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Original Article

Letting leaders spontaneously emerge yields better creative outcomes and higher leader–follower interbrain synchrony during creative group communication

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This study aimed to investigate how the ways leaders arise (appointed vs. emergent) affect the leader–follower interaction during creative group communication. Hyperscanning technique was adopted to reveal the underlying interpersonal neural correlates using functional near-infrared spectroscopy. Participants were assigned into 3-person groups to complete a creative problem-solving task. These groups were randomly split into conditions of appointed (condition A) and emergent (condition E) leaders. Creative group outcomes were better in condition E, accompanied by more frequent perspective-taking behaviors between leaders and followers. The interpersonal brain synchronization (IBS) increment for leader–follower pairs was significantly higher at the right angular gyrus (rAG), between the rAG and the right supramarginal gyrus (rSMG), and between the right middle temporal gyrus and the right motor cortex in condition E and positively correlated with perspective-taking behaviors between leaders and followers. The graph-based analysis showed higher nodal betweenness of the rAG and the rSMG in condition E. These results indicated the neural coupling of brain regions involved in mentalizing, semantic processing and motor imagery may underlie the dynamic information transmission between leaders and followers during creative group communication.

Key words: leader–follower interaction; group creativity; perspective-taking behaviors; interpersonal brain synchronization.

Introduction

Group creativity, i.e. a group of people working jointly to produce ideas or products that are novel and useful (Runco and Jaeger 2012), plays a vital role in scientific development and social progress. It's likely to thrive when group members actively share generated ideas and effectively consume others' perspectives (Hargadon and Bechky 2006; Hoever et al. 2012; Paulus and Kenworthy 2021). As an integral part of groups and organizations, leaders play a direct role in creative group processes such as producing and refining new ideas (Li and Yue 2019). Leaders exert themselves to produce novel ideas and use their influence to stimulate the creative potential of other group members (Mumford et al. 2003; Mainemelis et al. 2015).

Despite the clear importance of leaders in group creativity, how the ways of leaders arise may affect the creative group interaction remains an open question. For instance, a leader can be appointed by an authority outside the group, as is particularly commonplace in most traditional organizations (Ford 1981). In laboratory settings, the appointed leader is usually randomly selected by the experimenter and announced to the group (Chemin 2021). Alternatively, in project groups of organizations or in learning groups of schools or research institutions, group members often begin working without an appointed leader, and a leader may spontaneously emerge without any explicit direction or selection (Naquin and Kurtzberg 2018). Some individuals are perceived by others (i.e. group members or external observers) as taking over leadership responsibilities during the task in initially leaderless groups (Ensari et al. 2011; Gerpott et al. 2018). To reach the goal of group creativity, should a leader be exogenously appointed or emerge endogenously? Moreover, what interpersonal neural correlates underlie the effects of the appointed and emergent leaders on the creative group process? Addressing these questions may deepen our understanding of how the leader–follower (LF) interaction affects creative group communication from a neurocognitive perspective and offer practical suggestions for improving group efficiency in creativity.

Holding a formal leader role is not a guarantee of leadership qualities. Contemporary leadership theorists have questioned the traditional perspectives that treated leadership as static, hierarchical, and equivalent to a formal position (Uhl-Bien et al. 2007; Derue and Ashford 2010). Greater attention is now devoted to the dynamic interaction between leaders and followers (Morgeson et al. 2010). According to the adaptive leadership theory, leadership is an adaptive social process of mutual influence among group members, in which LF identities and relationships are constructed and internalized through repeated social interactions. Interactions between the leader and other members determine whether or not the leader can internalize the leader identity and undertake a leadership role (Derue 2011). Furthermore, based on the implicit leadership theory, congruence between the ideal leader prototypes and the actual behaviors is vital for categorizing someone (or oneself) as a leader in various contexts (Lord et al. 2020). Thus, the adaptive social interaction process could offer more space for sufficient LF identity construction, during which

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the person who matched the ideal leader prototypes most would be recognized as the emergent leader, exhibiting greater leadership compared with the appointed leaders.

Compared with exogenously appointing a leader, letting the leader spontaneously emerge might be more beneficial for creative group interactions. Social interaction between leaders and followers may affect 2 core cognitive processes of group creativity: idea generation and sharing. Idea generation involves the retrieval of task-relevant knowledge from memory and integration of existing knowledge into novel ideas (Paulus and Brown 2007). Idea-sharing may help individuals access less common categories of ideas in the semantic network, potentially leading to novel combinations of generated ideas (Paulus and Nijstad 2003). Only when group members pay attention to ideas shared by others, they might notice the potential associations and develop new ideas accordingly (Coskun and Yilmaz 2009). Therefore, the positive LF interaction pattern that benefits group creativity may be characterized by the balance between generating ideas oneself and attending to ideas shared by others (Paulus and Kenworthy 2021). According to the social learning theory, followers tend to mimic and display behaviors similar to those of leaders in their social interactions (Sung and Choi 2021). As an input to the group process, the appointed leader can be seen as a social reference point, making the followers adjust their idea generation rates based on the leader's performance. The group's creative outcomes would be limited if the appointed leader lacks necessary skills for generating numerous creative ideas. Moreover, appointing a leader may create unequal power relations among group members. Power was associated with a reduced tendency to consider others' perspectives (Galinsky et al. 2006; Muscatell et al. 2012). The empowered leader may tend to depend on themselves and unconsciously ignore ideas shared by others, which weaken the stimulating effect of idea-sharing on idea generation. In contrast, the emergent leaders are products of the social interaction process. Group members may spontaneously fit into the leader/follower roles in an adaptive manner during the process of task completion (Derue 2011; Jiang et al. 2015). Individuals who can express numerous ideas and make full use of the shared ideas to build novel associations might naturally be recognized as the emergent leaders (Liang et al. 2022). Compared with the appointed leaders, the emergent leaders engage in more horizontal communication and information-exchange with their followers (Faraj and Yan 2009). Meanwhile, followers might voluntarily learn from leaders and attempt to pay attention to others' perspectives and utilize them to produce more ideas. The active exchanging and sharing of ideas can better cope with complex cognitive tasks and facilitate group creativity (Oborn and Dawson 2010; Zhao et al. 2022).

The aim of the present study was to investigate the potential effects of the appointed and emergent leaders on the creative outcomes and interactive process of the group, and more importantly, reveal the underlying interpersonal neural correlates. Unlike most previous studies on how leadership affects group creativity, which often used questionnaires to measure the effects of different leadership styles or specific leader behaviors on self-reported team creativity in organizations (Ali et al. 2020; Gu et al. 2020; Sung and Choi 2021), the present study adopted the "second-person neuroscience" (Redcay and Schilbach 2019) approach to examine the neural process involved in real-time social interaction between leaders and followers during creative group communication. Particularly, we used functional near-infrared spectroscopy (fNIRS) to simultaneously track the brain activities of multiple individuals (i.e. hyperscanning) engaging in a group creativity task. Owing to the higher tolerance for motor artifacts and ecological validity compared with functional magnetic resonance imaging and electroencephalogram (Cui et al. 2012; Mayseless et al. 2019), the fNIRS-based hyperscanning technique is a powerful tool to investigate face-to-face communication, including creative group discussions (Nozawa et al. 2016; Xue et al. 2018; Lu et al. 2020).

Social interaction for group creativity and leadership construction can be tracked through interpersonal brain synchronization (IBS; Jiang et al. 2015; Lu et al. 2019; Liang et al. 2022). IBS is tightly associated with mutual understanding and information-exchange among individuals in social communication (Stephens et al. 2010; Hasson and Frith 2016). The emergence of leaders is accompanied by enhanced IBS for LF pairs in the temporal parietal junction (Jiang et al. 2015). IBS is increased in the right temporal parietal cortex in group creation (Lu et al. 2019, 2021). Therefore, we mainly focused on the right temporal parietal region to explore the interpersonal neural correlates in creative group communication. Brain regions involved in processing semantic information and understanding others' perspectives may play vital roles in the dynamic interactive process of creative group communication (Oztop et al. 2018; Beaty et al. 2020). For instance, the middle temporal gyrus (MTG) is commonly seen as the "semantic hub," which is involved in actively generating mental representations by integrating contents retrieved from memory (Benedek et al. 2016). The MTG has been shown the MTG plays a role in forming creative associations (Ren et al. 2020; Zhang et al. 2020). The angular gyrus (AG) is associated with orienting attention to semantic information (Cristescu et al. 2006). In addition, the AG is involved in understanding other people's minds (Schurz et al. 2017; Filmer et al. 2019). We anticipated to observe enhanced IBS between leaders and followers in these brain regions when they exhibited positive interaction patterns for group creativity.

