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# Cooperation makes two less-creative individuals turn into a highly-creative pair

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ABSTRACT

This study aimed to investigate which type of group (e.g., consisting of less-creative or highly-creative individuals) would perform better in solving creativity problems, and explore the underlying inter-brain neural correlates between team members. A preliminary test (an alternative-uses task) was performed to rank individuals' level of creativity, and divide participants into three types of dyads: high-high (two highly-creative individuals), low-low (two less-creative individuals), and high-low (one highly-creative and one less-creative individual). Dyads were then asked to solve a realistic presented problem (RPP; a typical creativity problem) during which a functional near-infrared spectroscopy (fNIRS)-based hyperscanning device was used to record the variation of interpersonal brain synchronization (IBS). Results revealed that less-creative individuals, while working together, would perform as well as highly-creative individuals. The low-low dyads showed higher levels of cooperation behaviour than the other two types of dyads. The fNIRS results revealed increased IBS only for low-low dyads at PFC (prefrontal cortex) and rTPJ (right temporal-parietal junction) brain regions during RPP task performance. In the rDLPFC (right dorsolateral prefrontal cortex), the IBS in the low-low dyads was stronger than that of high-high and high-low dyads. In the rTPJ, the IBS in the low-low dyads was only stronger than that of the high-low dyads. Besides, the IBS at rDLPFC and rTPJ regions in the low-low dyads was positively correlated with their cooperation behaviour and group creative performance. These findings indicated when two less-creative individuals worked on a creativity problem together, they tended to cooperate with each other (indicated by both behaviour index and increased IBS at rDLPFC and rTPJ), which benefited their creative performance.

## Introduction

In Chinese, there is a proverb that says: "Three stooges, one Zhu Geliang". The proverb means that by working together, even individuals with lower ability ("stooges") are capable of generating solutions as creative as someone with high ability ("Zhu Geliang," – a chancellor during the Three Kingdoms period of China widely recognized as one of the greatest and most accomplished strategists of his era). Creativity is defined as the ability to produce work that is novel (i.e., original and unique) and useful (Runco and Acar, 2012; Sternberg and Lubart, 1996). Group creativity is necessary for social development, and is garnering increasing attention from both scientists and entrepreneurs (Dunbar, 1995; West and Anderson, 1996).

Inspired by the Chinese proverb above, we sought to investigate whether putting individuals with different levels of creativity together would influence the overall creativity of the group's performance. Specifically, the goal of this study was to explore whether less-creative individuals would tend to cooperate in solving problems demanding high levels of creativity and catch up to the creative performance of highly-creative individuals.

The level of creativity of the individual members has been recognized as one of the pivotal factors that influences the creativity of the group (Burningham and West, 1995; Pirola-Merlo and Mann, 2004; Taggar, 2001, 2002). In 1995, Burningham and West proposed that the creativity of the group was determined by the proportion of creative individuals that made up that group. Similarly, Pirola-Merlo and Mann (2004) suggested that team creativity at a particular time point could be calculated by either the average or a weighted average of team member-creativity. Furthermore, Taggar (2001, 2002) demonstrated that groups made up of more creative members and higher levels of creativity-relevant

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behaviours produced higher overall group creativity. Therefore, it seems reasonable to speculate that the more highly-creative members a group contains the more creative potential the group will have.

However, Harvey (2014) suggested that the creative performance of a group depends on their ability to integrate both cognitive resources of the individual members (i.e., their ability to generate ideas) as well as social resources (interaction among individuals) while performing creative tasks. This implies that the creative performance of a group is not dependent solely on the creativity of the individual members. On the contrary, effective cooperation among team members is necessary so that individuals can use their partners' social resources.

Many researchers have found a beneficial effect of a cooperation goal on achievement in groups (Johnson et al., 1981; Roseth et al., 2008). Cooperation has also been shown to exert beneficial effects on creative performance (Amabile, 1996; Bittner and Heidemeier, 2013; Carnevale and Probst, 1998). For example, a recent study showed that participants with a cooperation goal and a promotion focus demonstrated the highest level of originality of ideas (Bittner et al., 2016). The theory is that better cooperation leads to a more efficient interactive process (i.e., sharing ideas with others, supporting others' ideas, building upon others' ideas, motivating others), which in turn, leads to a more creative performance for the whole group (Rhee, 2007).

Effective cooperation was thought to be based on the intelligibility of resources that are provided by team members. For example, Leggett Dugosh and Paulus (2005) found that, in addition to the unique ideas provided by their partners, participants' exposure to a large set of common (i.e., non-creative) ideas would enhance creative performance. Similarly, in a functional magnetic resonance imaging study, Fink et al. (2012) investigated the effect of cognitive stimulation on creativity via exposure to other people's ideas. Results found that common or moderately-creative ideas were more effective in improving creativity than highly-creative ideas. These findings suggest that the intelligibility of an idea, regardless of its level of creativity, may account for their benefits. Namely, when exposed to common ideas, the ideas are easier to understand, making it easier for them to search for potential related connections. Thereafter, individuals could generate more creative ideas by improving the existing ones, or by combining these ideas with their own knowledge. Conceivably, because less-creative individuals tend to generate more common ideas (i.e., less unique than those of highly-creative individuals), their ideas may be more easily understandable to their partners. This implies that less-creative individuals may contribute to group cooperation by producing more ideas that are more easily understood.

So far, the question about which type of dyad (i.e., dyads comprising less-creative or highly-creative individuals) is better at solving creativity problems is still under debate. Based on the correlation that exists between the creativity of the individual and creativity of the group (Pirola-Merlo and Mann, 2004; Taggar, 2001, 2002), one would predict that dyads consisting of highly-creative individuals would outperform dyads consisting of less-creative individuals. However, given that less-creative individuals may provide ideas that are more easily understood by their partners, and that cooperation is key to the creative performance of a group (Amabile, 1996; Bittner and Heidemeier, 2013; Carnevale and Probst, 1998), it would be inferred that dyads consisting of less-creative individuals might perform as well as those consisting of highly-creative ones.

In this study, we aimed to compare the creative performance of different groups (i.e., consisting of less-creative or highly-creative individuals) and reveal the underlying inter-brain neural correlates by means of fNIRS hyperscanning device. We particularly addressed two questions. First, "Do dyads consisting of less-creative individuals perform equally well on creativity tasks as those consisting of highly-creative individuals? Is the finding of equal creative performance attributed to the higher level of cooperation between less-creative individuals?" Second, "Does interpersonal brain synchronization (IBS) between team members show different patterns in various groups, which may reflect different levels of group cooperation?"

