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Cooperation Makes a Group be More Creative

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Abstract

This study investigated how cooperative and competitive interaction modes affect the group creative performance. The participants were recruited as dyads to solve 2 problems either demanding divergent thinking (alternative uses task, AUT) or not (object characteristic task, OCT). The dyads solved 1 of the 2 problems in the cooperative mode and the other in the competitive mode. Functional near-infrared spectroscopy (fNIRS)-based hyperscanning was used to record their neural activities in the prefrontal and right temporal–parietal junction (r-TPJ) regions. Results revealed the dyads showed higher AUT fluency, AUT originality, OCT fluency, and cooperation level in the cooperative mode than in the competitive mode. The fNIRS data revealed increased (task-baseline) interpersonal brain synchronization (IBS) in the right dorsolateral prefrontal cortex (r-DLPFC) and r-TPJ, only for dyads in the AUT/cooperation condition. In both r-DLPFC and r-TPJ, the IBS of dyads in the AUT/cooperation condition was stronger than in the AUT/competition and OCT/cooperation. Moreover, a stronger IBS was evoked between the regions in prefrontal and posterior temporal regions in the AUT/cooperation condition, as compared with the competition mode. These findings suggest that enhanced IBS may underlie the positive effects of cooperation as compared with the competition in terms of group creativity.

Key words: brainstorming, creativity, fNIRS, hyperscanning, interpersonal brain synchronization

Introduction

Creativity is defined as the ability to produce work that is novel (original and unique) and useful (Sternberg and Lubart 1996; Runco and Acar 2012). The evolution of human civilization essentially requires the involvement of such a capacity, especially group creativity. In recent years, many studies have been conducted to identify factors that can affect group creativity (Bittner et al. 2016; Choi et al. 2016; Curşeu and Brink 2016; Lebuda et al. 2016; Korde and Paulus 2017). In the current study, we expected to find out how different modes of interaction will affect group creativity.

Engaging in collective activities leads to interpersonal interactions among individuals, during which an individual's mind and behavior may be affected by others (Baumeister and Leary 1995). There are 2 primary modes of interpersonal interaction,

namely, cooperation and competition (Decety et al. 2004). In the cooperation mode, individuals may pursue one shared goal and facilitate others in achieving their goals. However, in the competition mode, the team members may strive for self-centered goals and even obstruct others' goal achievement. Thus, depending on these modes of interaction (cooperation vs. competition), the creative performance of brainstorming groups may be enhanced or inhibited.

Previous studies have suggested that group creativity is only likely to flourish when team members not only develop the ideas themselves but also share their ideas and actively process the ideas of others (Gilson and Shalley 2004; Van Knippberg et al. 2004; Vera and Crossan 2005; Hargadon and Bechky 2006). In other words, only when the ideas of others are carefully attended to and actively processed (i.e., building on the others'

ideas, or combining others' ideas with one's own), is it likely that the team members will explore ideas in new the categories previously not considered (Paulus and Yang 2000; Shin and Zhou 2007). In accordance with the social interdependence theory (Deutsch 1949, 1962), we defined cooperation as a positive social interdependence where a positive correlation exists among individual goal attainments. Cooperation tends to induce mutual assistance, exchange of resources and trust (Johnson 2003). In addition, Rhee (2007) proposed that cooperation can lead to a more efficient interactive process (i.e., building on and supporting others' ideas, motivating morale), which in turn, can lead to a more creative performance for the whole group. Therefore, it is likely that group creativity can be enhanced by cooperation since it can result in a more efficient interactive process (carefully attend to others', share ideas, build on others' ideas or combine others' ideas with their own). Although previous studies have reported that cooperation can exert beneficial effects on individual creativity (Hon et al. 2014; Carmeli et al. 2015; Bittner et al. 2016), its contribution towards group creativity remains to be investigated.

It has been suggested that competition tends to induce obstruction of others' success, tactics of coercion and threat, deceptive communication, and striving to "win" conflicts (McCain 1991; Johnson 2003; Anderson et al. 2007). Further, previous studies reported that creative performance could be hampered by competition (Deci et al. 1981; Amabile 1982; McGlynn et al. 1982). It was proposed that restricted communication, conflicting reinforcement contingencies and decreased intrinsic motivation resulting from competition can account for the loss in creative performance, lead to an inefficient communication exchange process. Eventually, it may hinder groups from leveraging the benefits associated with bringing individuals with different ideas and perspectives together. In contrast, the beneficial effects of competition on creative performance were also observed in a few studies (Raina 1968; Amabile and Gryskiewicz 1987; Cummings and Oldham 1997). These findings were interpreted based on the assumption that competing with the team members either for the resources, or to outperform others may further impel individuals to pursue creative ideas (Cummings and Oldham 1997). This implies that in order to obtain more resources or to prove their worth over others individuals tried harder to generate more creative ideas. However, it should be noted that these studies only focused on the differences in individual creative performance. Therefore, whether such an intragroup competition can benefit the creative performance of the whole group remains unexplored.

Subsequently, the question about which type of interpersonal interaction mode (cooperation vs. competition) is beneficial to group creativity is still under debate. This study aimed to compare the creative performance of brainstorming groups in different interaction modes and reveal the underlying interbrain neural correlates by means of fNIRS-based hyperscanning. We primarily addressed 2 questions. First, "Which interpersonal interaction mode is more effective in enhancing group creativity?" Second, "Do interpersonal neural correlates between team members show different patterns in these 2 interaction modes, thus reflecting different levels of cooperation?"

Recently, the hyperscanning technique, which can be conducted using fMRI (Chiu et al. 2008; Li et al. 2009), EEG (Lindenberger et al. 2009; Dikker et al. 2017; Hu, Hu et al. 2017; Hu, Pan et al. 2017), and fNIRS (Nozawa et al. 2016; Tang et al. 2016; Liu, Piazza, et al. 2017; Liu, Saito, et al. 2017) has been considered to investigate interpersonal interactions (Cui et al. 2012; Cheng et al. 2015; Hu, Hu et al. 2017; Hu, Pan et al. 2017; Ikeda

et al. 2017). Studies using this technique have successfully identified evidence of interpersonal synchronized neural activities in several brain regions, during interpersonal interactions across the group. In this study, we adopted fNIRS-based approach to explore the interpersonal brain interaction between individuals engaging in the problem-solving tasks demanding creativity, since it offers advantages of better temporal and spatial resolution when compared with fMRI and EEG, respectively, a higher tolerance for motor artifacts and higher ecological validity.

In the context of social interaction, brain regions, namely, PFC, orbitofrontal cortex (OFC), and r-DLPFC have been shown to be essential for tasks involving cooperation and interpersonal interactions (McCabe et al. 2001; Decety et al. 2004; Decety and Lamm 2007; Desmurget et al. 2009; Dumas et al. 2010; Suzuki et al. 2011; Chaminade et al. 2012; Cui et al. 2012; Baker et al. 2016). Recent hyperscanning based studies reported increased IBS in brain regions including PFC, superior frontal cortex, and r-TPJ, among the individuals engaged in cooperation (Funane et al. 2011; Cui et al. 2012; Dommer et al. 2012; Cheng et al. 2015; Tang et al. 2016). Similar patterns of increased IBS were observed in other interpersonal interaction related activities, including group humming (Osaka et al. 2014), teaching–learning interactions (Holper et al. 2013; Dikker et al. 2017), coordinated group walking (Ikeda et al. 2017), and verbal communication (Jiang et al. 2012; Nozawa et al. 2016; Liu, Piazza, et al. 2017; Liu, Saito, et al. 2017). In addition, recent fNIRS hyperscanning studies contrasting cooperation and competition conditions in a turn-taking game have also focused on the lateral frontal, temporal, and parietal brain regions (Liu et al. 2015; Liu, Piazza, et al. 2017; Liu, Saito, et al. 2017). Accordingly, we hypothesized that IBS in the PFC and r-TPJ could be an indicator for the state of cooperation among individuals.