In the current study, participants were assigned into 3-person groups to complete a creative group communication task (realistic presented problem, RPP); an fNIRS-based system was used to simultaneously record individual brain (i.e. the right temporal parietal region) activities within each group (Fig. 1A and B). These groups were randomly split into 2 conditions: appointed (condition A) and emergent (condition E) leaders. In condition A, a group member was randomly appointed as the leader before the discussion (Fig. 1C). In condition E, participants were required to independently rate who was most like a leader after the discussion (Fig. 1D). Accordingly, each group comprised of 1 leader and 2 followers, forming 2 LF pairs and 1 follower–follower (FF) pair. Participants in the group were not mutually acquainted before the experiment, thereby eliminating the interference of previous interaction experiences among group members. Thus, we could observe how the arising ways of leaders affected the creative outcomes and interactive processes in a highly ecological setting.

With regards to behavioral performance, creative outcomes were estimated based on the quantity (i.e. fluency) and quality (i.e. originality) of generated ideas. The interactive processes were evaluated based on the degree of ideas exchanged among group members, i.e. perspective-taking behaviors. We hypothesized that (I) the group's creative outcomes would be better in condition E and that (II) perspective-taking behaviors would be more frequent in condition E, particularly between leaders and followers. To reveal the interpersonal neural coupling, we used wavelet transform coherence (WTC, Grinsted et al. 2004) to assess the IBS for LF and FF pairs. Considering that leader emergence is characterized by higher IBS for LF pairs than that for FF pairs (Jiang et al. 2015) and that groups with higher creative performance have stronger IBS (Lu et al. 2019, 2020), we hypothesized that (III) the

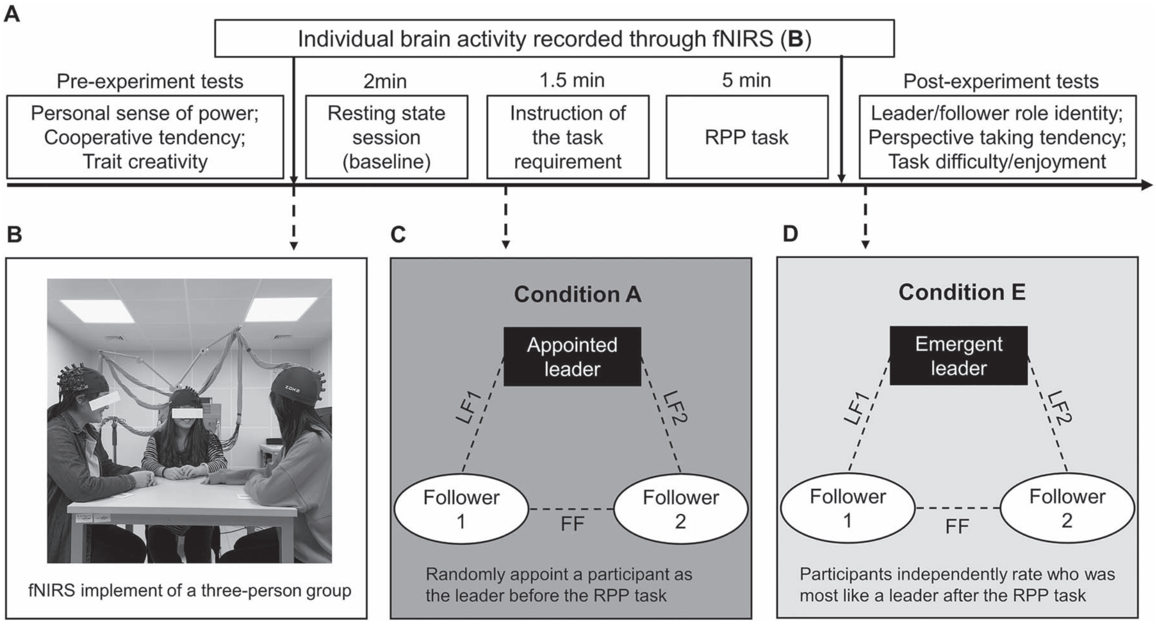

Fig. 1. Experimental design and procedures. A) Experimental procedure and B) setup. C/D) Experimental manipulation for the appointed (condition A) and emergent (condition E) leaders.

IBS increment for LF would be higher than that for FF in condition E. Finally, we adopted the graph theoretical approach (Bullmore and Sporns 2009) to explore the characteristics of the hyper-brain network consisting of intra- and interbrain synchronization across group members. The graph-based approach is a powerful way of quantifying brain systems to analyze complex brain networks that served as physiological basis of information transfer and mental representations (Strogatz 2001). It provides additional information about how efficiently information was exchanged over the hyper-brain network among all group members (Latora and Marchiori 2001), compared with the IBS that only shows neural coupling at the pair level. For instance, a recent study used the graph analysis and revealed the profile of the hyper-brain network of the high-creative group dynamics (Lu et al. 2022). In the current study, the global and local network efficiencies under 2 conditions were respectively calculated. As letting leaders emerge spontaneously may be more beneficial for effective information-exchange among group members, we hypothesized that (IV) the global and local efficiency of the hyper-brain network would be higher in condition E. We also calculated the nodal betweenness of each region of interest (ROI) in the measured brain area to locate the center of the network (Feng et al. 2021) without any specific hypothesis.

Materials and methods

Participants

A total of 180 healthy college students (108 females, age: 21.51 ± 2.33 years) were recruited and randomly assigned as 3-person groups. For each group, the members had to be of the same gender to avoid a potential confound of intergender interactions. All participants were Chinese native speakers, with normal or corrected-to-normal vision, and had no history of neurological or psychiatric disorders. Informed consent was provided to participants prior to the experiments to fully explain the experimental procedure and acknowledge their right to withdraw at any time during the study. Each participant was paid ¥ 35 for participation. The study procedure was approved by the University Committee on Human Research Protection of East China Normal University.

The sample size was determined a priori using G*power (Faul et al. 2007) to estimate the number of 3-person groups needed to detect significant effects with 90% statistical power. As we mainly focused on the interaction effect of Condition × Pair, a mixed-model analysis of variance (ANOVA) using Condition (condition A vs. condition E) as the between-subject factor and Pair (LF vs. FF) as the within-subject factor was performed. Based on the medium effect size ($f = 0.25$) (Cohen 1988), 46 three-person groups were needed to detect a reliable effect with $\alpha = 0.05$ and $\beta = 0.90$ for a Condition × Pair interaction. In case of dropouts due to the failures of neural data collection or leader identification, a total of 60 three-person groups were recruited. The 60 three-person groups were randomly split into condition A and condition E. Four groups in condition E were excludes because of the uncertainty of the emerging leaders, leaving 168 participants in 56 groups (33 female groups, age: 21.58 ± 2.28 years) for behavioral data analysis. One group in condition A was excluded because of technical failure with fNIRS measurements, leaving 165 participants in 55 groups (32 female groups, age: 21.59 ± 2.28) for neural data analysis. The leaders and followers under the condition A or condition E did not differ in gender and age (Table S1).

Procedures

For each group, 3 persons were required to sit around a 0.8 × 0.8-m square table. The seats were positioned to form an equilateral triangle, allowing participants to see each other's face clearly. Prior to the experiment, participants completed a series of pretests to measure their personal sense of power, cooperative tendency, and trait creativity (Supplementary Material, S1). The experimental procedure consisted of a 2-min resting-state session, a 1.5-min instruction session, and a 5-min task session (Fig. 1A). The initial 2-min resting-state session served as the baseline. During this session, participants were asked to remain as still as possible, with their eyes-closed and their mind relaxed (Lu et al. 2010). Immediately after the resting-state session, they were given a brief introduction on the task requirements: "You are a team, and the final task performance depends on all of you. There will be a creative discussion task during the experiment. You are required to discuss solutions to a realistic-related problem. Feel free to report your solutions loudly once you have any ideas. You are encouraged to combine and improve each other's perspective. Please do not judge the ideas of others." In each group, participants were assigned numbers to represent themselves based on the positions of their seats. The participant who sat in the middle (back to the fNIRS equipment) was No.1, who sat on the left-hand side of No.1 was No.2, and who sat on the right-hand side of No.1 was No.3. Importantly, in condition A, there was an additional instruction about the appointed leader (i.e. "The No.1 participant who sit in the middle will be the leader during the task. The leader is required to firstly come up with a solution at the beginning of the discussion. After then, all participants can report as soon as ideas arise. What's more, the leader can steer the direction of the discussion"). In condition E, participants started the task without the additional instruction and were required to independently rate who was most like a leader after the discussion (i.e. "Please write down the number of the group member that behaved as the group leader"). If at least 2 members chose the same person to be the leader, the person was identified as the emergent group leader.

