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Creating while taking turns, the choice to unlocking group creative potential

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ABSTRACT

This study aimed to examine how communication modes affect creative idea generation in groups. Three communication mode conditions were created: natural (N), turn-taking (T), and electronic brainstorming (E). Participants were randomly recruited and grouped in dyads to solve one alternative uses task (AUT) in each condition, during which functional near-infrared spectroscopy (fNIRS)-based hyperscanning was used to record interpersonal neural responses. No difference was observed in AUT fluency across the three conditions, but AUT uniqueness was higher in the T condition than in the E condition. In addition, AUT uniqueness, AUT fluency, and perspective-taking behaviours increased faster in the T condition than in the other conditions. The T condition also showed higher perspective-taking behaviours than did the other conditions. Moreover, fNIRS data showed higher interpersonal brain synchronisation (IBS) increments at the right angular gyrus in the T condition than in the other conditions, which positively predicted perspective-taking behaviours between individuals during group creativity tasks. These findings indicate that when group members create together while taking turns, both creative performance and interpersonal interaction processes can be stimulated.

1. Introduction

Group creativity is increasingly necessary for the development of scientific research, business organisations, and even human society. When we engage in the group generation of creative ideas, the issue inevitably arises of how we interact with each other while doing so. Since communication is the foundation of interpersonal interaction and facilitating communication between team members can have a positive effect on the group's creative performance (Michinov, 2012), we suppose that the mode of communication may affect creative idea generation within a group.

Turn-taking, natural communication, and electronic brainstorming are the most widely used communication modes in group creative idea generation in both experimental and real-world contexts, and each has advantages and disadvantages. In turn-taking, group members are asked to take turns reporting their ideas, and only one idea is allowed per turn. The turn-based design suffers from production blocking, which is the main cause of productivity loss in brainstorming groups because individuals who want to express their ideas have to wait until the other person has finished speaking (Nijstad et al., 2003). However, this communication mode can also force individuals to pay attention to ideas generated by others; thus, these ideas can serve as search cues activating relevant knowledge from long-term memory and increasing the breadth of ideas (Stroebe et al., 2010).

The natural communication mode is widely used in studies of interpersonal verbal communication (Jiang et al., 2012; Nozawa et al., 2016). Recently, it has also been adopted in some studies of group creativity (Mayseless et al., 2019). In this mode, individuals are allowed to report ideas as they occur, just like communicating with others in an outside-the-laboratory context. Use of such a communication mode in a group experiment can yield higher ecological validity. Although natural communication can avoid production blocking resulting from the turn-taking setting, it cannot eliminate the impacts of evaluation apprehension or free riding, which have been shown to harm group performance (Nijstad and Stroebe, 2006). Moreover, it should be noted that although there is no turn-taking setting, production blocking still occurs in the natural communication mode. For instance, when one person expresses more than one idea consecutively, production blocking occurs.

In the electronic brainstorming communication mode, group members are asked to report their ideas using a computer without taking turns, and they are able to see others' ideas on the computer. This allows individuals to share ideas without experiencing production blocking

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(Gallupe et al., 1991) and minimises individual evaluation apprehension by increasing anonymity. However, recent research has shown that the synchronisation of brain activity between group members could be affected by how involved the members are in the communication, and turn-taking behaviours, which have been seen as the major feature in face-to-face communication, may reflect a person's involvement in the communication (Schippers et al., 2010). Also, Jiang et al. (2012) suggested that face-to-face communication has a pivotal neural substrate (interpersonal neural synchronisation) that other types of communication lack (e.g. back-to-back dialog). They also found that the enhanced interpersonal neural synchronisation was mostly contributed by interpersonal interaction behaviours (e.g. facial expression and turn-taking behaviours). Thus, when team members are less involved during group creative idea generation in electronic brainstorming than the face-to-face communication mode (e.g. turn-taking), this may negatively affect the group's creative performance.

Although the three communication modes are widely used in both experimental and real-world contexts, it is still unknown how these modes affect the collaborative creative process and final creative outcomes in a group. We thus addressed the following questions: (1) 'How will communication modes affect the creative process in a group?' and (2) 'How will communication modes affect the creative outcomes of a group?' In addition, to reveal the interpersonal neural correlates that underlie the effect of different communication modes on group creativity, we used an functional near-infrared spectroscopy (fNIRS)-based hyperscanning technique to record the brain responses of team members simultaneously. Hence, we ask the additional question: (3) 'What are the interpersonal neural correlates that underlie the effect of communication modes on group creativity?' By addressing these questions, we can not only enrich our understanding of how communication modes affect group creativity and their underlying interpersonal neural correlates but also provide advice for innovation teams and organisations in the world outside the laboratory.