Moreover, PFC and r-TPJ have been implicated as the regions pivotal to the cognitive processing during tasks demanding creativity (Kleibeuker et al. 2013; Benedek et al. 2014; Goel et al. 2015; Wu et al. 2015; Beaty et al. 2016). For example, it has been revealed that the working memory and executive function system, both of which are associated with creativity, require the involvement of activities in PFC, particularly the DLPFC (Vartanian et al. 2014; Heinonen et al. 2016). In addition, r-TPJ has been identified as an important brain region for perspective taking, memory cues and attentional control, all of which can contribute to creative performance (Fink, Grabner, Benedek, et al. 2009; Fink, Graif, Neubauer, et al. 2009; Fink et al. 2010, 2012; Benedek et al. 2014; Goel et al. 2015). Therefore, in the present study, we chose the PFC and r-TPJ to explore the interpersonal neural correlates among the individuals engaging in problem-solving activities demanding creativity.

In the study, the participants were randomly assigned as dyads to solve 2 problems either demanding creativity (i.e., alternative uses task, AUT) or not (i.e., object characteristic task, OCT). Since divergent thinking performance has been demonstrated to be a key component of creativity and a reliable predictor of creative potential (Runco and Acar 2012), the current study focused on divergent thinking as an approach to study creativity. Further, since the AUT and OCT considerably differ with respect to their creativity demands, contrasting both can reveal specific interpersonal neural correlates underlying cognitive processes demanding creativity (Fink et al. 2010). All the dyads were instructed to solve one problem in the cooperation mode and the other in the competition mode. Changes in the cerebral activity during the tasks were continually recorded

in the PFC and r-TPJ using a fNIRS-based system. Considering that cooperation may lead to a more efficient interaction between team members which may enhance group creativity (Paulus and Yang 2000; Rhee 2007; Shin and Zhou 2007), we predicted that the dyads in cooperation mode will show better creative performance than those in the competition mode. Further, considering that IBS might indicate a cooperative interaction process (Funane et al. 2011; Cui et al. 2012; Dommer et al. 2012; Osaka et al. 2014; Cheng et al. 2015; Tang et al. 2016; Ikeda et al. 2017), we also predicted greater IBS during AUT, in the cooperation when compared with the competition mode.

Furthermore, we assessed the participants for the variables known to affect creative performance, including the emotional state, task-enjoyment and task-difficulty, to investigate whether the effect of interaction mode on group creative performance was independent of the aforementioned variables (De Dreu et al. 2008; Zenasni and Lubart 2011; Chae et al. 2015a, 2015b; Yang and Hung 2015).

Methods

Participants and Design

A total of 104 college students (64 females; age: 21 ± 1.52 years) took part in the study. All the participants were right-handed, with normal or corrected-to-normal vision. The participants were asked to perform the experimental tasks as dyads. In each dyad, the participants were unfamiliar with each other. Among 104 participants, a total of 52 dyads were formed. However, due to missing data, one dyad was excluded from the analysis. Before participating, each participant signed informed consent. The participants were paid ¥50 for their time and effort. The study procedure was approved by the University Committee on Human Research Protection (UCHRP) of East China Normal University.

The experiment consisted of a 2 (task: AUT vs. OCT) × 2 (interaction mode: cooperation vs. competition) factorial design, with task as the between-subject factor and interaction mode as the within-subject factor. All the dyads were randomly assigned to the AUT or OCT group. Consequently, the AUT and OCT group comprised of 25 and 26 dyads, respectively, and were age, as well as gender-matched (see details in Supplement (S1)).

Experimental Procedure and Tasks

Upon arrival, the participants in each dyad were asked to sit face-to-face (Fig. 1A). The experimental procedure consisted of three 1-min resting-state blocks, two 1-min instruction blocks and two 5-min task blocks (Fig. 1D,E). The 1-min resting-state between the 2 task sessions served as a baseline. During this session, participants were required to remain as still as possible, with their eyes closed, and their mind relaxed (Lu et al. 2010). Following the resting-state session, rules of brainstorming (i.e., deferment of judgment, quantity breeds quality, free-wheeling is encouraged, and combination and improvement are sought) and instructions of tasks were introduced in the instruction session.

In the AUT group, 25 dyads were asked to solve 2 AUT problems (Guilford 1967), in which participants were asked to generate as many alternative uses for everyday objects as possible. The AUT is a well-established divergent thinking task and is widely used in behavioral and neuroscience studies on creativity (Runco and Okuda 1991; Runco and Mraz 1992; Fink, Grabner, Benedek, et al. 2009; Fink, Graif, Neubauer, et al. 2009;

Hao et al. 2017; Wang et al. 2017). Performance on the AUT has been shown to be a reliable predictor of real-world creative performance (Runco and Acar 2012). Previous studies have shown differences in idea characteristics as a function of instruction (i.e., "be creative" or "be fluent") (Runco et al. 2005; Nusbaum and Silvia 2011; Edl et al. 2014; Nusbaum et al. 2014). Nusbaum et al. (2014) observed that asking participants to be creative boosts the quality of ideas but reduces the quantity, while instructions for fluency boost the number of ideas while compromising the quality. Since we aimed to explore the effect of interaction mode on both quantity, as well as the quality of the responses, the typical instruction for AUT, namely, "Please generate as many unusual or original uses as possible for the target object" was used in the present study (Guilford 1967; Fink, Grabner, Benedek, et al. 2009; Fink, Graif, Neubauer, et al. 2009; Hao et al. 2017). As previously discussed, the dyads were asked to solve 2 AUT problems, one each, in the cooperation, as well as the competition interaction mode. The sequence of the cooperation mode and competition mode was counterbalanced (Fig. 1D). In the cooperation mode, the following instruction was provided: 'During this task, your partner is your ally. Both of you are supposed to cooperate with each other and endeavor for better group performance. The performance for the whole group will be determined by combining the performance of both participants in this dyad'. In the competition mode, the instruction provided was as follows: 'During this task, your partner is your opponent. Both of you are supposed to compete against each other and endeavor for better personal performance. Winner of the task will be determined by comparing your personal task performance'.

In the OCT group, 26 dyads were asked to solve 2 OCT problems (Fink, Grabner, Benedek, et al. 2009; Fink, Graif, Neubauer, et al. 2009). These participants were asked to report typical characteristics of the everyday objects; broadly resembling a memory-retrieval task, which involves direct stimulus-related information (Binder et al. 2009; Fink, Grabner, Benedek, et al. 2009; Fink, Graif, Neubauer, et al. 2009; Fink et al. 2010; Hao et al. 2016). Similar to the AUT tasks, each dyad was asked to solve one OCT in the cooperation mode and the other in the competition mode, in a counterbalanced sequence (Fig. 1E).

During the task sections, the participants were asked to answer while taking turns and reporting one idea at a time. If they failed to present an idea during their respective turn, they were allowed to say "pass" (details on "the frequency of pass" can be found in the Supplement (S2)) and report again during the next turn. Two object cues were used for AUT and OCT, namely, "key" and "fishing rod." The participants were either asked to generate characteristics in the OCT or generate alternative uses for them in the AUT, with the assignment of the object cues to the cooperation versus competition modes being counterbalanced over dyads.

Pre-experiment and Postexperiment Assessment

Prior to the experiment, the valence and arousal of participants' emotional state were measured using scores on Self-Assessment Manikin (SAM) scale (Bradley and Lang 1994). Both valence and arousal were rated on a 9-point scale (valence: 1 = very unpleasant, 9 = very pleasant; arousal: 1 = not exciting at all, 9 = very exciting), which was illustrated by 5 cartoon figures with points listed between any 2 figures.