Recently, hyperscanning, which can be conducted with fMRI (Chiu et al., 2008; Li et al., 2009), EEG (Lindenberger et al., 2009), and fNIRS (Tang et al., 2016), has been applied to the field of social interactions (Cheng et al., 2015; Cui et al., 2012; Jiang et al., 2012). Studies using these techniques have identified evidence of interpersonal synchronized brain activities during dyadic interactions in some brain regions. In the current study, we adopted the fNIRS-based hyperscanning device, which offers advantages of obviating the need for calibration (required by fMRI and EEG hyperscanning studies) and a higher tolerance for motor artifacts, to explore interpersonal brain interactions between team members while engaging in problem-solving tasks demanding creativity.

In previous studies, the prefrontal cortex (PFC) has been associated with social cognition, reward system, decision-making, and goal maintenance (Kringelbach and Rolls, 2004; Miller and Cohen, 2001; Rushworth et al., 2011). In particular, the PFC is recruited during tasks involving learning about reward associations, selecting goals, choosing actions, and deliberating the potential value of switching (Rushworth et al., 2011). Moreover, the right temporal-parietal junction (rTPJ) is recruited in tasks involving semantic and number processing, reading and comprehension, conflict-resolution, spatial cognition, and more (Seghier, 2013). In the literature of social cognition, the rTPJ is consistently reported as an activated region (Decety and Lamm, 2007). Additionally, numerous neuroimaging studies have observed involvement of the bilateral angular gyrus (AG) in tasks demanding theory-of-mind or mentalizing (Mar, 2011; Spreng et al., 2009).

In addition, in the field of social interaction, the PFC, orbito-frontal cortex, right DLPFC and rTPJ have been implicated as brain regions important for tasks involving cooperation and social interaction (Baker et al., 2016; Chaminade et al., 2012; Cui et al., 2012; Decety et al., 2004; Decety and Lamm, 2007; Desmurget et al., 2009; Dumas et al., 2010; Mccabe et al., 2001; Suzuki et al., 2011). Recent hyperscanning studies report increased interpersonal brain synchronization (IBS) in the medial PFC, DLPFC, superior frontal cortex, and rTPJ between individuals while they were in the cooperation state (Cheng et al., 2015; Cui et al., 2012; Dommer et al., 2012; Funane et al., 2011; Nozawa et al., 2016; Tang et al., 2016). Similarly, increased IBS was also revealed in studies of social interaction activities, including face-to-face communication between partners (Jiang et al., 2012), group humming (Osaka et al., 2014), teaching-learning interactions (Holper et al., 2013), and coordinated walking (Ikeda et al., 2017). In light of these findings, we hypothesized that IBS in the PFC and rTPJ (assessed by hyperscanning) could be indicators for the state of cooperation between members in dyads.

Moreover, neuroscience studies in the field of creativity have revealed that the PFC and rTPJ play pivotal roles in cognitive processing during creative-tasks (Beaty et al., 2016; Benedek et al., 2014; Goel et al., 2015; Kleibeuker et al., 2013; Wu et al., 2015). For instance, it has been reported that the PFC (particularly the dorsal PFC) plays a key role in working memory and executive function systems, both of which are associated with creativity (Heinonen et al., 2016; Vartanian et al., 2014). In addition, the rTPJ has been identified as an important region for attention control, memory cues and perspective-taking, each of which can contribute to creative performance (Benedek et al., 2014; Fink et al., 2010, 2012; Fink et al., 2009b; Goel et al., 2015). Therefore, in this study, the PFC and rTPJ were chosen as the regions of interest to investigate inter-brain neural correlates while dyads engaging in creative activity.

To study this, in this study we created three types of dyads, which consisted of (1) two highly-creative individuals (high-high dyads), (2) two less-creative individuals (low-low dyads), or (3) a combination of a highly-creative and a less-creative individual (high-low dyad, which we used as a control group). During the study, we asked these three types of dyads to solve creativity problems. Participant's responses were recorded with a digital recording pen, and the brain synchronization data was recorded using fNIRS.

In this study, we predicted that: (1) low-low dyads would show higher levels of cooperation-related behaviours and exhibit similar levels of creativity as other types of dyads, and (2) that the low-low dyads would show stronger IBS in PFC and rTPJ brain regions than other types of dyads, which may reflect higher levels of cooperation. Furthermore, we measured participants' emotional state, task-enjoyment, and task-difficulty, because these variables were found to affect creative performance (De Dreu et al., 2008; Yang and Hung, 2015; Chae et al., 2015a,b; Zenasni and Lubart, 2011). We also measured participants' cooperative tendency using scores on the Group Preference Scale (Larey and Paulus, 1999). These measures allow us to check whether the effect of group composition (i.e., consisting of highly-creative or less-creative individuals) on group creative performance were independent from the factors mentioned above.

## Methods

### *Participants*

A total of 90 college students (mean age: 20 ± 2.13 years old) took part in the study, including 62 females and 28 males. All participants were right-handed with normal or corrected-to-normal vision. They were assigned as dyads to perform experimental tasks according to their level of creativity (see details in the following section). In each dyad, participants were unknown to each other. From the 90 participants, 30 dyads were created. Prior to participating, each participant signed informed consent and was paid ¥70 for their time and effort. The study procedure was approved by the University Committee on Human Research Protection (UCHRP) of East China Normal University.

### *Construction of three types of groups*

Participants first completed an Alternative Uses Task (AUT) problem (Guilford, 1967). In the AUT, participants were asked to think of as many alternative uses for everyday objects as possible. During the task, participants were encouraged to “try their best to produce ideas that would be thought of by no one else” (Fink et al., 2009b; Hao et al., 2017; Harrington, 1975). The AUT is a well-established divergent thinking task, and is widely-used in behavioural and neuroscience studies on creativity (Fink et al., 2009a; Hao et al., 2017; Runco and Mraz, 1992; Runco and Okuda, 1991; 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).

In this study, participants were asked to solve one AUT problem in 5 min. Afterwards, according to the participant's fluency scores on the AUT problem (see the section “Assessment of performance on the AUT and RPP” below), participants were divided into high and low creativity groups. To do this, participants were marked with a number ranging from 1 to 90 which indicated the level of their creativity. In the high-low dyads, participants ranging from 1 to 10 (i.e., highly-creative) were paired with individuals with fluency scores ranging from 81 to 90 (i.e., less-creative) (e.g., the No. 1 participant was paired with the No. 81