The hyperscanning technique is a nascent and promising research method that helps to improve our understanding of the neural mechanisms behind social interaction. It allows the brain activity of multiple individuals to be scanned simultaneously and can be conducted using functional magnetic resonance imaging (fMRI) (Li et al., 2009), electroencephalography (EEG) (Dikker et al., 2017), and fNIRS (Dai et al., 2018). Multiple studies have used this technique to successfully elucidate neural mechanisms in various social interactions (Gvirts and Perlmutter, 2019; Redcay and Schilbach, 2019). The reasons for using the fNIRS-based hyperscanning approach in the present study are as follows: (1) the fNIRS shows higher tolerance for motor artefacts than EEG or fMRI; (2) the fNIRS offers higher ecological validity than EEG or fMRI; and (3) fNIRS allows verbal communication during scanning. Moreover, since previous hyperscanning studies of group creativity have shown that the prefrontal cortex (PFC) and right temporal-parietal junction (r-TPJ) are recruited in group creative idea generation, these two brain regions were chosen as our regions of interest (Lu et al., 2019a,b; Xue et al., 2018).

In the present study, participants were randomly assigned to dyads to solve three creativity tasks (alternative uses tasks, AUTs) using different communication modes (natural, turn-taking, and electronic brainstorming). We primarily focused on the divergent thinking task because divergent thinking performance is a key component of creativity and a reliable predictor of individual creative potential (Runco and Acar, 2012). During the experiment, an fNIRS-based system was adopted to simultaneously record the continuous neural responses of both participants in each dyad. Since each communication mode has its own advantages (natural: no external constraint; turn-taking: forced interpersonal interaction; electronic brainstorming: no production blocking and lower evaluation apprehension), it was difficult to posit any precise hypothesis regarding the effect of communication modes on group creativity, especially the underlying interpersonal neural correlates. Consequently, we considered it more proper to posit no precise hypotheses. Hereafter, the letters N/T/E indicate the natural/turn-taking/electronic brainstorming communication modes, respectively.

2. Method

2.1. Participants

A total of 54 college students (44 females, age: 20.52 ± 2.22 years old) were recruited in this study. All participants were right-handed, with normal or corrected-to-normal vision. Participants were randomly assigned to a total of 27 dyads (22 female-female dyads and 5 male-male dyads). In each dyad, participants were unknown to each another. Informed consent was obtained from participants prior to the experiment. Each participant was paid ¥ 37 for participating. The study procedure was approved by the University Committee on Human Research Protection of East China Normal University.

The study consisted of a single-factor design, with CONDITION (natural communication mode, turn-taking communication mode, and electronic brainstorming communication mode) as the within-subject factor.

2.2. Experimental procedure

Upon arrival, participants were asked to sit facing each other at a 1.6-m table (made up of two 0.8-m tables) (see Fig. 1). The experiment began after the participants were given a brief introduction on the experimental setup (i.e. 'You are a team, and the final task performance depends on both of you. There will be three creativity tasks during the whole experiment. Please try your best!'). The experimental procedure consisted of three 1-min resting-state sessions, three 1.5-min instruction sessions, and three 5-min task sessions (see Fig. 1E). The two resting-state sessions, which were situated between each two tasks, served as the baseline. During this session, participants were asked to remain as still as possible, with their eyes closed and mind relaxed (Lu et al., 2010).

Immediately after the first resting-state session, four typical rules of group brainstorming (i.e. deferment of judgement, quantity breeds quality, freewheeling is encouraged, and combination and improvement are sought) were introduced to the participants (Osborn, 1957). In addition, following each resting-state session, the participants were introduced to and given instructions for each creativity task at length.

In this study, three AUTs were used as the target creativity tasks. In each task, the participants were explicitly instructed to be creative and generate as many creative uses for an everyday object as possible (Guilford, 1967). The AUT is a well-established divergent thinking task, a reliable predictor of real-world creative performance (Runco and Acar, 2012), and has been widely used in behavioural and neuroscience studies of creativity (Fink et al., 2009; Lu et al., 2019b; Runco and Okuda, 1991). Here, a 'toothbrush,' a 'candle,' and a 'clip' were used as the target everyday objects. The task sequence was determined by random draw.

During each task session, participants were required to complete one AUT using one of the three communication modes. The mode sequences were counterbalanced among dyads. In the N condition, participants could orally report as soon as they generated an idea. The participants were allowed to report more than one idea whenever ideas came to mind, unless their partner was already reporting (see Fig. 1A). Similarly, in the E condition, the participants were allowed to type their ideas and send them to their partner using the computer as soon as ideas came to mind. The online operation interface was located on the left half of the computer screen. Meanwhile, participants could read the ideas sent by their partners on the right half of the screen (see Fig. 1C). However, in the T condition, the reporting sequence of the two participants in each dyad was randomly determined by the experimental assistant before the experiment. The participants were asked to take turns orally reporting ideas, one idea at a time. They were allowed to say 'pass' if they failed to present an idea during their respective turn (see Fig. 1B). In the N and T conditions, participants' responses were recorded by a recording pen (an audio recorder), whereas responses were recorded by the computer in the E condition.