Immediately following the experiment, participants were asked to rate the valence and arousal of their emotional state
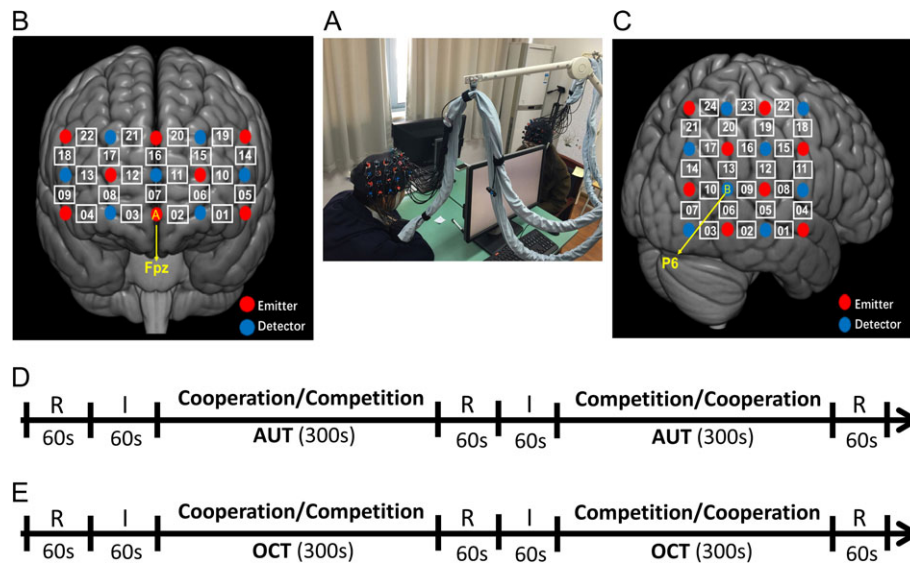
Figure 1. Experimental design. (A) Experimental setup. (B) The 3×5 optode probe set placed on the prefrontal cortex. (C) The 4×4 optode probe set placed on the right temporal–parietal junction. (D) task design in the AUT group. (E) task design in the OCT group. -(R)- the resting state session; -(I)- the instructions of the task and brainstorming rules; -(Cooperation/Competition)- the task was performed in the cooperation or competition mode; -(Competition/Cooperation)- the task was performed in the competition or cooperation mode.

again. To assess participants' enjoyment while they worked on the task, we developed an Enjoyment task Scale. The scale consisted of 5 items: 1) "The test was fun"; 2) "I enjoyed completing the test"; 3) "The test was boring (contradictive item)"; 4) "I felt happy when I worked on the test"; and 5) "I disliked performing the test (contradictive item)". Items on this scale were scored on a 5-point Likert scale ranging from 1 ("not at all") to 5 ("very much"). Total scores on 5 items indicated the participants' level of enjoyment of the task. The reliability of the Enjoyment task Scale in this study was satisfactory (Cronbach's α = 0.85). Moreover, participants were also asked to rate the difficulty associated with performing the tasks by answering the question "I think this test was difficult for me" on a scale ranging from 1 ("not at all") to 7 ("very much"). No discussion was allowed during the rating session.

Assessment of Performance on the AUT and OCT

Participants' performance on the AUT was assessed based on the fluency and originality of their generated ideas (Guilford 1967; Runco and Okuda 1991). The fluency score was based on the total number of ideas that each participant generated. The fluency score for each dyad was obtained by combining the fluency scores of participants in the dyad. The originality score was assessed using a subjective method. Five trained raters independently rated the originality of each idea generated by the participants on a 5-point Likert scale ranging from 1 ("not original at all") to 5 ("highly original"). The inter-rater agreement (Internal Consistency Coefficient, ICC = 0.85) was satisfactory. Individual ratings for each idea from all the 5 raters were averaged into a single originality score for each idea. The final originality score for each participant was calculated by averaging the originality scores of all ideas generated in the task. The originality score for each dyad was obtained by averaging the originality scores of participants in the dyad.

Participants' performance on the OCT was evaluated using the fluency of their ideas, as explained previously.

Behavioural Index of Cooperation Between Partners in Each Dyad

The combination of ideas was measured as the behavioral index for cooperation between participants in each dyad, and was measured as follows: 2 trained raters independently assessed the collective flexibility of each dyad (the total number of categories for ideas generated by each dyad). The inter-rater agreement for this method was satisfactory (ICC = 0.95). Further, the collective flexibility of each dyad was calculated by averaging ratings from the 2 raters. Finally, "Combination of ideas" for each dyad was calculated by "Dyad fluency score/ Collective flexibility" (Xue et al. 2018), which was suggestive of the extent to which the dyad explored ideas in a single category. Accordingly, the more team members cooperated with one another, the more improvement and combination of ideas would occur. These improved (or combinative) ideas were recognized as the responses in the same category. Therefore, such an index would reflect the extent to which the group members combined their ideas with others, and indicate, to what degree the group members cooperated with each other.

fNIRS Data Acquisition

A NIRS system (ETG-7100, Hitachi Medical Corporation, Japan) was used to record the oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentrations for each dyad. The absorption of near-infrared light (wavelengths: 695 and 830 nm) was measured at a sampling rate of 10 Hz. Two optode probe sets were placed over each participant's PFC and r-TPJ regions, based on the previous studies suggesting the involvement of the PFC and r-TPJ regions in group creativity and social interaction (e.g., cooperation) (Decety et al. 2004; Funane et al. 2011; Benedek et al. 2014; Cheng et al. 2015; Goel et al. 2015; Heinonen et al. 2016; Sun et al. 2016; Tang et al. 2016). One 3 × 5 optode probe set (8 emitters and 7 detectors, 3 cm optode separation) consisting of 22 measurement channels (CHs), and one 4 × 4 optode (eight emitters and detectors, 3 cm optode separation) probe set

consisting of 24 measurement channels (CHs), were used. For the 3 × 5 optode probe set, the lowest probes were positioned along the Fp1–Fp2 line, in accordance with the international 10–20 system for electroencephalography, with the middle optode A placed on the frontal pole midline point (Fpz) (Sai et al. 2014). Meanwhile, the middle probe of patches was aligned precisely along the sagittal reference curve. For the 4 × 4 optode probe set, the lowest probe was aligned with the sagittal reference curve, with the optode B placed on P6. The virtual registration method was used to determine the correspondence between the NIRS channels and the measurement points on cerebral cortex (Singh et al. 2005; Tsuzuki et al. 2007) (Fig. 1B,C).

IBS Within PFC or r-TPJ

Based on modified Beer-Lambert law, both HbO, as well as HbR signals can be employed to measure changes in cerebral blood flow. However, we mainly focused on the HbO signal, since it has been shown to be more sensitive to the changes in cerebral blood flow (Hoshi 2007; Jiang et al. 2012).

For each dyad, the data were preprocessed with hrf low-pass filtering and Wavelet minimum description length (Wavelet-MDL) detrending algorithm in NIRS-SPM (Jang et al. 2009; Ye et al. 2009; Brigadoi et al. 2014; Tang et al. 2016). By applying low-pass filtering, we could attenuate high-frequency non-neuronal components in the NIRS data. Meanwhile, a Wavelet-MDL detrending algorithm was used to remove the unknown global trend due to breathing, cardiac, vaso-motion or other experimental errors. Further, wavelet transform coherence (WTC) was used to assess the relationship between HbO time series for each dyad (Grinsted et al. 2004). Average coherence value (IBS) in the brainstorming session was computed to subtract the average coherence in the resting-state session.