In the 5-min task session, participants engaged in a discussion about a revised RPP that has been widely used to assess group creativity (Agnoli et al. 2016; Runco et al. 2016). To exclude the potential effect of one specific problem (Wang et al. 2022), 2 problems were used in the current study: (i) "Your classmate's parent is seriously ill and in urgent need of money. Do you think there are any novel ways to help him/her raise money while not make him/her feel burdened?"; (ii) "Because of the road reconstruction, people are not willing to make a detour to the restaurant. Do you think there are any novel ways to help the restaurant manager to improve the business?" The experimenter randomly picked 1 of these 2 problems for each group. During the discussion, participants were required to come up with as many creative solutions as possible to solve the open-ended problem. They were allowed to orally report whenever ideas come to mind, unless their partner was already reporting (Lu et al. 2020). There were 3 main reasons why we asked participants to report freely during RPP. Firstly, letting group members report freely whenever ideas arise was often used in studies of interpersonal verbal communication (Nozawa et al. 2016; Mayseless et al. 2019), which is a more natural way of communicating and can yield higher ecological validity. Secondly, although most previous research on group creativity adopted the turn-taking paradigm (Xue et al. 2018; Duan et al. 2022), the features of turn-taking setting (e.g. equal chance of utterance) may impede the emergence of leaders. Thirdly, using free talking can also exclude the potential effect of "sequence of utterance" (required by the turn-taking paradigm) on the interpersonal communication process (Lu et al. 2020). Therefore, we considered it was more appropriate to allow participants to report freely in the current study. Immediately following the experiment, participants completed several posttests to rate their leader and follower role identities, perspective-taking tendency, and feelings of task difficulty and enjoyment (Supplementary Material, S1 and S2; for results, see Table S2 and Fig. S1, see online supplementary material for a color version of this figure).

Behavioral assessments

Creative outcomes were measured using the (i) fluency (i.e. quantity) and (ii) originality (i.e. quality) of their ideas (Runco and Okuda 1991). The fluency and originality were assessed at both the individual and group levels. At the individual level, the individual fluency score was determined by the total number of nonredundant ideas that each participant generated. For instance, if 1 participant generated a total of 8 ideas, but one of the ideas was a simple repetition of the previous ideas without any improvement or elaboration, the individual fluency score was 7. The individual originality score was assessed using a subjective method (Lu et al. 2019). Specifically, 3 trained raters independently rated the originality of each idea 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 = 0.83) was satisfactory. Thus, scores were averaged across raters 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 whole task. At the group level, the group fluency score was assessed by the total number of ideas that all 3 participants generated in each group. The group originality score was determined by averaging the individual originality scores of all 3 participants in each group.

The interactive processes were evaluated based on the perspective-taking behaviors (i.e. considering another's viewpoint by deliberately adopting their perspectives; Galinsky and Ku 2004). The operational definition of the perspective-taking behaviors in the present study was the number of ideas that belonged to the same category as the previous ideas generated by others. The index of convergence (IOC; Larey and Paulus 1999; Lu et al. 2020) was calculated to measure the perspective-taking behaviors at both the group and pair levels. The group IOC was assessed as follows: (i) the generated ideas of the 3 participants were listed in chronological order; (ii) from the first response to the last, when an idea belonged to the same category as the previous ideas, it scored "1," and the number of ideas that scored "1" was counted (i.e. if there were 5 ideas that scored "1," the Sum would be "5," indicating there were 5 ideas pertaining to the same category as the previous responses); (iii) the IOC for each group was obtained using the equation: IOC = Sum/[Group fluency − Sum]. Two trained raters independently assessed the IOC for each group. The inter-rater agreement was satisfactory (ICC = 0.92). The final IOC score for each group was obtained by averaging across raters. At the pair level, the IOC of LF and FF were assessed in a similar way. Based on the chronological order, when a participant came up with an idea pertained to the same category as the previous ideas that generated by another participant, it scored "1." Accordingly, LF-1 score represented the number of ideas generated by any of the 2 followers that belonged to the same category as the previous ideas that generated by the leader. FL-2 score represented the number of ideas generated by the leader that belonged to the same category as the previous ideas that generated by any of the 2 followers. The IOC of LF was thus obtained by averaging the LF-1 and FL-2 scores. The IOC of FF was measured by the number of ideas generated by any follower that belonged to the same category as the previous ideas that generated by the other follower.

Behavioral data analysis

At the individual level, a series of 2-way ANOVAs using Condition (condition A vs. condition E) and Role (leader vs. followers) as the between-subject factors were performed on: (i) the individual fluency; and (ii) the individual originality scores. At the group level, a series of independent sample *t*-tests using Condition as the between-subject factor were performed on: (i) the group fluency, (ii) the group originality, and (iii) the group IOC scores. At the pair level, mixed-model ANOVAs with Condition as a between-subject factor and Pair (LF vs. FF) as a within-subject factor were performed on the paired IOC scores. Note to normalize the scores of the individual/group fluency and the group/paired IOC, we converted them into sqrt (n) values.

fNIRS data acquisition and preprocessing

A NIRS system (ETG-7100, Hitachi Medical Corporation, Japan) was used to simultaneously record the hemoglobin signals of the 3 participants in each group. The raw optical intensities were converted to the relative concentration changes of oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) based on the modified Beer–Lambert law (Obrig and Villringer 2003). The absorption of near-infrared light (wavelengths: 695 and 830 nm) was measured at a sampling rate of 10 Hz. One 4×4 optode probe set (8 emitters and detectors, 3-cm optode separation) consisting of 24 measurement channels (CHs) was placed over the right temporal parietal region of each participant. According to the international 10–20 system for electroencephalography, the lowest probe was aligned with the sagittal reference curve, with the optode A placed on P6 (Fig. 2A). The optode probe set was positioned using individualized caps made from swimming caps, which increases the consistency of the signals across variations in head size (Chen et al. 2020). In addition, we recorded the Montreal Neurological Institute (MNI) coordinates of the CHs of a typical participant (Table S3) and used the virtual registration method (Singh et al. 2005; Tsuzuki et al. 2007) to determine the correspondence between the NIRS channels and the measurement points on the brain. To remove global physiological noise such as the blood pressure and respiration, a wavelet-based denoise approach was used (Duan et al. 2018). In addition, a correlation-based signal improvement (CBSI) method was used to remove head motion artifacts (Cui et al. 2010). As the CBSI approach maximally made the corrected HbO and HbR signals negatively correlated (Pan et al. 2022), and the HbO signal is more sensitive to changes in cerebral blood flow than the HbR signal (Hoshi 2007), the subsequent analysis mainly focused on the HbO signals. Next, A total of 7 ROIs were created based on the shared source localizations according to the MNI coordinates of the CHs (Fig. 2B). One CH was associated to one ROI only if >70% of the CH areas belonged to that ROI (Lu et al. 2021). For example, since >70% of the areas of CH10, CH13, CH17 belonged to the angular gyrus (ROI 3), ROI 3 consisted of the abovementioned CHs. The ROIs were (i) the right middle temporal gyrus (r-MTG), (ii) the right superior temporal gyrus (r-STG), (iii) the right angular gyrus (r-AG), (iv) the right supramarginal gyrus (r-SMG), (v) the right primary somatosensory cortex (r-PSC), (vi) the right motor cortex (r-Motor), and (vii) the right somatosensory association cortex (r-SAC). The present study mainly focused on the ROI-wise analysis.