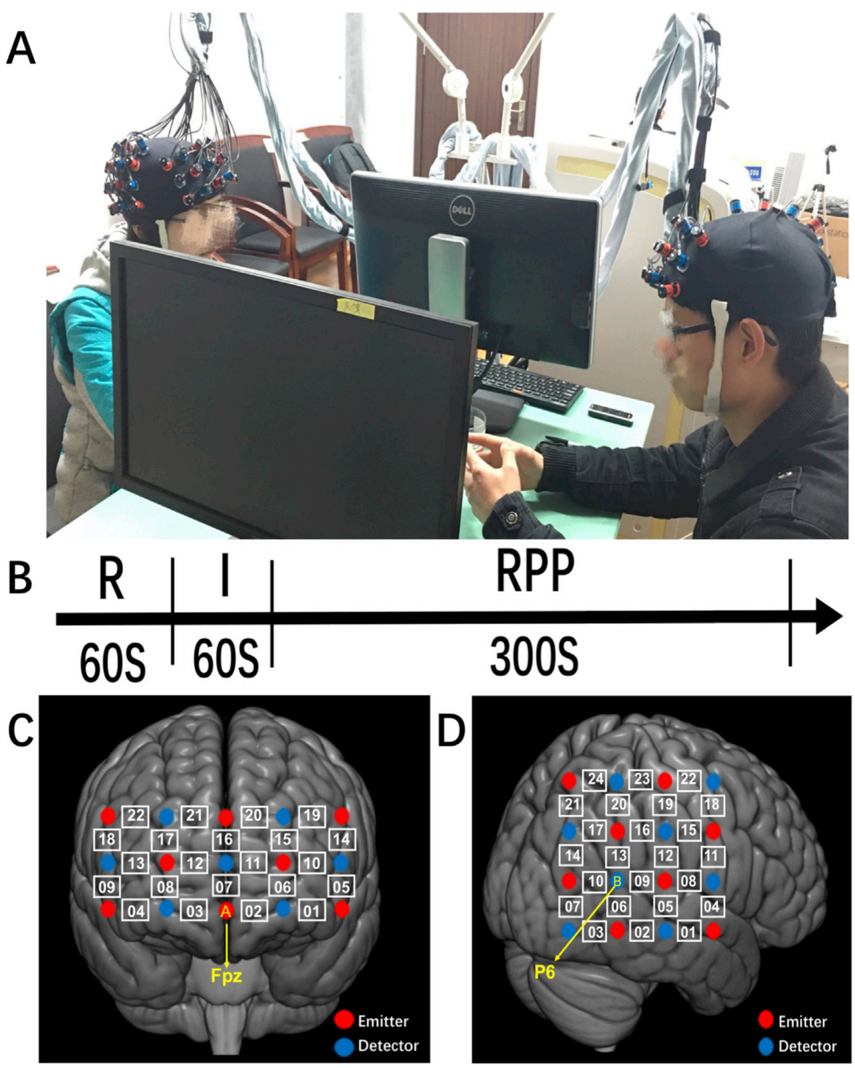


**Fig. 1.** Experimental design. (A) Experimental setup. (B) Task design. -(R)- the resting state session; -(I)- the instructions of the task and brainstorming rules; -(RPP)- Realistic presented problem task session. (C) The 3*5 optode probe set. The 3*5 patch was placed on the prefrontal cortex. (D) The 4*4 optode probe set. The 4*4 patch was placed on the right temporal-parietal junction.

participant; the No. 2 participant was paired with the No. 82 participant, etc…). In the low-low dyads, participants with fluency scores ranging from 61 to 79 were paired with participants with fluency scores ranging from 62 to 80 (i.e., the No. 61 participant was paired with the No. 62 participant). In the high-high dyads, participants with fluency scores ranging from 11 to 29 were paired with participants with fluency scores ranging from 12 to 30 (i.e., the No. 11 participant was paired with the No. 12 participant) (see Figure S1).

Given that the creativity of participants ranging from 31 to 60 was moderate, these participants were excluded from the subsequent experiment. A total of sixty ($n = 60$) participants (43 females and 17 males; mean age: 21 ± 1.4 years old) participated in the subsequent experiment.

### Experimental tasks and procedures

In each dyad, the two participants sat face-to-face (see Fig. 1A). The experimental procedure consisted of a 1-min resting-state session and a 5-min task session. The initial 1-min resting-state session served as a baseline (see Fig. 1B). During this session, participants were asked to remain as still as possible, with their eyes closed and their mind relaxed (Lu et al., 2010). The instructions of tasks and rules of brainstorming (i.e., deferment of judgment, quantity breeds quality, free-wheeling is encouraged, and combination and improvement are sought) were then introduced.

Each dyad was required to solve a Realistic Presented Problem (RPP) (Agnoli et al., 2016; Hao et al., 2017; Runco et al., 2016). In the RPP, participants were asked to generate as many solutions as possible to solve the open-ended realistic problems. The "concert problem" used in this study was as follows: "*You go to a concert, but it is right after school, so you tell your friend that you will meet them there at their seats. The tickets are at the Will Call window, outside of the concert hall. When you arrive and give your name, the person working at that window says 'The concert just started, and your friend is there already. Do you have identification?' You realize that you have forgotten your wallet and ID! What are some things you could do to get your ticket and see the show?*" In the task section, participants were asked to answer in turn and report one idea or potential solution at a time. If they could not obtain any idea during their turns, they were allowed to say "pass" and report their ideas during the next turn.

### Pre- and post-experiment tests

Prior to the experiment, participants' cooperative tendency was measured using scores on the Group Preference Scale (GPS) (Larey and Paulus, 1999). The GPS has 10 items which are scored on 5-point Likert scale ranging from 1 ("not at all") to 5 ("very much"). In the current study, the internal consistency reliability of the GPS was satisfactory (Cronbach's $\alpha = .83$). The valence and arousal of participants' emotional state was measured using scores on the Self-Assessment Manikin (SAM) (Bradley and Lang, 1994). Both valence and arousal were rated on a 1 to 9 scale (valence: 1 = very unpleasant, 9 = very pleasant; arousal: 1 = not exciting at all, 9 = very exciting), which is illustrated by five cartoon figures with points listed between the two figures.

Immediately following the experiment, participants were asked to rate the valence and arousal of their emotional state again. To assess the participants' enjoyment while they worked on the creativity tests/tasks, we developed an Enjoyment Task Scale. The scale had five 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"; (5) "I disliked performing the test (contradictive item)". Items on the Enjoyment Task 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' enjoyment of the task. The reliability of the Enjoyment Scale in the present study was satisfactory (Cronbach's $\alpha = .88$). In addition, participants were also asked to rate the difficulty associated with performing the task by answering the question "I think this test was difficult for me" on a scale from 1 ("not at all") to 7 ("very much"). No discussion was allowed during the rating session.

### Assessment of performance on the AUT and RPP

Participants' performance on the AUT and RPP was measured using the (1) fluency and (2) originality of their ideas (Guilford, 1967; Runco and Okuda, 1991). The fluency of participant's ideas was based on the total number of ideas that each participant generated. The originality of participant's ideas was assessed using a subjective method. Five trained raters independently assessed the originality of each idea reported by the participants on a 5-point Likert scale (1 = not original at all, 5 = highly original). The inter-rater agreement of this method was satisfactory (Internal Consistency Coefficient, ICC = .83). Individual ratings for each idea from each of the five raters were averaged into a single originality score for each idea. Finally, a mean originality score for all of the ideas that a participant produced during the AUT or RPP was calculated.