To identify the frequency band of interest, one-sample t-test was conducted to evaluate time-averaged IBS increments in each CH combination (22 in PFC and 24 in r-TPJ) along the full frequency range (0.01–0.7 Hz) (Nozawa et al. 2016; Xue et al. 2018; Zheng et al. 2018). The analysis was carried out in 4 separate conditions (i.e., AUT/PFC, AUT/r-TPJ, OCT/PFC, OCT/r-TPJ). To avoid bias, the IBS values in both interaction modes were averaged before t-tests in each condition. Previous studies reported that the data above 0.7 Hz suffered from aliasing of higher frequency physiological noise such as cardiac activity (0.8–2.5 Hz) (Guijt et al. 2007; Tong et al. 2011; Barrett et al. 2015). Therefore, we excluded the data above 0.7 Hz from the study. Moreover, the data below 0.01 Hz were not considered as well, to avoid very low-frequency fluctuations. The t-test results were thresholded at $P < 0.0005$. Considering that this analysis was only used to identify the frequency band of interest rather than to obtain the final results, no further correction was performed (Zheng et al. 2018). Results showed that significantly IBS increases were observed in both AUT/PFC and AUT/ r-TPJ conditions in the frequency band between 0.042 and 0.045 Hz (22.2–23.6 s). However, no significant IBS increase was observed in OCT conditions. Based on these findings, the frequency band between 0.042 and 0.045 Hz was eventually chosen as the frequency band of interest in the present study. For further analysis, IBS values in this band were converted to Fisher z-statistics (Chang and Glover 2010; Cui et al. 2012; Cheng et al. 2015). In each of the conditions, IBS values from bad channels were replaced with the mean IBS value. A one-sample t-test with false discovery rate (FDR) correction across all channels (CHs) ($P < 0.05$) was calculated for each condition of the brainstorming session. The t-maps of IBS were generated and smoothed using the spline method. If a channel was found with significant IBS in at least one condition, a 2-way analysis of variance (ANOVA) using interaction mode as the within-subject factor and task as the between-subject factor was performed on the IBS. Follow-up simple effect analyses with Bonferroni corrections were performed, when necessary. Finally, bivariate Pearson correlations between IBS and behavioral indices (i.e., fluency/originality scores and behavioral index of cooperation) were estimated to reveal brain–behavior relationship (correlation results are provided in the Supplement (S5)).

IBS Between PFC and r-TPJ

In order to explore whether the interaction mode and task can affect IBS in not only the corresponding CHs within PFC or r-TPJ but also across different CHs between PFC and r-TPJ, we calculated IBS in the target frequency band (0.042–0.045 Hz) of different CH combinations between PFC and r-TPJ (a total of 528 channel combinations: 22CHs × 24CHs). Since the report sequences of 2 participants in dyads were counterbalanced, the IBS values of CH combinations between PFC (participant 1) and r-TPJ (participant 2) and the IBS values of CH combinations between PFC (participant 2) and r-TPJ (participant 1) were averaged before further analysis. For instance, the IBS value of CH1 (PFC) and CH1 (r-TPJ) (i.e., PFC1- r-TPJ1) was calculated by averaging the IBS value of PFC1 (participant 1) and r-TPJ1 (participant 2) and the IBS value of PFC1 (participant 2) and r-TPJ1 (participant 1). Initially, one-sample t-test with FDR correction across all CH combinations ($q = 0.01$) was calculated for each condition. If a CH combination was found with a significant increase in IBS in at least one condition, 2-way analysis of variance (ANOVA) using interaction mode as the within-subject factor and task as the between-subject factor was performed on the IBS. Follow-up simple effect analyses with Bonferroni corrections were carried out, as required. Finally, bivariate Pearson correlations between IBS and behavioral indices were performed to reveal brain–behavior relationship (correlation results are provided in the Supplement (S5)).

Results

Performance on AUT and OCT in Different Interaction Modes

Two-way mixed-design ANOVA using task as the between-subject factor and interaction mode (cooperation vs. competition) as the within-subject factor was performed on the fluency scores. Results showed a significant main effect of interaction mode on fluency, $F(1, 49) = 13.36$, $P < 0.001$, $\eta_p^2 = 0.21$. Post hoc tests showed fluency scores were significantly higher in the cooperation mode ($M = 26.14$, Standard Deviation (SD) = 5.83) than in the competition mode ($M = 22.98$, SD = 6.30). No other significant main effect or interaction effect was observed (Fig. 2A).

One-way repeated measures ANOVA using interaction mode as the within-subject factor was performed on AUT originality scores. Results showed a significant main effect of interaction mode on AUT originality, $F(1, 24) = 15.45$, $P < 0.001$, $\eta_p^2 = 0.39$. Post hoc tests showed that originality scores were significantly higher in the cooperation mode ($M = 2.72$, SD = 0.24) than in the competition mode ($M = 2.36$, SD = 0.38) (Fig. 2B).

Moreover, the main effect of interaction mode on fluency scores remained significant after other variables (i.e., emotional state, enjoyment of task, and difficulty of task) were added to the aforementioned ANOVA model as covariates, $F(1, 45) = 8.76$,
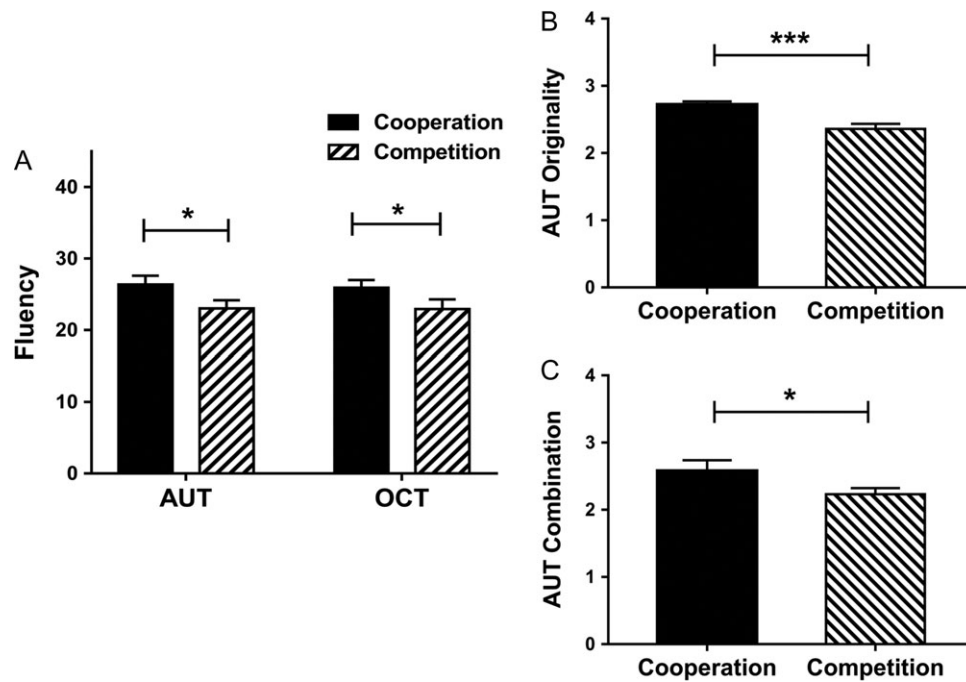
Figure 2. Performance of brainstorming dyads in the AUT and OCT. (A) AUT and OCT fluency scores of brainstorming dyads in different interaction modes. (B) AUT originality scores of brainstorming dyads in different interaction modes. (C) Behavioral index of cooperation of brainstorming dyads during AUT in different interaction modes. Error bars indicate standard errors of the mean. *P < 0.05; ***P < 0.001.

$P = 0.005$, $\eta_p^2 = 0.16$. Similarly, the main effect of interaction mode on originality scores also remained significant, $F(1, 20) = 17.57$, $P < 0.001$, $\eta_p^2 = 0.47$.

Behavioural Indices of Cooperation in Different Interaction Modes

One-way repeated measures ANOVA using interaction mode as the within-subject factor was performed on the collective flexibility scores. Results showed no significant main effect of interaction mode on flexibility, $F(1, 24) = 0.21$, $P = 0.65$, $\eta_p^2 = 0.01$.

Further, one-way repeated measures ANOVA with interaction mode as the within-subject factor was also performed on the behavioral indices of cooperation during AUT. Results demonstrated a significant main effect of interaction mode on the behavioral indices of cooperation, $F(1, 24) = 4.34$, $P = 0.048$, $\eta_p^2 = 0.15$. Post hoc tests showed that the behavioral indices of cooperation in the cooperation mode ($M = 2.58$, SD = 0.79) was significantly higher than in the competition mode ($M = 2.23$, SD = 0.46) (Fig. 2C).