Interpersonal brain synchronization analysis

Data collected from the ROIs during the resting-state and the task sessions were entered into further analysis. To obtain steady-state data, the data from the initial and final 10 s of the resting-state were removed. Meanwhile, the data from the initial and final 30 s of the task were removed, leaving 240 s of data for the task session (Lu et al. 2021; Wang et al. 2022). Three HbO time series were obtained simultaneously for each ROI from the 3 participants of each group. WTC was performed to each pair of the HbO time series to generate coherence values (i.e. IBS; Grinsted et al. 2004). WTC can reveal a locally phase-locked behavior, which has been widely used in recent hyperscanning studies (Yang et al. 2020; Lu et al. 2021). As each group had 2 LF pairs (i.e. LF1 and LF2) and one FF pair, the IBS for 2 LF pairs were averaged for further analysis (Jiang et al. 2015; Fig. 2C). According to previous studies, IBS increased when there were interactions between participants, compared with that during the resting-state (Cui et al. 2012). To assess the IBS increment, we subtracted the time-averaged IBS of the baseline from that of the RPP session (i.e. IBS increment $=$ IBS$_{\text{RPP}}$ $-$ IBS$_{\text{baseline}}$). For further analysis, the IBS increments for the LF and FF pairs were converted to Fisher z-statistics (Chang and Glover 2010). Note that the IBS increment for the FF pairs between same ROI pairings were averaged and compared with the IBS increment for the LF pairs at that ROI combination. For instance, the IBS increment between the rMTG (follower1) and the rMotor (follower2) was averaged with the IBS increment between the rMotor (follower1) and the rMTG (follower2). In addition, the IBS increment of rMTG–rMotor for LF1 and LF2 were averaged (Fig. 2D).

A series of mixed-model ANOVAs using Condition as the between-subject factor and Pair as the within-subject factor were performed on the IBS increments across all ROI combinations ($7*7=49$ in total) along the full frequency range (0.015–0.7 Hz). According to pervious findings, data above 0.7 Hz were excluded to remove the high-frequency noise such as cardiac activity (~0.8–2.5 Hz; Tong et al. 2011). Data below 0.015 Hz were not considered due to the IBS enhancement had often been observed at frequencies above 0.015 Hz in previous hyperscanning studies on group creativity (Xue et al. 2018; Lu et al. 2019, 2020). This high pass filtering can also remove very low-frequency fluctuations that are mostly noise. Besides, data within the frequency range of respiratory activity (~0.15–0.3 Hz) were not considered (Zheng et al. 2018). There were 55 total frequencies within the full frequency range and 49 ROI combinations. Therefore, the total number of resulting P values was $55*49=2{,}695$. Note 3 F-maps were generated by the ANOVAs: the main effect of Condition, the main effect of Pair, and the interaction effect of Condition × Pair (Fig. 2E and Fig. S2, see online supplementary material for a color version of this figure). For each F map, all the resulting P values were corrected using the false discovery rate (FDR) method ($P < 0.05$) at one time, respectively. For the survived ROI combinations that showed significant interaction effect of Condition × Pair, follow-up simple effect analysis with Bonferroni corrections were performed.

Validation analysis on interpersonal brain synchronization

To validate the observed effects of Condition × Pair on the IBS increment in the actual interacting groups, a within-condition permutation approach was applied (Jiang et al. 2015; Yang et al. 2020). Specifically, 55 within-condition pseudo groups (29 groups in condition A and 26 groups in condition E) were generated using the simple random sampling without replacement to ensure the leaders and followers from different real groups assigned to a pseudo group. The IBS increment for the LF and FF pairs of each pseudo group were calculated in the same way as we did for the real groups. Then the mixed-model ANOVA using Condition as the between-subject factor and Pair as the within-subject factor was performed on the IBS increment of the pseudo groups. This process was repeated for 1,000 times.

Brain-behavior relationship analysis

A series of bivariate Pearson correlations were conducted to identify the relationship between the IBS increment and behavioral indices (i.e. creative outcomes and perspective-taking behaviors). The resulting P values were corrected using the FDR method for

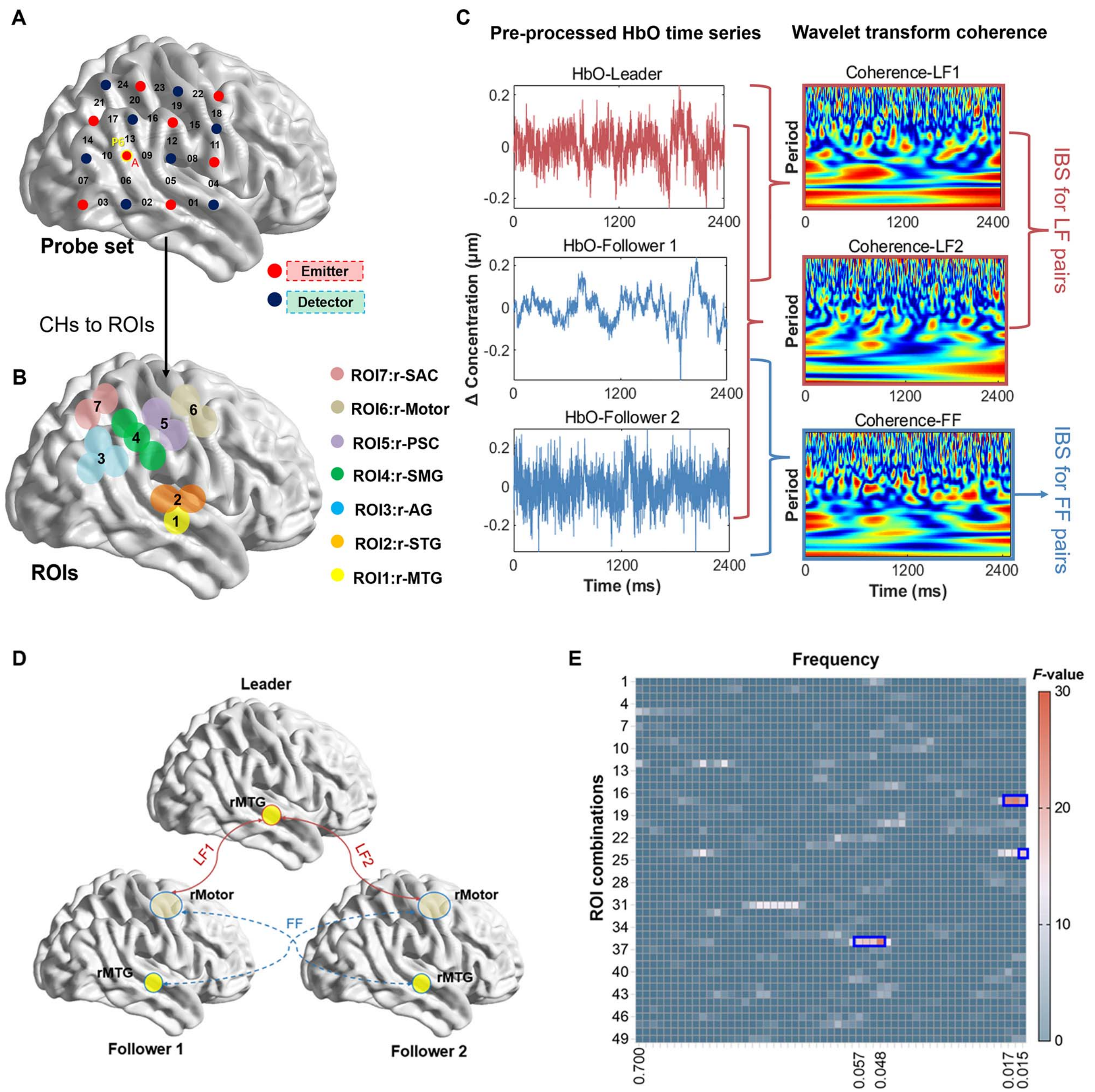

Fig. 2. fNIRS data collection and analysis. A) fNIRS optode probe set on the right temporal parietal region. B) A total of 7 regions of interest (ROIs) were created based on shared source localizations according to the Montreal Neurological Institute coordinates of the CHs. C) Illustration of the wavelet transform coherence analysis to assess the IBS for the leader–follower (LF) and follower–follower (FF) pairs. D) Illustration of the IBS increment between the rMTG and the rMotor for the LF and FF pairs. E) The *F*-map for interaction effect of Condition × Pair on the IBS increments of all ROI combinations along the full frequency range (0.015–0.7 Hz). The color bar denotes the *F* value. The blue rectangles indicate the interaction effect on the ROI combinations at the frequency band of 0.048–0.057 Hz and 0.015–0.017 Hz survived the false discovery rate correction ($P_{corr} < 0.05$).

the IBS increment of LF and FF pairs, respectively. Specifically, the IBS increment for the LF and FF pairs were correlated with creative outcomes (6 indices: the individual fluency of leaders/followers, the individual originality of leaders/followers, the group fluency, and the group originality) and the perspective-taking behaviors (3 indices: the group IOC, the paired IOC of LF/FF), respectively.