### Behavioral index of cooperation between partners in a pair

Combination of ideas was measured as the behavioural index for cooperation between partners in each dyad. To do this, first, two trained raters independently assessed the total number of categories for ideas reported by each dyad. The inter-rater agreement for this method was satisfactory (ICC = .93). Then, the number of idea-categories generated by each dyad was calculated by averaging the two raters' ratings for each dyad. Finally, "Combination of ideas" was calculated by "Group fluency score/Number of idea category". This definition of "combination of ideas" suggested the extent to which the dyad explored ideas in a single category. Namely, the more team members cooperated with one another, the more improvement and combination of ideas would occur. These improved (or combinative) ideas should be recognized as the responses in the same category. Therefore, such an index would reflect the extent to which group members combined their ideas on each other, and indicate to what degree 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 prefrontal and temporal-parietal junction regions, based on previous studies showing group creativity and social interaction (e.g., cooperation) involved prefrontal and right temporal-parietal conjunction regions (Benedek et al., 2014; Cheng et al., 2015; Decety et al., 2004; Funane et al., 2011; Goel et al., 2015; Heinonen et al., 2016; Sun et al., 2016; Tang et al., 2016). One 3*5 optode probe set (eight emitters and seven 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 exactly 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 the cerebral cortex (see Fig. 1C and D) (Singh et al., 2005; Tsuzuki et al., 2007).

### Interpersonal brain synchronization (IBS)

Based on the modified Beer–Lambert law, both HbO and HbR have been used to measure changes in cerebral blood flow. However, we chose the HbO signal as our index since most scholars have demonstrated it was more sensitive to changes in cerebral blood flow (Hoshi, 2007; Jiang et al., 2012).

For each dyad, data were preprocessed with hrf low-pass filtering, and Discrete cosine transform (DCT), based detrending algorithm in NIRS-SPM (Ahmed et al., 1974; Ye et al., 2009). By applying low-pass filtering, the temporal autocorrelation in NIRS data can be corrected. Meanwhile, a DCT-based detrending algorithm was used to remove an unknown global trend due to breathing, cardiac, vaso-motion or other experimental errors. Next, wavelet transform coherence (WTC) was used to calculate the relationship between HbO time series for each dyad (Grinsted et al., 2004).

Resting-state fMRI studies show that the low-frequency oscillations (typically in the range of 0.01–0.1 Hz) are more reliable markers of within-brain neuronal synchronization than higher frequencies (Achard et al., 2006; Zuo et al., 2010). In addition, increased neuronal synchronization has been observed in natural communication in the aforementioned frequency band (Jiang et al., 2012). According to these findings, we tested difference in time-averaged WTC values between task session and resting session at each period in [10,100] s (0.01–0.1 Hz) for all channels (Nozawa et al., 2016). A false discovery rate (FDR) adjustment was applied for the multiple-comparisons. Significantly changed IBS (task session - resting session) was observed in these timescales: 11.8–42.0 s, 49.9–52.9 s, and 84.0–100 s (FDR corrected, $ps < 0.05$). Considering that the duration of one cycle in the task (the elapsed time from the beginning of Participant 1's report to the end of participant 2's report) ranges from 14 to 50 s and visual inspection on WTC graph indicates the frequency band between 12.8 and 51.2 s (see Fig. 2C and D), the frequency band between 12.8 and 51.2 s was chosen as the target frequency band in the present study. Increased IBS in the similar frequency band has been successfully observed in one of the previous studies on social interaction (Tang et al., 2016). Moreover, the selection of this band enables the removal of high and low-frequency artificial noises, such as those related to respiration (about 0.2–0.3 Hz) and cardiac pulsation (0.7–4 Hz). Then average coherence value (IBS) in this band in the brainstorming session was computed to subtract the average coherence in the resting-state session, and the IBS values were converted to Fisher *z*-statistics (Chang and Glover, 2010; Cheng et al., 2015; Cui et al., 2012). A one-sample *t*-test with false discovery rate (FDR) correction across all CHs ($p < 0.05$) was calculated. The *t*-maps of IBS would be generated and smoothed by the spline method. If a channel was found with significant IBS, a one-way ANOVA analysis was performed on that IBS with Group as between-subject factor (high-high, high-low and low-low). Post-hoc Bonferroni correction was used to account for multiple comparisons. Finally, bivariate Pearson correlations between IBS and creativity scores were computed to reveal brain-behaviour relationship.

## Results

### *Validity of group construction*

One-way ANOVAs with Group (i.e., low-low, high-high and high-low dyads) as the between-subject factor were performed on the AUT fluency and originality scores in the preliminary test. Results demonstrated a significant main effect of Group on fluency ($F$ (2, 27) = 10.71, $p < .001$, $\eta_p^2 = .44$), with lower AUT fluency in the low-low dyads ($M = 8.5$, $SD = 1.5$) than in the high-low dyads ($M = 13.5$, $SD = 4.5$) and high-high dyads ($M = 14.6$, $SD = 2.6$) (see Fig. 3A). The main effect of Group was also found significant on AUT originality ($F$ (2, 27) = 17.35, $p < .001$, $\eta_p^2 = .56$), with lower originality among low-low dyads ($M = 1.40$, $SD = .41$) than high-low dyads ($M = 2.29$, $SD = .47$) and high-high dyads ($M = 2.36$, $SD = .33$) (see Fig. 3B).

Results of a separate analysis using one-way ANOVA found no difference in AUT fluency and originality among the highly-creative participants in the high-low dyads and high-high dyads. Similarly, results showed no difference in AUT fluency or originality between less-creative participants in the high-low dyads and low-low dyads (see Fig. 3A and B). These results support the validity of our group construction.

### *Performance on RPP in three groups*

One-way ANOVAs using Group as the between-subject factor were performed on the RPP fluency and originality scores. Results found no significant effect of Group on RPP fluency or RPP originality (see Fig. 3C and D). In addition, the main effect of Group on RPP fluency or RPP originality remained insignificant after other variables (i.e., emotional state, cooperation tendency, the enjoyment of task and the difficulty of task) were entered into the ANOVA model as covariates. These results indicate that while working together, less-creative individuals performed as well as dyads consisting of highly-creative individuals.