Effects of Task and Interaction Mode on IBS Within PFC

A series of one-sample t-tests were conducted on IBS across all channels in 4 conditions (AUT/cooperation, AUT/competition, OCT/cooperation, OCT/competition). After FDR correction ($q = 0.05$), a significant increase in the IBS was observed at CH17 ($t[24] = 5.66$, $P_{corr} = 0.0002$) in the PFC (Fig. 3A). In contrast, no significant changes in IBS were observed in other conditions (Fig. 3A).

Moreover, 2-way mixed-design ANOVA using task as the between-subject factor and interaction mode as the within-subject factor was performed on the IBS at CH17 in the PFC. Results showed a significant main effect of interaction mode on IBS at CH17, $F(1, 49) = 8.64$, $P = 0.005$, $\eta_p^2 = 0.15$. Post hoc tests

showed that IBS was significantly higher in the cooperation mode ($M = 0.09$, SD = 0.15) as compared with the competition mode ($M = 0.04$, SD = 0.16). Results also showed a significant interaction effect of task × interaction mode on IBS at CH17, $F(1, 49) = 6.05$, $P = 0.017$, $\eta_p^2 = 0.11$ (Fig. 3B). During AUT, the IBS in the cooperation mode ($M = 0.14$, SD = 0.12) was significantly higher as compared with the competition mode ($M = 0.04$, SD = 0.14; $P < 0.001$, Bonferroni corrected). In contrast, no significant difference between 2 interaction modes was observed during OCT (Fig. 3C). In addition, in the cooperation mode, the participants engaged in AUT ($M = 0.14$, SD = 0.12) showed significantly higher IBS than those in OCT ($M = 0.04$, SD = 0.16; $P = 0.017$, Bonferroni corrected). Moreover, Pearson correlations showed that IBS at CH17 in the AUT/cooperation condition covaried with AUT fluency and behavioral index of cooperation (see details in the Supplement (S5)). In contrast, no significant difference between AUT and OCT was observed in the competition mode (Fig. 3C).

Effects of Task and Interaction Mode on IBS Within r-TPJ

A series of one-sample t-tests were conducted on IBS across all channels in 4 conditions. After FDR correction ($q = 0.05$), significant IBS increases were observed at CH3 ($t[24] = 3.63$, $P_{corr} = 0.015$), CH10 ($t[24] = 5.81$, $P_{corr} = 0.0002$), CH14 ($t[24] = 4.34$, $P_{corr} = 0.003$) in the r-TPJ in the cooperation mode (Fig. 4A). In contrast, no significant changes in IBS were observed in other conditions (Fig. 4A).

Two-way mixed-design ANOVA using task as the between-subject factor and interaction mode as the within-subject factor was performed on the IBS at CH3 in the r-TPJ. Results showed no significant main effect or interaction effect.

Moreover, 2-way mixed-design ANOVA using task as the between-subject factor and interaction mode as the within-
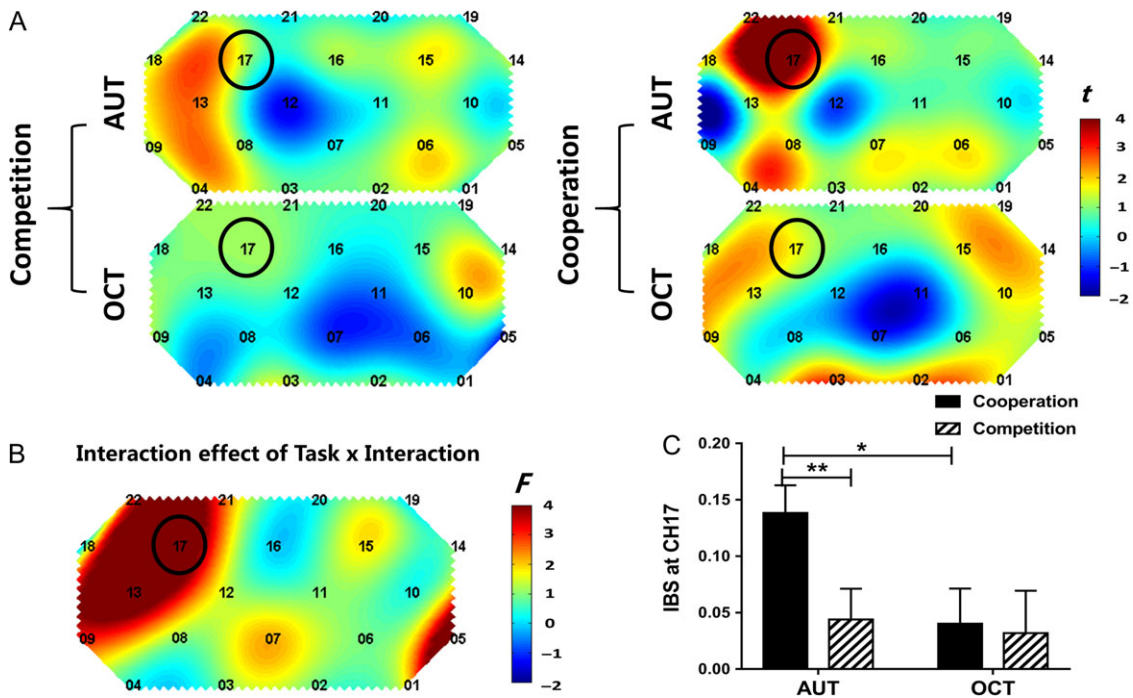
Figure 3. IBS in the prefrontal cortex (PFC). (A) One-sample t-test maps of IBS in 4 conditions (AUT/competition, AUT/cooperation, OCT/competition, OCT/cooperation). (B) Two-way mixed-design ANOVA results to identify the interaction effect of task × interaction mode on IBS. (C) The amplitude of IBS at CH17 in the PFC under different conditions. Note that in the AUT/cooperation condition, a significant IBS at CH17 was observed after FDR correction. Results also showed a significant interaction effect of task × interaction mode on IBS at CH17. *P < 0.05; **P < 0.01, after Bonferroni correction.
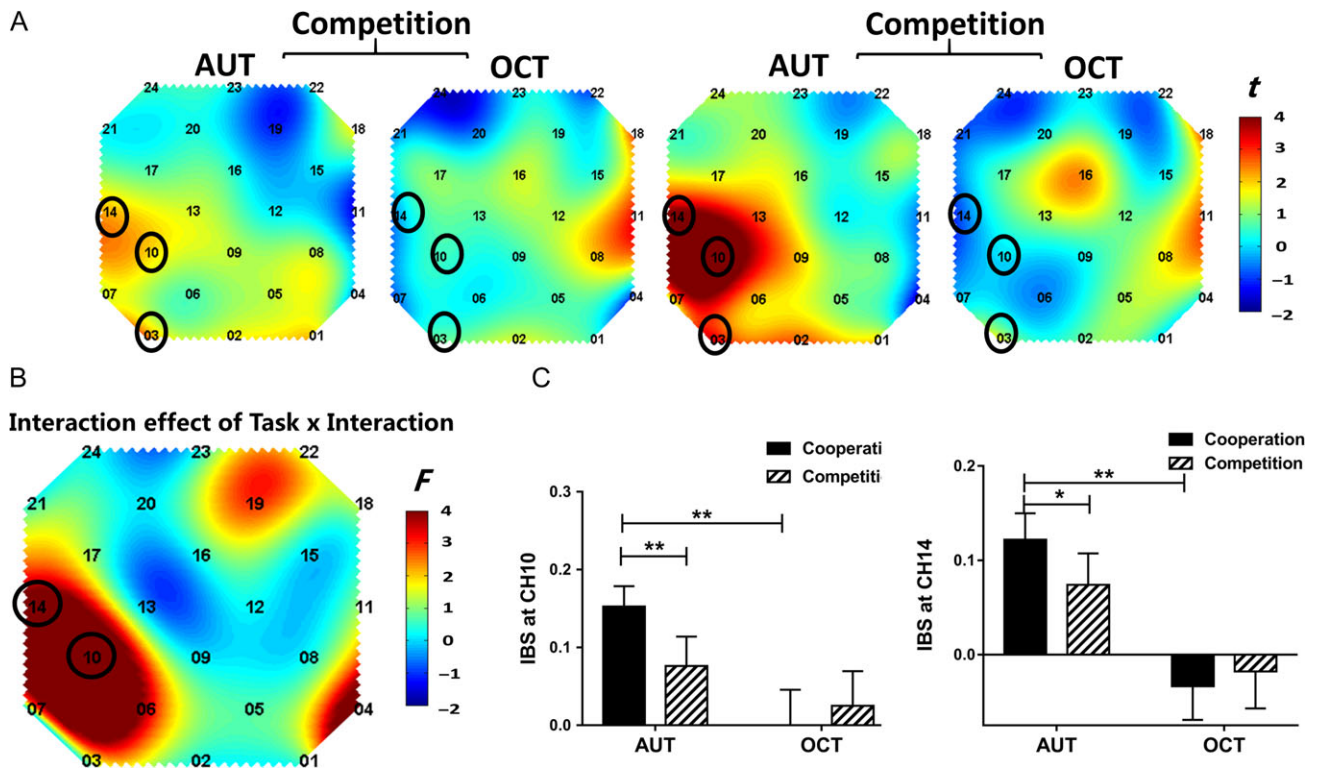