Hyper-brain network analysis

To explore the network organization among ROIs at the group level, a graph-based network analysis was conducted. For each group, a 21 × 21 hyper-brain neural coupling matrix (including 7 ROIs of 3 group members) was obtained, in which the ROIs were treated as the nodes, and the edges were defined as the cross-correlation (untransformed using Fisher's *r*-to-z) between any 2 of them (Silbert et al. 2014; Lu et al. 2022; for details, see Supplementary Material, S3). We implemented network analysis in MATLAB using GRETNA (Wang et al. 2015), a toolbox that allows to perform comprehensive analysis on the topology of brain connections. Two typical network measure parameters were calculated: the global (E_{glob}) and local efficiency (E_{loc}). To determine the network characteristics specific to group creativity, we subtracted the network efficiency of the baseline from that of the RPP session (i.e. $E_{glob} = E_{glob\_RPP} – E_{glob\_baseline}$; $E_{loc} = E_{loc\_RPP} – E_{loc\_baseline}$). Independent sample *t*-tests using Condition as the between-subject factor were performed on E_{glob} and E_{loc} of

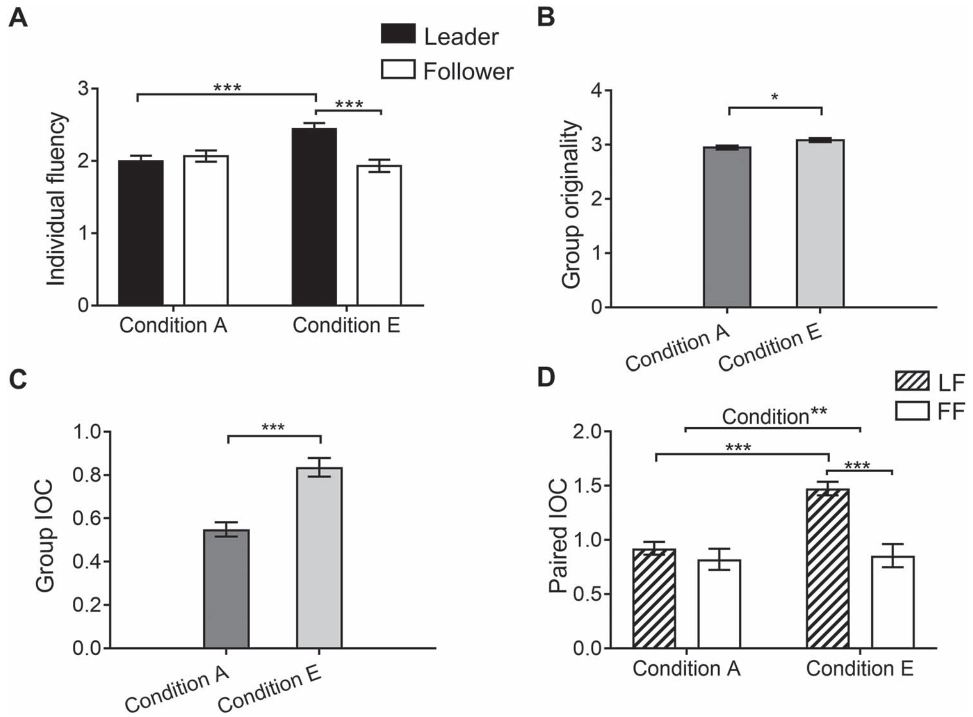

Fig. 3. Behavioral index. A) Individual fluency. B) Group originality. C) Group index of convergence (IOC). D) Paired IOC. Data are shown as the mean ± SE *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

hyper-brain networks. Regarding nodal parameters, the nodal betweenness of each ROI was calculated. The nodal betweenness reflects the influence of a node in the global network (Freeman 1977). The higher the nodal betweenness of a node, the more node pairs passing through the node and the more likely it is to be in the center of the network (Feng et al. 2021). For further analysis, the betweenness of the same node of 2 followers were averaged and compared with that of the leaders. We also subtracted the nodal betweenness of the baseline from that of the RPP session. Next, a series of 2-way ANOVAs using Condition and Role as the between-subject factors were performed on the nodal betweenness across all ROIs. The resulting P values were corrected using the FDR method ($P < 0.05$).

Results

Creative outcomes

Regarding the fluency, 2-way ANOVA result showed a significant main effect of Role (leader vs. follower) on the individual fluency ($F_{1108} = 7.299$, $P = 0.008$, $\eta^2 = 0.063$). The individual fluency of leaders was higher than that of followers. Result also showed a significant interaction effect of Condition × Role on the individual fluency ($F_{1108} = 12.845$, $P = 5.09 \times 10^{-4}$, $\eta^2 = 0.106$; Fig. 3A). The individual fluency of leaders was significantly higher in condition E than in condition A ($P < 0.001$, Cohen's $d = 0.943$). Besides, only in condition E, the individual fluency of leaders was significantly higher than that of followers ($P < 0.001$, Cohen's $d = 1.311$). Regarding the originality, 2-way ANOVA result showed significant main effect of Condition on the individual originality ($F_{1108} = 9.313$, $P = 0.003$, $\eta^2 = 0.079$). Result of t-tests showed a significant difference of Condition on the group originality ($t_{54} = 2.616$, $P = 0.012$, Cohen's $d = 0.702$; Fig. 3B). Both the individual and group originality were significantly higher in condition E than in condition A. Table S4 reported the full statistics of creative outcomes.

Interactive processes

At the group level, t-test result showed a significant difference of Condition on the group IOC ($t_{54} = 5.375$, $P = 1.68 \times 10^{-6}$, Cohen's d = 1.431; Fig. 3C). The group IOC was significantly higher in condition E than in condition A. At the pair level, the IOC of LF and FF were calculated (Fig. 3D). The mixed-model ANOVA result showed a significant main effect of Condition on the paired IOC ($F_{1,54} = 11.288$, $P = 0.001$, $\eta^2 = 0.173$). The paired IOC was significantly higher in condition E than in condition A. Moreover, result showed a significant main effect of Pair on the paired IOC ($F_{1,54} = 19.803$, $P = 4.33 \times 10^{-5}$, $\eta^2 = 0.268$). The IOC of LF was significantly higher than that of FF. Result also showed a significant interaction effect of Condition × Pair on the paired IOC ($F_{1,54} = 10.257$, $P = 0.002$, $\eta^2 = 0.160$). The IOC of LF was significantly higher in condition E than in condition A ($P < 0.001$, Cohen's $d = 1.724$). In addition, only in condition E, the IOC of LF was significantly higher than that of FF ($P < 0.001$, Cohen's $d = 1.308$). We further identified the direction of the perspective-taking behaviors between leaders and followers. The ANOVA result showed that both the LF-1($P < 0.001$, Cohen's $d = 1.189$) and FL-2 ($P < 0.001$, Cohen's $d = 1.381$) scores were significantly higher in condition E, indicating perspective-taking behaviors between leaders and followers were reciprocal (Supplementary Material, S4; Table S4 and Fig. S3, see online supplementary material for a color version of this figure).

Interpersonal brain synchronization increment

A series of mixed-model ANOVAs were performed on the IBS increments across all ROI combinations along the full frequency range (0.015–0.7 Hz). The resulting P values were corrected by the FDR method ($P < 0.05$). Results showed significant interaction effects of Condition × Pair on the IBS increments at the frequency band of 0.015–0.017 Hz and 0.048–0.057 Hz that survived the FDR correction (Fig. 2E; Table S5).

Specifically, significant interaction effect on the IBS increment of rAG–rAG was observed at the frequency of 0.015 Hz ($P_{corr} = 0.011$), 0.016 Hz ($P_{corr} = 0.005$), and 0.017 Hz ($P_{corr} = 0.005$). Therefore, we averaged the IBS increments of rAG–rAG at these 3 adjacent frequencies and reported the result at the frequency band of 0.015–0.017 Hz. The ANOVA result showed a significant interaction effect on the IBS increment of rAG–rAG ($F_{1, 53} = 28.845$, $P = 1.78 \times 10^{-6}$, $\eta^2 = 0.352$; Fig. 4A and B). The IBS increment was significantly lower for the LF pairs than for the FF pairs in condition A ($P = 0.002$, Cohen's $d = 0.752$), whereas the IBS increment was significantly higher for the LF pairs than for the FF pairs in condition E ($P < 0.001$, Cohen's $d = 0.922$). In addition, the IBS increment for the LF pairs was significantly lower in condition A than in condition E ($P < 0.001$, Cohen's $d = 1.295$).