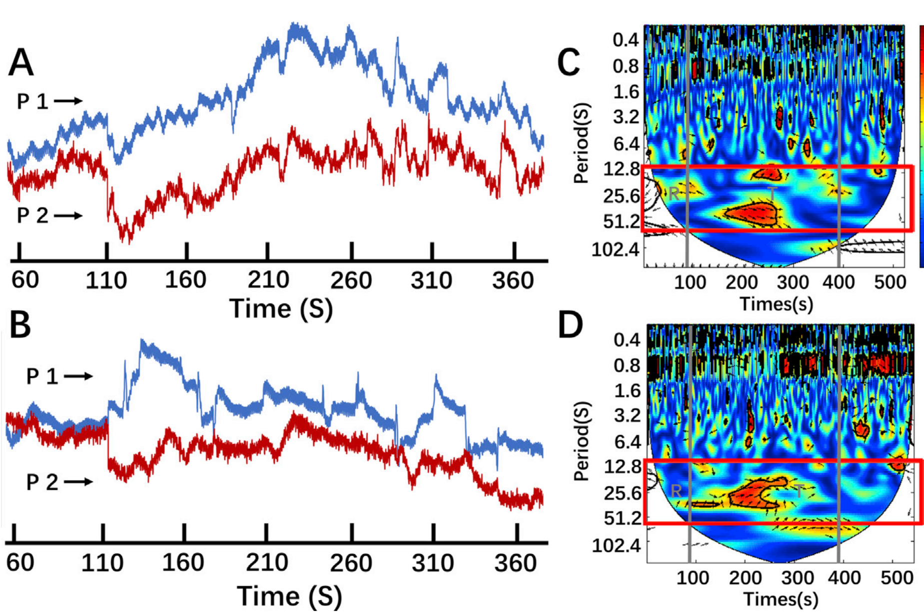


**Fig. 2.** Frequency band of interest. Interpersonal brain synchronization (IBS) indicated by wavelet transform coherence (WTC). (A) Raw HbO time courses. Raw HbO time courses of Participant 1(P1) (blue) and Participant 2 (P2) (red) in the RPP from channels in PFC in the low-low dyads (i.e. raw HbO time courses in Channel21 of P1 and P2 in a representative dyad). (B) Raw HbO time courses. Raw HbO time courses of P1 (blue) and P2 (red) in the RPP from channels in rTPJ in the low-low dyads (i.e. raw HbO time courses in CH9 of P1 and P2 in a representative pair). (C) The WTC in the PFC. The coherence based on raw HbO signal from CH17 in a representative low-low dyad. (D) The WTC in the rTPJ. The coherence based on raw HbO signal from CH9 in a representative low-low dyad. The red borders represent the frequency band of interest (12.8–51.2 periods). Also, the two gray lines indicated the beginning and end of the RPP task respectively. The color bars denote the value of WTC (1 = highest coherence, 0 = lowest coherence).

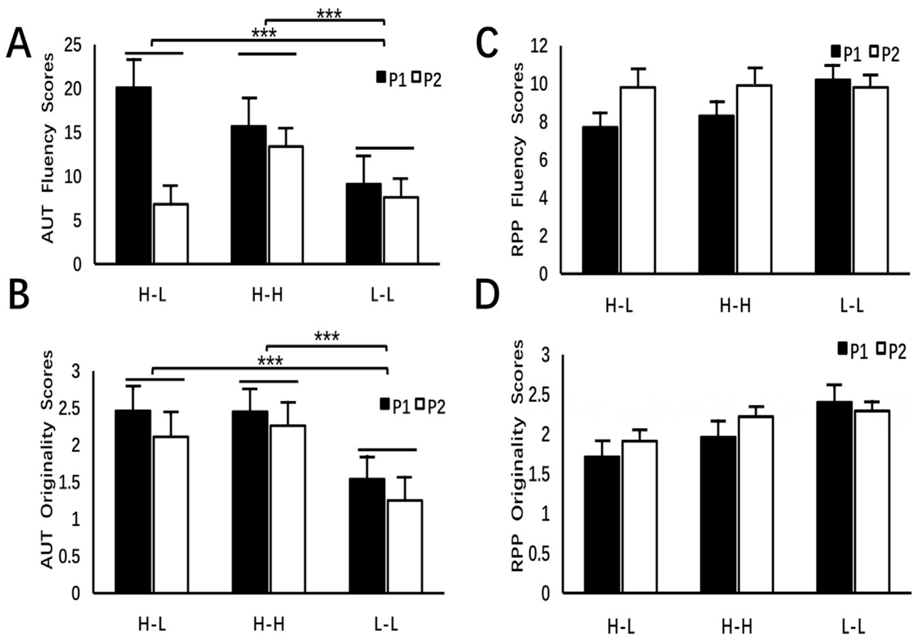


**Fig. 3.** Creative performance of nominal dyads in the preliminary test (AUT) and brainstorming dyads in the RPP task. (A) AUT fluency scores of nominal dyads in three groups. (B) AUT originality scores of nominal dyads in three groups. (C) RPP fluency scores of brainstorming dyads in three groups. (D) RPP originality scores of brainstorming dyads in three groups. Error bars indicate standard errors of the mean. P1 means participant 1, P2 means participant 2. ***p < 0.001.

*Behavioral index of cooperation in three groups*

One-way ANOVA with Group as the between-subject factor was performed on the behavioural indices of cooperation. Results demonstrated a significant main effect of Group on cooperation ($F$ (2, 27) = 4.27, $p = .024$, $\eta_p^2 = .24$). Post-hoc tests showed that the behavioural index of cooperation in the low-low dyads ($M = 1.74$, $SD = .48$) was higher than in the high-low dyads ($M = 1.36$, $SD = .22$) and high-high dyads ($M = 1.40$, $SD = .17$) (see Fig. 4A). Pearson correlations revealed a positive correlation between RPP originality scores and behavioural indices of cooperation in the low-low dyads ($r = .78$, $p = .007$) (see Fig. 4B). However, no similar correlation was found in the high-low or high-high dyads.

*Interpersonal brain synchronization (IBS) in three groups*

A series of one-sample $t$-tests were conducted on IBS across all channels in three groups. Significant differences in IBS were found at CH6 ($t$ (9) = 5.46, $p < 0.001$), CH17 ($t$ (9) = 3.52, $p < 0.001$), CH21 ($t$ (9) = 4.63, $p < 0.001$) in the PFC (see Fig. 5A) and CH9 ($t$ (9) = 5.34, $p < 0.001$) in the rTPJ in the low-low dyads (see Fig. 6A). All of these IBS remained significant after FDR correction ($ps < 0.05$).

In contrast, no significant difference in IBS was found either in the high-low or high-high dyads. One-way ANOVAs indicated that IBS at CH6 ($F$ (2, 27) = 6.89, $p = .004$), CH17 ($F$ (2, 27) = 6.04, $p = .007$) and CH21 ($F$ (2, 27) = 4.16, $p = .027$) in the PFC was affected by Group (see Fig. 5B). Post-hoc tests (Bonferroni corrected) revealed that IBS at CH6 was lower in the high-low dyads ($M = -.05$, $SD = .10$) than in the low-low dyads ($M = .10$, $SD = .08$, $p = .003$), and almost significantly lower (at $\alpha = 0.05$) than in the high-high dyads ($M = .05$, $SD = .10$, $p = .068$); IBS at CH17 was higher in the low-low dyads ($M = .09$, $SD = .08$) than in the high-low dyads ($M = -.05$, $SD = .09$, $p = .025$) and the high-high dyads ($M = -.07$, $SD = .15$, $p = .012$); IBS at CH21 was higher in the low-low dyads ($M = .09$, $SD = .14$) than in the high-high dyads ($M = -.07$, $SD = .07$, $p = .005$) (see Fig. 5C).