Figure 4. IBS in the right temporal–parietal junction (r-TPJ). (A) One-sample t-test maps of IBS in 4 conditions (AUT/competition, AUT/cooperation, OCT/competition, OCT/cooperation). (B) Two-way mixed-design ANOVA results to identify the interaction effect of Task × Interaction Mode on IBS. (C) The amplitude of IBS at CH10, CH14 in the r-TPJ under different conditions. Note that significant IBS was observed at CH3, CH10, CH14 in the AUT/cooperation condition (FDR corrected). Results also showed a significant interaction effect of Task × Interaction Mode on IBS at CH10, CH14. *P < 0.05; **P < 0.01, after Bonferroni correction.

subject factor was performed on the IBS at CH10 in the r-TPJ. Results showed a significant interaction effect of task × interaction Mode on IBS at CH10, $F(1, 49) = 8.68$, $P = 0.005$, $\eta_p^2 = 0.15$ (Fig. 4B). During AUT, the IBS in the cooperation mode ($M = 0.15$, SD = 0.13) was significantly higher as compared with the competition mode ($M = 0.08$, SD = 0.19; $P = 0.003$, Bonferroni corrected). In contrast, no significant difference between 2 interaction modes was observed during OCT. In addition, in the cooperation mode, the participants engaged in AUT ($M = 0.15$, SD = 0.13) showed significantly higher IBS than those in OCT ($M = 0.00$, SD = 0.23; $P = 0.006$, Bonferroni corrected). In contrast, no significant difference between AUT and OCT was observed in the competition mode (Fig. 4C). No other significant main effect was observed.

Further, 2-way mixed-design ANOVA using task as the between-subject factor and interaction mode as the within-subject factor was performed on the IBS at CH14 in the r-TPJ. Results showed a significant main effect of task on IBS at CH14, $F(1, 49) = 6.98$, $P = 0.01$, $\eta_p^2 = 0.12$. Post hoc tests showed that IBS was significantly higher in the AUT condition ($M = 0.10$, SD = 0.15) as compared with the OCT condition ($M = -0.02$, SD = 0.19). Results also showed a significant interaction effect of task × interaction Mode on IBS at CH14, $F(1, 49) = 5.21$, $P = 0.027$, $\eta_p^2 = 0.10$ (Fig. 4B). During AUT, the IBS in the cooperation mode ($M = 0.12$, SD = 0.14) was significantly higher than in the competition mode ($M = 0.07$, SD = 0.17; $P = 0.02$, Bonferroni corrected). In contrast, no significant difference between 2 interaction modes was observed during OCT. In addition, in the cooperation mode, the participants engaged in AUT ($M = 0.12$, SD = 0.14) showed significantly higher IBS than those in OCT ($M = -0.03$, SD = 0.18; $P = 0.001$, Bonferroni corrected). By contrast, no significant difference between AUT and OCT was observed in the competition mode (Fig. 4C). No other significant main effect was observed.

In addition, Pearson correlations showed that IBS at CH10, CH14 in the AUT/cooperation condition covaried with behavioral index of cooperation (see details in Supplement (S5)).

Effects of Task and Interaction Mode on IBS Between PFC and r-TPJ

A series of one-sample t-tests were conducted on IBS across all CH combinations in 4 conditions (AUT/cooperation, AUT/competition, OCT/cooperation, OCT/competition). After FDR correction ($q = 0.01$), significant IBS increases were observed at PFC3–r-TPJ10 ($t[24] = 5.49$, $P_{corr} = 0.002$), PFC6–r-TPJ10 ($t[24] = 5.00$, $P_{corr} = 0.004$), PFC8–r-TPJ10 ($t[24] = 6.17$, $P_{corr} = 0.0004$), PFC17–r-TPJ3 ($t[24] = 8.47$, $P_{corr} < 0.0001$), PFC18–r-TPJ10 ($t[24] = 6.34$, $P_{corr} = 0.004$), PFC19–r-TPJ3 ($t[24] = 4.98$, $P_{corr} = 0.004$) in the AUT/cooperation condition (Fig. 5). In contrast, no significant IBS increase was observed in other conditions.

Two-way mixed-design ANOVA using Task as the between-subject factor and Interaction Mode as the within-subject factor was performed on the IBS of PFC3–r-TPJ10. Results showed a significant main effect of Interaction Mode on IBS of PFC3–r-TPJ10, $F[1, 49] = 4.49$, $P = 0.039$, $\eta_p^2 = 0.08$. Post hoc tests showed that IBS was significantly higher in the cooperation mode ($M = 0.10$, SD = 0.12) than in the competition mode ($M = 0.07$, SD = 0.13). No other significant main effect or interaction effect was observed.

Two-way mixed-design ANOVA using Task as the between-subject factor and Interaction Mode as the within-subject factor was performed on the IBS of PFC8–r-TPJ10. Results showed a significant main effect of Interaction Mode on IBS of PFC8–r-TPJ10,
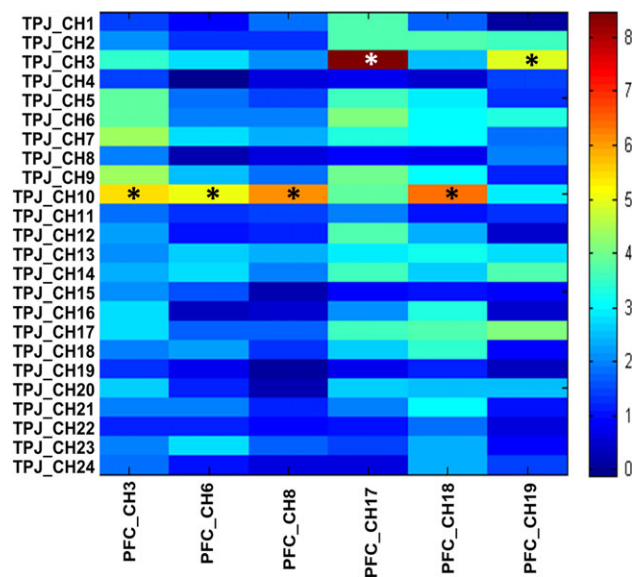

Figure 5. Heatmaps of the t values for IBS of the CH combinations between PFC and r-TPJ. The colors reflect t values for CH combinations. *Significant t value of the CH combinations. The vertical axis represents CHs in the r-TPJ. The horizontal axis represents CHs in the PFC. It should be noted that significant IBS was observed in the following CH combinations: PFC3–r-TPJ10, PFC6–r-TPJ10, PFC8–r-TPJ10, PFC17–r-TPJ3, PFC18–r-TPJ10, PFC19–r-TPJ3. The color bars denote the t values.