Significant interaction effect on the IBS increment of rAG–rSMG was observed at the frequency of 0.015 Hz ($F_{1, 53} = 17.439$, $P = 1.11 \times 10^{-4}$, $P_{corr} = 0.037$, $\eta^2 = 0.248$; Fig. 4D and E). The IBS increment was significantly lower for the LF pairs than for the FF pairs in condition A ($P = 0.036$, Cohen's $d = 0.520$), whereas the IBS increment was significantly higher for the LF pairs than for the FF pairs in condition E ($P < 0.001$, Cohen's $d = 0.801$). Besides, the IBS increment for the LF pairs was significantly lower in condition A than in condition E ($P = 0.002$, Cohen's $d = 0.878$).

Significant interaction effect on the IBS increment of rMTG-rMotor was observed at the frequency of 0.048 Hz ($P_{corr} = 0.009$), 0.050 Hz ($P_{corr} = 0.037$), 0.053 Hz ($P_{corr} = 0.034$), and 0.057 Hz ($P_{corr} = 0.037$). Therefore, we averaged the IBS increments of rMTG-rMotor at these 4 adjacent frequencies and reported the result at the frequency band of 0.048–0.057 Hz. The ANOVA result showed a significant interaction effect on the IBS increment of rMTG-rMotor ($F_{1, 53} = 24.643$, $P = 7.53 \times 10^{-6}$, $\eta^2 = 0.317$; Fig. 4G and H). The IBS increment was significantly lower for the LF pairs than for the FF pairs in condition A ($P < 0.001$, Cohen's $d = 1.338$), whereas the IBS increment was significantly higher for the LF pairs than for the FF pairs in condition E ($P = 0.028$, Cohen's $d = 0.621$). Besides, the IBS increment for the LF pairs was significantly lower in condition A than in condition E ($P < 0.001$, Cohen's $d = 1.165$), whereas the IBS increment for the FF pairs was significantly higher in condition A than in condition E ($P = 0.006$, Cohen's $d = 0.770$).

Validation analysis

The validation analysis confirmed that the observed interaction effect of Condition × Pair on the IBS increments of rAG–rAG, rAG–SMG, and rMTG–rMotor for the real group sample were in top 1% of the permutation distribution (Fig. 4C, F, I).

Brain-behavior relationships

Bivariate Pearson correlation results showed the IBS increment of rMTG-rMotor for the LF pairs was positively correlated with the group IOC ($r = 0.379$, $P = 0.004$, $P_{corr} = 0.048$; Fig. 4J) and the IOC of LF ($r = 0.336$, $P = 0.012$, $P_{corr} = 0.072$; Fig. 4K). Table S6 reported the full correlation results.

Hyper-brain network analysis

Regarding the global network parameters, independent sample t-tests showed that the E_{glob} or E_{loc} did not differ in 2 conditions ($Ps > 0.1$). Regarding the nodal parameters, 2-way ANOVA results showed significant main effects of Condition on the nodal betweenness of the rAG ($F_{1, 106} = 11.420$, $P = 0.001$, $P_{corr} = 0.007$, $\eta^2 = 0.097$) and the rSMG ($F_{1, 106} = 8.167$, $P = 0.005$, $P_{corr} = 0.018$, $\eta^2 = 0.036$). The nodal betweenness of the rAG and the rSMG were significantly higher in condition E than in condition A (Fig. 5A and B; Table S7).

Discussion

In this study, we explored the effects of the appointed and emergent leaders on creative group communication and uncovered the underlying interpersonal neural correlates using an fNIRS-based hyperscanning technique. Previously unacquainted participants were randomly assigned to 3-person groups to complete a creative problem-solving discussion (RPP). The emergent leaders generated more ideas compared with the appointed leaders. In condition E, the group's creative outcomes (i.e. the group originality) were significantly better, and participants exhibited more perspective-taking behaviors, particularly between leaders and followers. The fNIRS results revealed that the IBS increments of rAG–rAG, rAG–rSMG, and rMTG–rMotor for the LF pairs were significantly higher in condition E. Moreover, the IBS increment of rMTG–rMotor for the LF pairs was positively correlated with the IOC of the group and LF. In addition, the graph-based analysis revealed higher nodal betweenness of the rAG and the rSMG in condition E. These findings indicated that letting leaders spontaneously emerge is beneficial to both creative outcomes and interactive processes. The IBS among brain areas involved in mentalizing, semantic information retrieval, and motor imagery may underlie the effects of LF interactions on group creativity.

Through adaptive social interactions in creative group communication, individuals who fit the prototype of the ideal leader were recognized as emergent leaders (Derue 2011; Lord et al. 2020). We investigated the ideal leader prototype in group creativity. The individual fluency was significantly higher for the emergent leaders than for followers in condition E. Because the RPP task mainly demands creative idea generation, effective leaders might try their best to produce as many ideas as possible in a short duration (i.e. 5 min). Participants elected those who could produce more ideas to be emergent leaders, indicating that at least in creative idea generation by groups, the quantity of verbal communication is vital for predicting leader emergence. We asked group members to evaluate which of their peers emerged as the leader (Ensari et al. 2011), rather than employing several trained observers to make the judgment on who the leader was by watching the video records of group interaction (Jiang et al. 2015). A recent study used the latter method to identify the leaders and followers in dyads of participants who were engaged in a creative group task (Liang et al. 2022). Consistent with the results of our study, they found that the leaders expressed more views than the followers. This suggests that external judgers and group members share beliefs regarding what the ideal leader should be in group creativity, i.e. individuals who are good at generating numerous ideas (but not necessarily novel ideas).

Regarding the creative group outcomes, the group originality was higher in condition E than in condition A. Accordingly, hypothesis (I) was supported. Group creativity occurs when idea-sharing stimulates group members' semantic networks of related ideas (Brown and Paulus 2002). Researchers have confirmed the basic presumption of brainstorming that quantity breeds quality (Paulus et al. 2011). In other words, generating more ideas leads to the generation of more creative ideas. The emergent leaders generate numerous ideas, and such generous idea-sharing can stimulate group members to think of additional ideas. By refining or combing the generated ideas, participants can come up with novel ideas more easily. The current result is in accordance with previous findings that the shared leadership enhanced group