One-way ANOVA showed that IBS at CH9 ($F$ (2, 27) = 6.25, $p = .006$) in the rTPJ was also affected by Group (see Fig. 6B). Post-hoc tests (Bonferroni corrected) showed that IBS at CH9 was higher in the low-low dyads ($M = .14$, $SD = .08$) than in the high-low dyads ($M = -.03$, $SD = .08$, $p = .005$) (see Fig. 6C).

*The IBS-behavior relation*

Pearson correlations were performed on significant IBS at channels (PFC: CH6, 17, 21; rTPJ: CH9) and behavioural indices (e.g., RPP originality, behavioural index of cooperation) in the low-low dyads. Total originality of the group was positively correlated with IBS at CH17 in the PFC ($r = .85$, $p = .002$) and with the IBS at CH9 in the rTPJ ($r = .82$, $p = .003$) (see Fig. 7A and B). In addition, behavioural indices of cooperation showed significant, positive correlations with IBS at CH17 in the PFC ($r = .66$, $p = .038$) and with IBS at CH9 in the rTPJ ($r = .71$, $p = .022$) (see Fig. 7C and D). These results suggest a positive relationship between the increased IBS and cooperative behaviour.

## Discussion

In this study, we compared the creative performance of different dyads (i.e., consisting of less-creative and highly-creativity individuals)

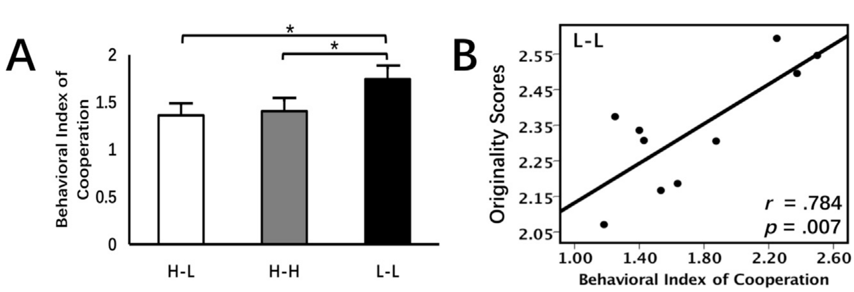


**Fig. 4.** Behavioral cooperation performance. (A) The behavioral indices of cooperation in three groups. (B) Correlation between the RPP originality scores and behavioral indices of cooperation in the low-low dyads. Error bars indicate standard errors of the mean. *p < 0.05.

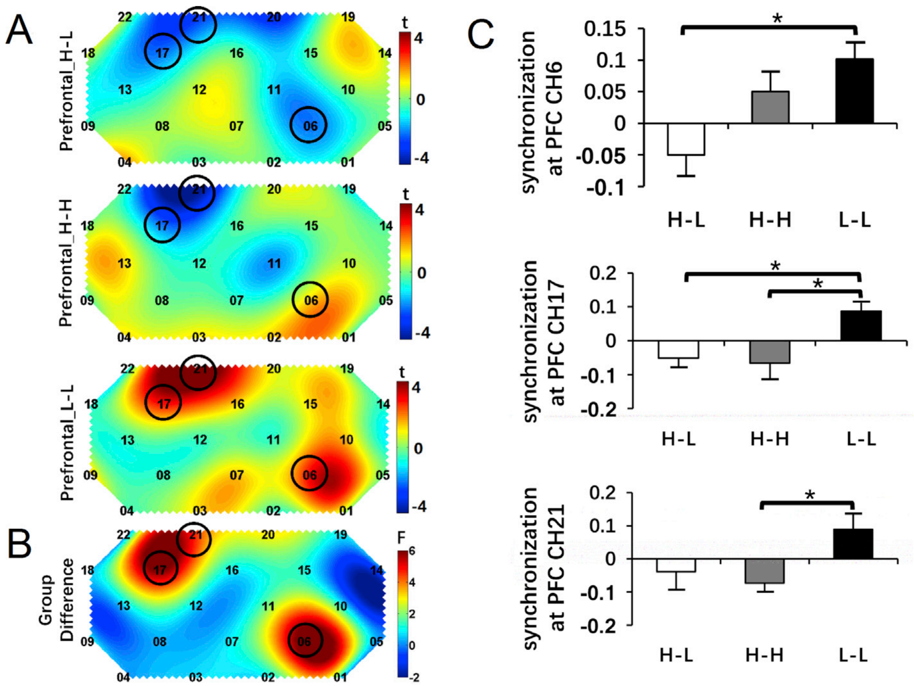


**Fig. 5.** Interpersonal brain synchronization (IBS) in the prefrontal cortex. (A) One-sample *t*-test maps of IBS in three groups. (B) One-way ANOVA results of the IBS to identify group differences. (C) The amplitude of IBS at CH6,17,21 in the prefrontal cortex. Note that in the low-low dyads, a significant IBS at CH6 was observed after FDR correction (IBS in the low-low dyads was higher than in the high-low dyads); a significant IBS at CH17 was observed after FDR correction (IBS in the low-low dyads was higher than in the high-low and the high-high dyads); a significant IBS at CH21 was observed after FDR correction (IBS in the low-low dyads was higher than in the high-high dyads). $^*p < 0.05$, after correction.

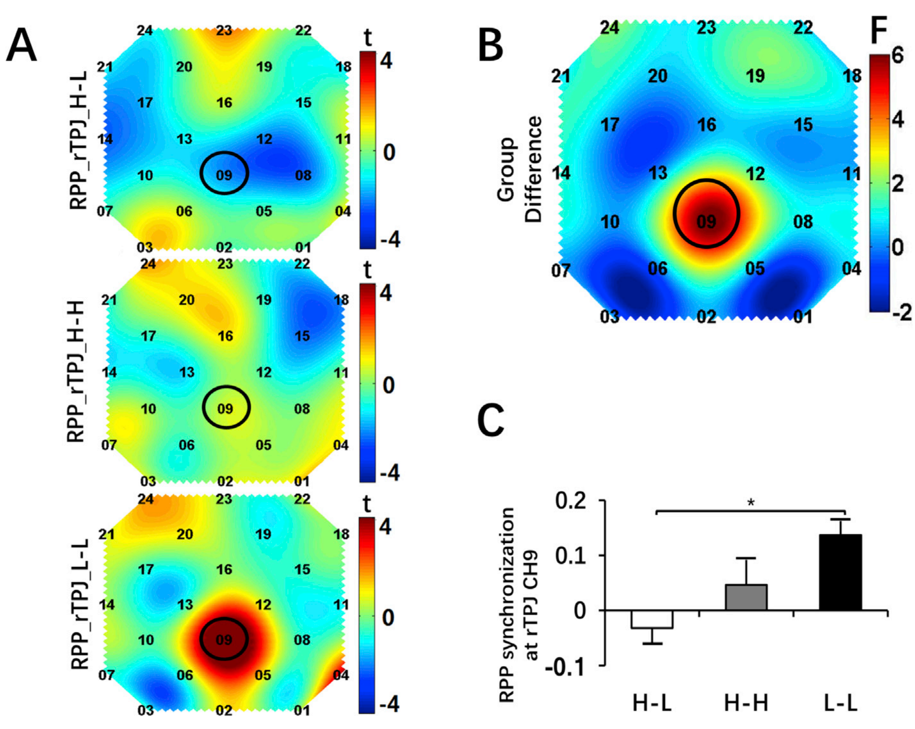


**Fig. 6.** Interpersonal brain synchronization (IBS) in the right temporal-parietal junction. (A) One-sample *t*-test maps of IBS in three groups. (B) One-way ANOVA results of the IBS to identify group differences. (C) The amplitude of IBS at CH9 in right temporal-parietal junction. Note that in the low-low dyads, a significant IBS at CH9 was found after FDR correction (IBS in the low-low dyads was higher than in the high-low dyads). $^*p < 0.05$, after correction.