$F[1, 49] = 9.82$, $P = 0.003$, $\eta_p^2 = 0.17$. Post hoc tests showed that IBS was significantly higher in the cooperation mode ($M = 0.06$, SD = 0.17) than in the competition mode ($M = 0.02$, SD = 0.16). The main effect of Task was also significant, $F(1, 49) = 7.93$, $P = 0.007$, $\eta_p^2 = 0.14$. Post hoc tests showed that IBS was significantly higher in AUT ($M = 0.10$, SD = 0.11) than in OCT ($M = -0.02$, SD = 0.19). No significant interaction effect was observed.

Two-way mixed-design ANOVA using Task as the between-subject factor and Interaction Mode as the within-subject factor was performed on the IBS of PFC17–r-TPJ3. Results showed a significant main effect of Interaction Mode on IBS of PFC17–r-TPJ3, $F(1, 49) = 11.92$, $P = 0.001$, $\eta_p^2 = 0.20$. Post hoc tests showed that IBS was significantly higher in the cooperation mode ($M = 0.08$, SD = 0.12) than in the competition mode ($M = 0.03$, SD = 0.13). The main effect of Task was also significant, $F(1, 49) = 5.42$, $P = 0.024$, $\eta_p^2 = 0.10$. Post hoc tests showed that IBS was significantly higher in AUT ($M = 0.09$, SD = 0.09) than in OCT ($M = 0.02$, SD = 0.15). No significant interaction effect was observed.

Two-way mixed-design ANOVA using Task as the between-subject factor and Interaction Mode as the within-subject factor was performed on the IBS of PFC18–r-TPJ10. Results showed a significant main effect of Task on IBS of PFC18–r-TPJ10, $F(1, 49) = 6.56$, $P = 0.014$, $\eta_p^2 = 0.12$. Post hoc tests showed that IBS was significantly higher in AUT ($M = 0.12$, SD = 0.11) than in OCT ($M = 0.02$, SD = 0.17). No other significant main effect or interaction effect was observed.

Similar 2-way mixed-design ANOVA using Task as the between-subject factor and Interaction Mode as the within-subject factor were also performed on the IBS of PFC6–r-TPJ10, PFC19–r-TPJ10. No significant main effects or interaction effects were observed.

Although no significant interaction effect of task × interaction mode was observed on increased IBS, we further performed simple effect analyses to examine the effect of interaction mode on the IBS specific to AUT (see details in Supplement (S4)).

Discussion

In the present study, we explored the effects of different interpersonal interaction modes (i.e., cooperation vs. competition) on group creative performance and revealed the underlying interpersonal neural correlates using the fNIRS-based hyperscanning system. The results showed that AUT fluency, AUT originality and behavioral index of cooperation were significantly higher in the cooperation mode when compared with the competition mode, during AUT. Conversely, AUT flexibility showed no significant difference between the cooperation vs. competition modes. fNIRS results demonstrated increased IBS in the r-DLPFC and r-TPJ only for the dyads engaged in cooperation mode during AUT task performance. In both, r-DLPFC and r-TPJ, IBS of dyads in the AUT/cooperation condition was stronger than that in the AUT/competition condition and OCT/cooperation condition. Increased IBS in the r-DLPFC could positively predict AUT fluency and the level of cooperation behavior. In addition, increased IBS in the r-TPJ could positively predict the level of cooperation behavior (see details in Supplement (S5)). In addition, a stronger IBS between regions in PFC (i.e., DLPFC, frontopolar) and posterior temporal regions was evoked in the AUT/cooperation condition as compared with the competition mode. These findings may indicate that cooperation exerts a beneficial effect on the creative performance of brainstorming groups. Moreover, cooperation can evoke strong IBS in the r-DLPFC and r-TPJ between the individuals engaged in tasks demanding creativity.

More specifically, the results revealed that the brainstorming dyads in cooperation mode showed higher AUT fluency and AUT originality than those in the competition mode (Fig. 2). These findings could corroborate the previous observations regarding the benefits of cooperation on creative performance (Hon et al. 2014; Carmeli et al. 2015; Bittner et al. 2016). Concerning the beneficial effects of cooperative interaction mode on the creative performance of brainstorming dyads, we propose that a more efficient interpersonal interaction process resulting from cooperative interaction mode should be beneficial. Since the participants were instructed to cooperate with their partners in the cooperation mode, they pursued a shared goal, which could positively contribute to the creative performance of the whole group (Decety et al. 2004); possibly through the induction of mutual assistance, exchange of needed resources and trust among the partners (Johnson 2003). Consequently, it could encourage the team members to not only share their own ideas but also to utilize and incorporate the ideas shared by their partners, to enhance the group performance. (Rhee 2007). Summarily, the generated ideas would be more carefully attended to and more actively processed, thus, enabling the team members to explore ideas in new categories that the participants would not have considered while working on the task alone. This can lead to a more efficient interactive process (Paulus and Yang 2000; Gilson and Shalley 2004; Van Knippberg et al. 2004; Vera and Crossan 2005; Hargadon and Bechky 2006; Shin and Zhou 2007). In our study, we did observe higher behavioral index of cooperation in the cooperation mode as compared with the competition mode, which further corroborates the positive effects of cooperation mode on the group performance. Moreover, to rule out the possibility that the difference in fluency between different interaction modes could be attributed to the variations in "frequency of speaking" (dyad's chances to report), we calculated the frequency of speaking by summing up the participants' chances to report in each dyad. Two-way mixed-design ANOVA using task as the between-subject factor and interaction mode as the within-subject factor was performed on the frequency of speaking. Results showed no significant main effect or interaction effect (Ps > 0.05), thus ruling out the effect of the frequency of speaking on the lower fluency observed in the competition mode.

Concerning the competition mode, we propose that restricted communication, namely a less efficient interactive process, might account for the significantly poorer creative performance of dyads in the competition mode (Deci et al. 1981; Amabile 1982; McGlynn et al. 1982). On the one hand, to avoid being outperformed, individuals may be less willing to share their ideas (especially the unique ones) at an early stage during the task; thus, preventing the ideas from being utilized by the opponents to generate more creative ideas of their own. On the other hand, to outperform others, individuals may be more reluctant to support and build upon others' ideas. For instance, if one participant reports an idea "A," the opponent may try to generate other more creative ideas rather than spend time on building upon "A" (McCain 1991; Johnson 2003; Anderson et al. 2007).

The fNIRS results showed increased IBS in the r-DLPFC and r-TPJ in the AUT/cooperation condition. The increased IBS in the r-DLPFC and r-TPJ could positively predict behavioral indices of cooperation (see details in the Supplement (S5)). Previous studies have shown that increased IBS is generally associated with mutual understanding between individuals and can be interpreted as an interpersonal neural marker for an efficient interpersonal interaction process (Funane et al. 2011; Cui et al. 2012; Dommer et al. 2012; Holper et al. 2013; Osaka et al. 2014; Cheng et al. 2015; Tang et al. 2016; Dikker et al. 2017; Ikeda et al. 2017). In this study, since the participants in each dyad were unknown to each other prior to the study, the possibility of IBS being influenced by prior familiarity or emotional factors was ruled out. Therefore, the observations of increased IBS, along with the outcomes above, might indicate that the dyads in the AUT/cooperation condition experienced more effective interpersonal interaction, as compared with the other groups.

The increased IBS observed in the AUT/cooperation condition could be roughly mapped to the r-DLPFC (PFC, CH17), and was significantly higher than that in the AUT/competition condition (Fig. 3). The r-DLPFC is known to be associated with creativity-related cognitive functions, including cognitive control, working memory and goal maintenance (Macdonald et al. 2000; Miller and Cohen 2001; Sanfey et al. 2003; Knoch et al. 2009; Silton et al. 2010; Sai et al. 2014), monitoring responses, and top-down inhibition of prepotent ideas, as well as task-irrelevant stimuli (Jahanshahi et al. 2000; Petrides 2000; Miller and Cohen 2001; Mansouri et al. 2007, 2009; Nachev et al. 2008; Anticevic et al. 2012). In addition, previous studies showed that the PFC, especially the DLPFC, is recruited during the suppression of "ego-centered" behavior (Baeken et al. 2010) and commitment in significant relationships (Petrican and Schimmack 2008). In the present study, we found a higher level of the behavioral index of cooperation in the AUT/cooperation condition. Moreover, increased IBS in r-DLPFC positively predicted the behavioral indices of cooperation in the AUT/cooperation condition (see details in Supplement (S5)). This may indicate that the individuals in the AUT/cooperation condition possibly paid more attention to the ideas of their partners, made more of an effort to renounce their ego-centric thoughts, and had a higher interest in cooperating with their partners.