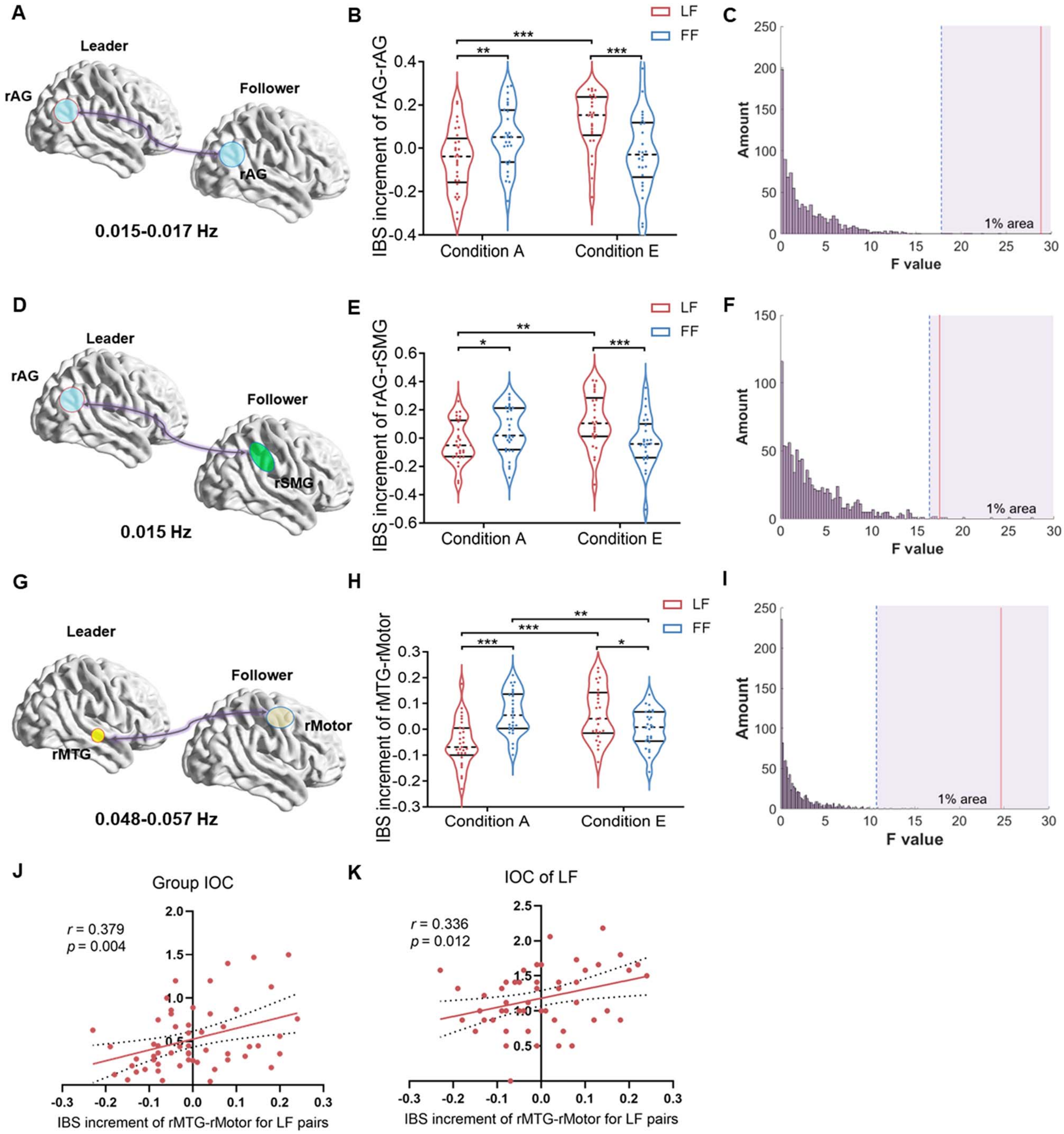

Fig. 4. IBS increment. A/D/G) The location of the IBS increment of rAG–rAG/rAG–rSMG/rMTG–rMotor on the cerebral cortex. B/E/H) The IBS increment of rAG–rAG/rAG–rSMG/rMTG–rMotor for the LF and FF pairs under 2 conditions. Data are plotted as violin plot to show the distribution of all points. The black solid lines denote quartiles and dotted lines denote median values. $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$. C/F/I) The permutation distribution of *F* values from the mixed-model ANOVAs on the IBS increment of rAG–rAG/rAG–rSMG/rMTG–rMotor of the pseudo groups. The vertical axis indicates the amount of the occurrence of the corresponding *F* values. The 1% upper area is highlighted by the lavender rectangle. The red solid line denotes the position of the *F* value of the Condition × Pair interaction effect of the real group sample, which is outside the upper limit of 99% confidence interval (denoted by the blue dotted line). J) The correlation between the group index of convergence (IOC) and the IBS increment of rMTG–rMotor for the LF pairs. K) The correlation between the paired IOC of LF and the IBS increment of rMTG–rMotor for the LF pairs.

members' creative self-efficiency and individual creativity, which in turn improved group creativity (He et al. 2019). In contrast to the vertical leadership that stems from a formally appointed leader, the shared leadership is an emergent phenomenon in which group members enact leadership roles and functions with the objective of achieving group goal (Hiller et al. 2006; Ali et al. 2020). As the adaptive leadership theory suggests, the shared leadership is embedded in the dynamic social interaction process that engages each group member simultaneously perform leading and following roles to successfully attain group-level outcomes (Derue 2011; Chiu et al. 2016). Compared with the "top-down" influence of the appointed leadership, the "bottom-up" emergent leadership mobilize the group members and brings better group creative outcomes.

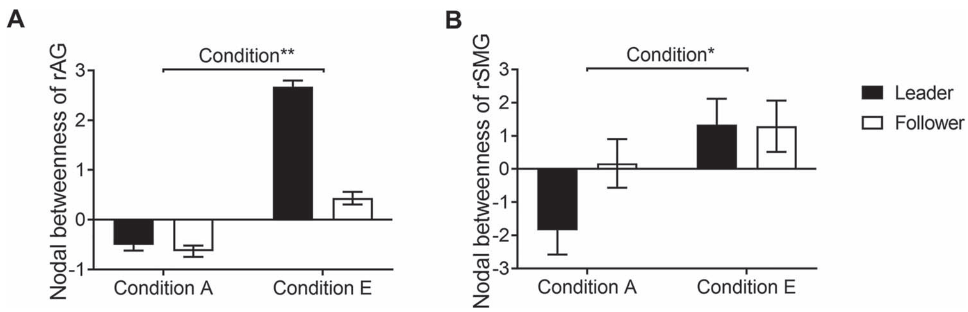

Fig. 5. Hyper-brain network parameters. A) Nodal betweenness of the rAG. B) Nodal betweenness of the rSMG. Data are shown as the mean ± SE $^*P < 0.05$, $^{**}P < 0.01$.

We assessed the perspective-tasking behaviors with both the group and paired IOC to quantify the interactive processes. The results showed that the group IOC was significantly greater in condition E than in condition A. In addition, the paired IOC of LF was more frequent in condition E. These results supported hypothesis (II). As a key process of creative interaction, the perspective-taking behaviors can increase the chance of developing novel ideas (Oztop et al. 2018). Although we had encouraged participants to learn from others' perspectives in both conditions, more perspective-taking behaviors occurred in condition E. A possible explanation is that appointing leaders before the task may create unequal power relations among individuals who are labeled as leaders and followers, shown to be harmful to perspective-taking (Galinsky et al. 2006; Muscatell et al. 2012). As products of the adaptive interaction process, leaders and followers that spontaneously emerge exhibit more mutual information-exchange. The emergent leaders generate numerous ideas themselves and listen to the ideas shared by others. The followers are more likely to consider the leaders' views owing to the leaders' better performance. Creative group outcomes may benefit from such stimulating effect of idea-sharing on idea generation.

The fNIRS results showed similar patterns of the IBS increments of rAG–rAG, rAG–rSMG, and rMTG–rMotor. The IBS increments were lower for the LF pairs than for the FF pairs in condition A, whereas the IBS increments were higher for the LF pairs than for the FF pairs in condition E. These findings support hypothesis (III). Previous hyperscanning studies on verbal communication demonstrated that the IBS increment may serve as the neural base of information-exchange and mutual understanding (Silbert et al. 2014; Liu et al. 2019; Wang et al. 2022). The higher IBS increments for the LF pairs indicated that the mutual information-exchange between leaders and followers were more active in condition E, whereas that for the FF pairs indicated that followers were more focused on each other's ideas in condition A.

The IBS increments of rAG–rAG and rAG–rSMG were significantly higher for the LF pairs in condition E. In social interaction, understanding other minds (i.e. "mentalizing" or "theory of mind") is fundamental for people to predict and interpret others' behaviors (Saxe and Kanwisher 2003; Frith and Frith 2005). Both the rAG and the rSMG are subregions of the right temporal parietal junction, which is a hub in the mentalizing network (Saxe and Powell 2006; Santiesteban et al. 2012; Brethel-Haurwitz et al. 2022). The rAG is involved in theory of mind (Schurz et al. 2017; Filmer et al. 2019). Previous hyperscanning studies on group creativity have repeatedly observed the IBS increment at the rAG (Xue et al. 2018; Lu et al. 2019, 2021, 2022), indicating the importance of the rAG in creative thinking within social interaction contexts. The rSMG is involved in self-other distinction, particularly in overcoming egocentric biases when judging others' internal states (Silani et al. 2013; Steinbeis 2016). The rSMG plays a unique role in processing others' thoughts (Grosse et al. 2020). Taken together, the higher IBS increments of rAG–rAG and rAG–rSMG for the LF pairs in condition E suggested that leaders and followers paid more attention to each other's ideas and tried to understand others' perspectives. This result was consistent with previous evidence that the IBS increment at the TPJ was higher for the LF pairs than for the FF pairs in leader emergence (Jiang et al. 2015), indicating the function of mentalizing in LF relationship construction. Accordingly, the lower IBS increment for the LF pairs than for the FF pairs in condition A may be interpreted as the less success of establishing and maintaining the relationship between leaders and followers, resulting in reduced willingness of group members to listen to others' ideas.