and revealed the underlying inter-brain neural correlates using an fNIRS hyperscanning device. Participants were required to complete one RPP task in two-person brainstorming dyads, during which brain activity was recorded in the PFC and rTPJ. Behavioural results from our study revealed that less-creative individuals, while working together, performed as well as dyads of more creative individuals. Specifically, the low-low dyads showed higher levels of cooperative behaviour than the other types of dyads. In addition, results from the fNIRS demonstrated an increase in IBS in PFC and rTPJ brain regions during RPP task only for low-low dyads. In the right PFC, the increased IBS was stronger for the low-low dyads than for high-high and high-low dyads. Similarly, in the rTPJ, IBS was stronger for the low-low dyads than for high-low dyads, while no significant difference was observed between low-low dyads and high-high dyads. Furthermore, IBS in the low-low dyads was found to be positively correlated with their cooperative behaviour and group creative performance.

Before participants were assigned to dyads, they completed the AUT task (the preliminary test) independently. Results revealed that the creative performance of individuals in the low-low dyads was significantly worse than those in the high-low and high-high dyads. Considering the positive relationship between individual creativity and group creative performance (Burningham and West, 1995; Pirola-Merlo and Mann,

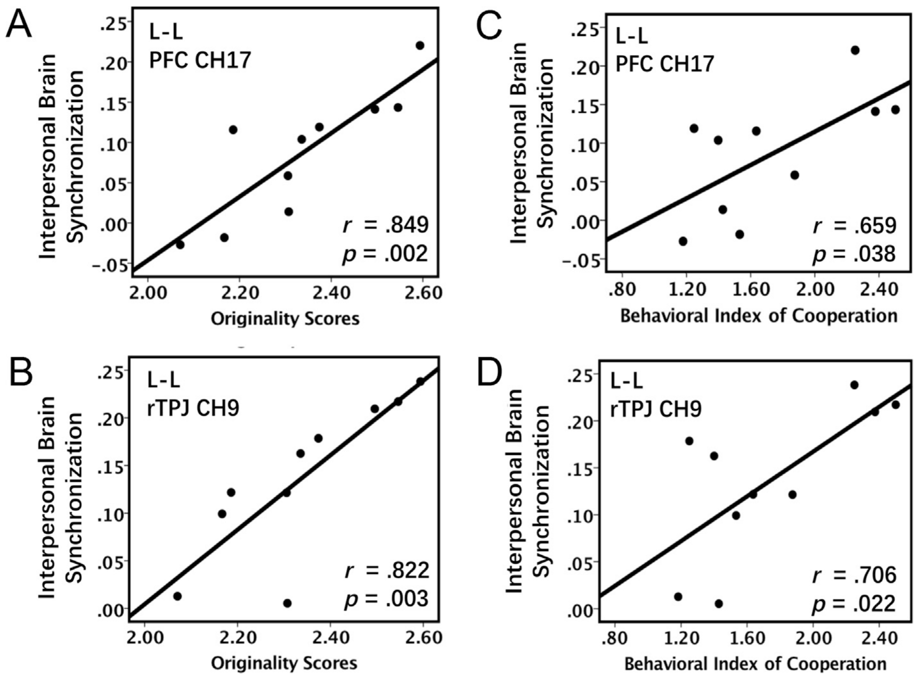


**Fig. 7.** IBS-behavior correlations in the low-low dyads. (A) Correlation between the IBS at CH17 in the PFC and RPP originality scores. (B) Correlation between the IBS at CH9 in the rTPJ and RPP originality scores. (C) Correlation between the IBS at CH17 in the PFC and behavioral indices of cooperation. (D) Correlation between the IBS at CH9 in the rTPJ and behavioral indices of cooperation.

2004; Taggar, 2001, 2002), we would have expected that the high-high and high-low dyads would have performed better than the low-low dyads on these tasks.

However, when participants performed the RPP task as a team, no significant difference was found among these three groups. That is, dyads consisting of two less-creative individuals performed just as well to dyads made up of more creative individuals. This might imply that the inherent weakness of dyads consisting of less-creative individuals had been offset by the interaction process. Earlier, we suggested that the ideas generated by less-creative individuals might still benefit the group's creative performance by enhancing cooperation. One reason for this is that since common ideas are easier to understand, it might be easier for individuals in the low-low dyads to improve upon and combine the ideas generated by their partners. Such an explanation is supported by the finding that behavioural cooperation indices were highest in the low-low dyads, as well as the fact that IBS was positively correlated with creative performance (see Figs. 4 and 7). In addition, because the less-creative individuals in the high-low dyads generated more common, easily understood ideas, it is reasonable to suppose high-low dyads would be capable of exhibited higher overall creative performance than the high-high dyads. However, our results showed that high-low and high-high dyads exhibited similar levels of creative performances during the study. The Social Comparison Theory (Festinger, 1954) may offer some explanations for this discrepancy. Social Comparison Theory proposes that group performance can be improved when comparison happens between group members. This social comparison is assumed to cease when there is a wide gap between the ability levels of the group's members (Jörg and Michael, 2003; Michinov and Primois, 2005). In light of this, in the high-low dyads, the contribution of less creative ideas by the one part of the dyad might be offset by the lack of social comparison. Although this theory may offer some possible explanations for our findings, further investigation should be conducted.

In contrast, the unique (i.e., more novel, but also potentially less accessible) ideas generated by higher creativity individuals would not be expected to enhance cooperation between team members. Specifically, when individuals were exposed to novel ideas (which could be harder to understand) these ideas might be more difficult for them to utilize and combine with other ideas. This may suggest lower levels of cooperation between team members in the high-high or high-low dyads. Therefore, we propose that the higher levels of cooperation between individuals in low-low dyads contributed to their creative performance, which may have made their performance equal to that observed in dyads consisting of more creative individuals.