Increased IBS was also observed in the angular gyrus (AG) (r-TPJ, CH10; CH14) in the AUT/cooperation condition, and was found to be significantly higher than that in the AUT/competition condition (Fig. 4). Several studies have shown that the

r-TPJ is recruited during social cognitive processes, such as reading characters' minds (Saxe and Powell 2006) and mediating joint attention of individuals (Redcay et al. 2010). In addition, AG is also involved in the Theory of Mind (ToM), which emphasizes the importance of perspective-taking in social interactions. Perspective-taking has also been suggested as an important mechanism for unlocking team creativity in diverse teams (Hoever et al. 2012). Moreover, increased IBS in the AG positively predicted the behavioral indices of cooperation in the AUT/cooperation condition. Accordingly, increased IBS observed in the AG may in part denote that the individuals attempted to understand, improve on and build upon his/her partner's ideas during AUT. However, further study should be carried out to explore the precise significance of IBS observed in these 2 brain regions (i.e., r-DLPFC and r-TPJ).

It should be noted that no significant increase in the IBS (task-baseline) was observed in both, OCT/cooperation condition, as well as OCT/competition condition. We propose that since the goal of the participants during OCT was to generate typical characteristics of an everyday object, attributes like idea combination or building upon others' ideas were not required for better task performance. Consequently, the efficiency of the interaction process between individuals might be quite low while they engaged in OCT together, even if they were asked to cooperate with each other. In addition, increased IBS in the r-DLPFC in the AUT/cooperation condition could positively predict AUT fluency and cooperation. Increased IBS in r-TPJ in the AUT/cooperation condition could positively predict cooperation. Moreover, IBS in r-DLPFC and r-TPJ in the AUT/cooperation was significantly higher than that in the AUT/competition and OCT/cooperation conditions. However, no significant difference was observed between OCT/cooperation and OCT/competition conditions. This may imply that increased IBS in r-DLPFC and r-TPJ observed in the present study is specifically associated with the effect of cooperation on group creative performance.

The object characteristics task (OCT) has been commonly used as a control task in the neuroimaging studies involving creativity. However, these studies usually conducted much shorter trials as compared with the current study (5 min). Therefore, in order to rule out the possibility that the neural differences could be due, in part, to sustained task engagement during the AUT versus the OCT, we investigated whether sustained task engagement affected these tasks. Considering that the time duration till the last idea was reported may reflect the dyads' persistence in each task, we compared the duration between the AUT and OCT and found no significant difference between AUT and OCT conditions. These results partly ruled out the possibility of the neural difference being a result of sustained task engagement during the AUT versus the OCT (see details in Supplement S3). Nevertheless, trials with shorter duration might be more insightful for future hyperscanning based studies on group creativity.

Interestingly, significantly higher IBS from CH combinations between PFC and r-TPJ, which was affected by task or interaction mode, was observed in the AUT/cooperation condition (PFC3–r-TPJ10, PFC8- r-TPJ10, PFC17–r-TPJ3, PFC18–r-TPJ10). PFC3 and PFC8 are located in the frontopolar cortex, while PFC17and PFC18 are located in the r-DLPFC. Further, TPJ3 can be mapped to the posterior middle temporal gyrus (MTG) and TPJ10 to the AG. It implies that a significant increase in IBS was observed between the frontopolar cortex/r-DLPFC and AG, as well as between r-DLPFC and posterior MTG in the AUT/cooperation condition. Moreover, simple effect analyses on the IBS further validated the observations of higher IBS in the AUT/

cooperation condition as compared with the AUT/competition condition, while no difference was observed between OCT/cooperation and OCT/competition conditions (see details in Supplement (S4)). This may indicate that the IBS was also specifically associated with the effect of cooperation on group creative performance. Previous studies have implicated that the frontopolar cortex is involved in cognitive processes essential for successful communication, including mentalizing, understanding others' beliefs and intentions, and multitask coordination (Amodio and Frith 2006; Gilbert et al. 2006; Stephens et al. 2010). Nozawa et al. (2016) also reported a significant increase in IBS in the frontopolar cortex, during cooperative verbal communication. Accordingly, IBS between the frontopolar cortex/r-DLPFC and AG may be interpreted as arising from high-level social processing during cooperative communication. Moreover, MTG has been implicated as pivotal to extensive semantic processing and forming remote associations (Shen et al. 2017). We propose that the IBS between r-DLPFC and right posterior MTG may reflect the efforts of the team members towards forming remote associations between the partner's ideas and their own semantic network in the AUT/cooperation condition. However, its exact significance must be further explored.

The use of fNIRS in hyperscanning studies has been widely accepted as a promising technique to unveil the interpersonal neural correlates in the context of social interactions. However, the limitations of the fNIRS should be noted. Primarily, physiological activities in the peripheral system, including respiration and cardiac pulsation, as well as the low-frequency oscillations (Mayer wave) can contaminate fNIRS signals (Cui et al. 2012; Dommer et al. 2012; Cheng et al. 2015). To eliminate these potential sources of noise, we performed hrf low-pass filtering and Wavelet-MDL detrending algorithm on the raw data during preprocessing (Jang et al. 2009; Ye et al. 2009; Brigadoi et al. 2014; Tang et al. 2016). In addition, since the frequency bands lower than 0.2 Hz in the frontal cortex are associated with cognition-related NIRS activity (Cui et al. 2012; Jiang et al. 2012; Duan et al. 2013; Cheng et al. 2015), we deemed that IBS observed in this study should be independent of the aforementioned noise. Further, Nozawa et al. (2016) reported that removal of the skin blood flow component improves the sensitivity to communication-enhanced IBS. However, since our system was not equipped to measure the skin blood flow component, we were unable to account for its effect on the fNIRS signals in the present study. For future investigations, removal of Skin blood flow should be considered to explore the communication-enhanced IBS more precisely. Furthermore, changes in HbR can also be recorded by fNIRS, which might provide additional information (Zhang et al. 2016; Pan et al. 2017). However, considering the higher sensitivity of HbO to changes in cerebral blood flow during fNIRS measurements, we primarily focused on the changes in HbO during our analysis (Hoshi 2007; Ou et al. 2009; Cui et al. 2012).

The study has several additional limitations. Primarily, the small sample size in this study, especially for the group-wise correlation analyses, might have increased the false positive rate and given rise to inflated effect sizes (Yarkoni 2009; Button et al. 2013). Therefore, larger sample sizes should be considered in future hyperscanning studies concerning group creativity. Moreover, although divergent thinking is central to creativity, it fails to encompass all the attributes of creativity. Hence, the other aspects of creativity should also be assessed in future studies. Further, during task periods, the participants interacted with their eyes open, while during the baseline-rest, they sat with their eyes closed. Since the eye contact between

individuals may serve as a basic mode of interpersonal interaction, a baseline-rest condition where participants are asked to keep their eyes open may be able to unveil underlying interpersonal brain synchrony that is specific to the effects of interaction mode and task, by ruling out the differences in interpersonal brain synchrony underlying the eye contact. Therefore, an eyes-open baseline-rest condition should be considered in future studies on interpersonal interaction. In addition, previous studies have reported the effect of gender composition on the relationship between neural coherence and behavior (Baker et al. 2016). In this study, the effect of gender composition was also observed on IBS of several CH combinations (see details in the Supplement (S6)). The effect of gender on IBS during brainstorming should be investigated in future studies. Finally, in addition to the derivative behavioral measure of cooperation used in this study, it may be informative to inquire about the subjective feelings of participants on whether the cooperation was productive, in future studies.

Supplementary Material

Supplementary material is available at *Cerebral Cortex* online.

Funding

Notes

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