IPL, as this type of condition request the participant to respond to the stimulus on the same side and consider their own feelings and emotions more closely.

5. Conclusion

The present study employed fNIRS hyperscanning to demonstrate that interpersonal situations affect the performance of participants in the joint task, providing evidence on two levels including the behavioral and neural mechanisms. Firstly, in cooperative, competitive, and independent situations, the co-representation of self and others was realized simultaneously, but the competitive situation will weaken this representation, while the cooperative situation has the tendency to enhance the collaborative ability. The second finding revealed underlying neural mechanism of different interpersonal situations on collaborative ability in joint task, and both cooperative and competitive situations demonstrated increased INS in the bilateral IPL due to task demands of joint attention and intention understanding. Specifically, participants showed higher INS in the right IPL in competition than the independence and the cooperation, and had better performance of joint task (the RT was shortest under competition) as well. In sum, the behavior and fNIRS results together indicate that participants in cooperative situations need more shared representations with the co-actors, while in competitive situations need to pay more actively attention to distinguish themselves from others, and the INS and performance were better than the other conditions eventually.

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Disclosure statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Author contributions

SX and QY conceived and designed the study. QY, LJ performed the experiments. RWP provided some advice and comments. SX and LJ wrote the paper. SX, LJ, QY, DM, and RWP edited drafts of the manuscript and contributed to the final version. All authors read and approved the manuscript.

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