Results from the fNIRS demonstrated increased IBS in the timescale between 12.8 and 51.2 s in right PFC and rTPJ in the low-low dyads. In addition, the increased IBS covaried with group creative performance and behavioural indices of cooperation. Previous studies have shown that increased IBS is usually associated with mutual understanding, which could be interpreted as an indicator of cooperation between individuals (Cheng et al., 2015; Cui et al., 2012; Dommer et al., 2012; Funane et al., 2011; Stephens et al., 2010; Tang et al., 2016). In this study, because participants in each dyad had not met before being paired together during the study, IBS could not be influences by prior familiarity or emotional factors. Therefore, the increased IBS we observed (and other outcomes discussed above) suggest that individuals in the low-low dyads were in the state of cooperation. On the other hand, such a cooperative state may have led to increased oral reporting and head motions associated with communication such as nodding in the low-low dyads. Hence, the increased IBS in the low-low dyads may have also resulted from spurious factors such as increased oral reporting and motions. However, participants were asked to remain as motionless as possible during the study, especially with regard to the use of non-verbal cues such as head motions. Therefore, we proposed that the IBS observed in this study might not be due to body motions.

The increased IBS observed in the low-low dyads was roughly located in the right dorsolateral prefrontal cortex (rDLPFC) (CH17) (see Fig. 5). Involvement of the rDLPFC has been confirmed in functions such as cognitive control, working memory and goal maintenance (Knoch et al., 2009; Macdonald et al., 2000; Miller and Cohen, 2001; Sai et al., 2014; Sanfey et al., 2003; Silton et al., 2010). Studies have also shown that the rDLPFC is responsible for overriding self-interested motivation (Knoch et al., 2006), monitoring responses, and for top-down inhibition of pre-potent ideas as well as task-irrelevant stimuli (Anticevic et al., 2012; Jahanshahi et al., 2000; Mansouri et al., 2007; Mansouri et al., 2009; Miller and Cohen, 2001; Nachev et al., 2008; Petrides, 2000). Considering the range of functions the rDLPFC is involved in, the increased IBS at CH17 might reflect greater attempts by participants to override their self-interested motivation and monitor responses generated by participants themselves and the partners. That is, individuals in low-low dyads may have been paying more attention to the ideas from his/her partner and making more of an effort to override their own self-interested motivation to cooperate better with their partner. In addition, previous studies found that the PFC (and especially the DLPFC) is recruited during the suppression of "ego-centered" behaviour (Baeken et al., 2010) and commitment in significant relationships (Petrican and Schimmack, 2008). Accordingly, our findings may also imply that highly-creative individuals found it more difficult to renounce to their personal ideas and had less interest in cooperating with their less-creative partners.

The increased IBS roughly located in the angular gyrus (AG) (CH9) was also found in the low-low dyads (see Fig. 6). The AG is in the temporal-parietal junction, which has two disparate function roles of "attention" and "social cognition". Studies show that the rTPJ acts as a "circuit-breaking" signal that interrupts ongoing attentional process and effectively reorients attention (Kubit and Jack, 2013). Previous research has suggested that the rTPJ plays roles in reading character's thoughts (Saxe and Powell, 2006), mediating joint attention between pairs of individuals during face-to-face interactions (Redcay et al., 2010), and inducing greater intentionality between partners (Tang et al., 2016). Meanwhile, AG is also involved in the Theory of Mind (ToM), which emphasizes the important role of perspective-taking has in social interactions. Perspective-taking has also been suggested as an important mechanism for unlocking team creativity in diverse teams (Hoever et al., 2012). It should be noted that only at PFC CH17 that low-low dyads showed higher IBS than the other two types of dyads. At rTPJ CH9, there was no significant difference between the low-low and high-high dyads. Considering the functions of rTPJ, the ToM may offer an explanation. ToM is used in social cognition to infer the mental states of others at the level of their beliefs, emotions, goals, and motivations (Seghier, 2013). Because of the wide gap in creative ability in our high-low dyads, it may have been more challenging for them to see each other's ideas (e.g., the highly-creative individuals may be unwilling to consider the ideas of the less-creative individuals, whereas the ideas of highly-creative individuals may have been difficult for less-creative individuals to understand). Comparatively, it may be easier for participants in high-high and low-low dyads to connect with each other's intentions or ideas. This may explain why no significant difference was observed in IBS between the high-high and low-low dyads at rTPJ CH9. Although this may account for the results we observed in this study, further study should be carried out.

We also observed significant changes in the frequency band between 84.0 and 100 s. Given that the duration of one cycle in the experimental task is far from this timescale, this may imply that the observed IBS in this frequency band was not related to the task. Alternatively, this IBS may reflect the influence of other aspects of social interaction in the group brainstorming context. Future studies will be needed to explore the meaning of such IBS in task-unrelated frequency band.

The use of hyperscanning devices such as fNIRS are increasingly being accepted as an important technique for revealing the inter-brain neural correlates in the context of social interactions. However, the limitations of fNIRS should be noted. First, physiological activities in the periphery such as heart rate, respiration, cardiac pulsation can influence fNIRS signals (Cheng et al., 2015; Cui et al., 2012; Dommer et al., 2012). Because of this, hrf low-pass filtering and a DCT-based detrending algorithm were used to rule out the potential contaminant effects of these noises (Ahmed et al., 1974; Ye et al., 2009). Previous studies have also suggested that frequency bands in the frontal cortex lower than 0.2 Hz are due to cognition-related NIRS activity (Cheng et al., 2015; Cui et al., 2012; Duan et al., 2013; Jiang et al., 2012). Hence, the IBS found in the current study should not be primarily determined by the above noises, although it was hard to eliminate the effect of these noises on our results completely. Second, changes in HbR can also be recorded by fNIRS, which might provide some additional information (Pan et al., 2017; Zhang et al., 2016). However, considering the sensitivity of HbO to changes in cerebral blood flow during fNIRS measurements, we mainly focused on changes in HbO during our analysis (Cui et al., 2012; Hoshi, 2007; Ou et al., 2009).

There were several additional limitations in the present study. First, the small sample size might have inflated our effect size estimates, led to the problematic false-positive/true-positive ratio in neuroscience (Button et al., 2013). While the sample size in the present study is comparable to other hyperscanning studies, larger samples should be sought in future studies on group creativity using fNIRS hyperscanning. Second, Nozawa et al. (2016) reported that removal of the skin blood flow component improves sensitivity to communication-enhanced IBS. However, due to the device limitation that our device cannot measure the skin blood flow component, we are not capable of removing the effect of skin blood flow on fNIRS signals in the present study. Future studies should remove skin blood flow to allow communication-enhanced IBS to be explored more precisely. Third, previous studies show that differences in the gender composition of groups can confound the relationship between neural coherence and behaviour (Baker et al., 2016). In this study, the number of male participants was too small to use gender as a variable. In future studies, a higher number of male participants will need to be recruited so that the effect of gender on the relationship between individual creativity and group creative performance can be investigated fully.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.neuroimage.2018.02.007.

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