Significant interaction effect of Condition × Pair was observed on the IBS increment of rMTG–rMotor. The IBS increment for the LF pairs was higher in condition E, whereas that for the FF pairs was higher in condition A. Generating creative ideas requires individuals to search their relevant semantic knowledge for relevant ideas (Paulus and Brown 2007). The MTG plays the pivotal role in semantic memory processing, forming new concepts, and integrating creative associations (Binder et al. 2009; Ren et al. 2020). In addition, the motor cortex is associated with motor imagery, i.e. mentally simulating possible future actions, which benefits creative idea generation (Matheson et al. 2017; Matheson and Kenett 2020). In the RPP task, participants were required to suggest solutions to a real-world problem. These solutions were essentially a series of action plans that could be mentally simulated. Therefore, the IBS increment of rMTG–rMotor for the LF pairs may represent information-exchange whereby leaders generate ideas by searching for the semantic memory and integrating novel associations, and followers simulate action plans described in the shared ideas. The synchronization between the brain regions involved in semantic processing and motor imagery may help individuals understand others' perspectives more efficiently and discover their own ideas by combining or elaborating the existing ideas. This is supported by our findings that the IBS increment of rMTG–rMotor for the LF pairs correlated positively with both the group and paired IOC.

We adopted the graph-based analysis to explore the characteristics of the hyper-brain network composed by the observed ROIs of all group members. Hypothesis (IV) was not supported as the lack of differences in global topological network properties (E_{glob} or E_{loc}) in 2 conditions. This may partly be due to the potential confounding effects of the inter- and intra-brain networks, as previous studies reported significantly higher E_{glob} in the interbrain networks in higher-performing groups (Liu et al. 2021; Wang et al. 2022). We observed that the nodal betweenness of the rAG and the rSMG were higher in condition E than in condition A. The nodal betweenness can reflect the centrality of each ROI in the hyper-brain network (Freeman 1977; Feng et al. 2021). Therefore, the higher nodal betweenness of the rAG and the rSMG implied that more node pairs passed through these 2 ROIs, indicating that the rTPJ is more likely to be in the center of the hyper-brain network in condition E. Combining the results of the higher IBS increments of rAG–rAG and rAG–rSMG for the LF pairs in condition E, this finding suggests that the rTPJ plays a pivotal role in LF interactions during creative group communication.

The knowledge about functional connectivity (FC) and creativity may also shed light on the current findings. The right temporal parietal region is known to be highly connected to the default mode network (DMN; e.g. medial prefrontal cortex and posterior cingulate cortex), the cognitive control network (CNN; e.g. dorsolateral prefrontal cortex) and the sensory regions (Perennou et al. 2000; Kubit and Jack 2013; Schuwerk et al. 2017). To further explore the effects of different arising ways of leaders on the FC of group members during creative group communication, we calculated the intra-brain FC within the right temporoparietal region (see Supplementary Material, S5 and Fig. S4, see online supplementary material for a color version of this figure). Results showed significant interaction effects of Condition × Role on the FC between the rAG and the rPSC, and the FC between the rAG and the rSAC. Specifically, the intra-brain FC of leaders was significantly stronger in condition E, whereas significantly lower in condition A. What's more, the FC of rAG–rPSC and rAG–rSAC were both positively correlated with the individual fluency scores. The rAG is a core hub of the DMN that involves in automatic generation of candidate ideas during creative thinking (Beaty et al. 2016). The somatosensory cortex is related to speech production (Guenther et al. 2006; Brownsett and Wise 2010). Hence, the stronger FC between the rAG and somatosensory cortices (rPSC and rSAC) may be interpreted to play a role in verbally expressing the automatically generated ideas, which serves as the neural base of higher individual fluency. A recent study revealed the inferior parietal lobe (IPL; including the AG and SMG) was positively connected to the MTG during creative thinking, all of which are subregions of the DMN (Sun et al. 2019). Nevertheless, we did not observe such significant difference between 2 conditions. This may indicate the FC of regions within the DMN is important for creative group communication no matter how leaders arise. In addition, creative cognition also involves the interaction between 2 large-scale networks (i.e. DMN and CNN), which is thought to reflect a coordination of spontaneous and controlled idea generation processes (Beaty et al. 2018, 2021). However, due to the technical limitation of fNIRS (e.g. limited optode), the FC across other regions, especially those belonging to the DMN and CNN, remained unexplored in the current study. Future investigation should examine the function of the FC across regions within the DMN and CNN in creative group communication.

This study had several limitations. First, in small groups, the group performance is susceptible to the dominant individuals, such as the group leaders. The group size affects the LF exchange quality and task performance (Li et al. 2020). Future studies should investigate interaction dynamics between leaders and followers during creative group communication in larger groups. Second, we mainly focused on the idea generation stage of group creativity. The leaders' ability to generate more ideas and integrate perspectives of group members may be significant predictors of leadership at this stage. However, leaders may also contribute to creative group outcomes by evaluating and providing feedbacks on the followers' ideas (Mumford et al. 2003). Further investigation is required to fully understand the role of leadership at different stages of group creativity. Third, although the emergent leaders can be identified in most groups, 4 groups in condition E were exceptions. Group members chose different individuals as leaders and failed to reach an agreement. This phenomenon could be interpreted as no leader emergence or the shared leadership (Wang et al. 2014), and the underlying mechanism deserves further investigation. Fourth, this study did not introduce an active control condition including a communicative noncreative task. It could hardly distinguish whether the observed IBS was related to the perspective-taking behaviors between leaders and followers or the emergent leaders being more creative (i.e. building their leadership upon successful creative behavior). Therefore, a control condition with noncreative tasks should be considered in future investigations. Fifth, we asked participants to keep their eyes-closed in the resting-state session. This session served as the baseline. Although this method was widely used in previous hyperscanning studies (Lu et al. 2010; Jiang et al. 2015; Lu et al. 2021), we could not exclude the effects of the potential differences between the brain activities of eyes-closed and eyes-opened states. As participants were supposed to open their eyes and make eye contacts during the RPP session, future studies can adopt an eyes-opened baseline (Pan et al. 2022) to control the potential effects. Finally, we only measured the neural activity in the right temporoparietal region due to the limited number of optode. The right TPJ has been identified as an important region for cognitive processes related to creative performance (Benedek et al. 2014; Goel et al. 2015) such as attention reorienting (Corbetta et al. 2008), memory processing (Binder and Desai 2011), and social cognition (Decety and Lamm 2007). Nevertheless, the functional lateralization of the TPJ in socio-cognitive processes have been debated for years. With respect to theory of mind, several studies reported bilateral TPJ involvement (Jenkins and Mitchell 2010; Santiesteban et al. 2015), whereas others reported unilateral involvement of the right TPJ (Santiesteban et al. 2012) or the left TPJ (Samson et al. 2004). In addition, the bilateral dorsolateral prefrontal cortex also plays a role in group creativity and social interaction (Lu et al. 2019). Future studies may simultaneously record signals in bilateral frontal, temporal, and parietal cortices of multiple individuals by adjusting the arrangement of measurement probes.

In conclusion, the present study showed that letting leaders spontaneously emerge through social interaction, rather than appointing the leader, is beneficial for the LF relationship construction and the perspective-taking behaviors, resulting to better creative group outcomes. Neuroimaging results showed that mutual information-exchange between leaders and followers was accompanied by the IBS increment in the brain regions that are typically involved in mentalizing, semantic memory retrieval, and motor imagery. These results revealed the neural correlates of the LF interaction during creative group communication. Our findings extend the applicability of the adaptive leadership theory to the area of group creativity and provide feasible suggestion to stimulate the creative potential of newly-formed groups by letting leaders emerge spontaneously.

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Supplementary material

Supplementary material is available at *Cerebral Cortex* online.

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Conflict of interest statement: The authors declare that they have no competing interests.

Author contributions

Y.H., X.W., K.L., and N.H. conceived of the project and designed the experiments. Y.H. implemented the experiment and collected data. Y. H., X. W., and K.L. preprocessed the data, performed analysis, and discussed results. Y.H., X. W., K.L., and N.H. wrote the paper.

Data and code availability

The data and code used to support the findings of this study are available from the corresponding author upon request. The data can only be for research use. If the associated research is to be published, the statement "The data and code were acquired from the Shanghai Key Laboratory of Mental Health and Psychological Crisis Intervention, School of Psychology and Cognitive Science, East China Normal University" is required in the manuscript.

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