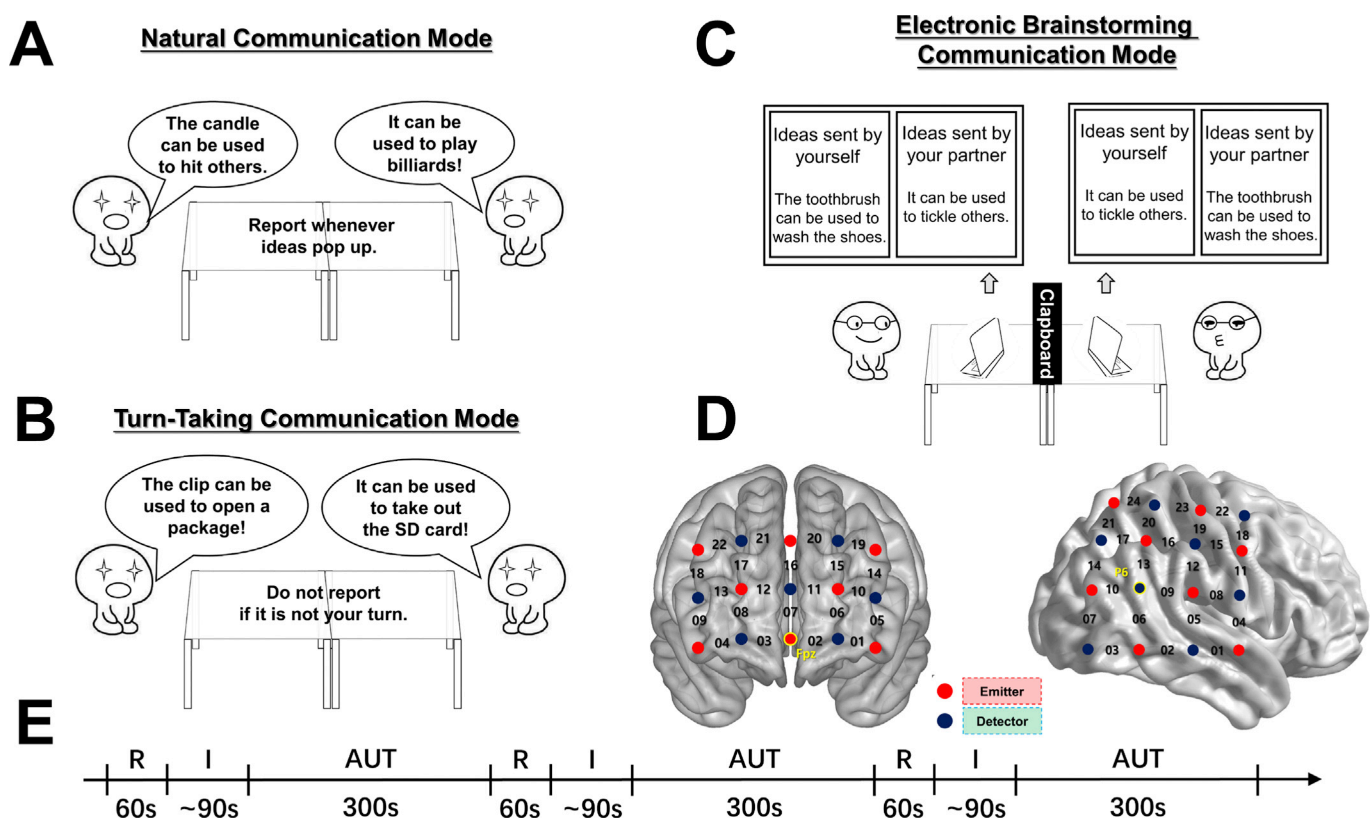

Fig. 1. Communication mode in different conditions and hyperscanning design. (A) Natural communication mode. Participants were allowed to report ideas whenever they generated ideas. (B) Turn-Taking communication mode. Participants were asked to report while taking turns and only one idea was allowed during one turn. (C) Electronic brainstorming communication mode. Participants were asked to report ideas by using the computer. Hereafter, N/T/E in the following figures indicates the natural/turn-taking/electronic brainstorming communication mode, respectively. (D) Optode probe set. The probe patch is placed on the PFC and r-TPJ areas. (E) Hyperscanning procedure. R: 60-s resting state session; I: ~90-s instruction introduction session; AUT: 5-min AUT session. The sequence of the three tasks was counterbalanced.

2.3. AUT performance assessment

Each dyad's AUT performance was assessed using the fluency and uniqueness of the reported responses (Guilford, 1967; Runco, 1991; Runco and Acar, 2012). The fluency score was determined by the total number of responses reported by each dyad. The uniqueness score was determined using an objective scoring method. Reponses from all dyads were collected into a comprehensive lexicon. Next, synonyms were identified and responses collapsed accordingly. If a response was statistically infrequent (i.e. the response was reported by 5% or fewer of the participants in the sample), it was scored as '1'. All other responses were scored as '0'. Following this procedure, two trained raters blind to experimental conditions independently assessed the uniqueness score for each dyad. The inter-rater agreement of this method (internal consistency coefficient [ICC] = 0.95) was satisfactory. It should be noted that ICC was calculated as Cronbach's α. The final uniqueness score for each dyad was obtained by averaging the individual ratings of the two raters. We also calculated the uniqueness percentage for each dyad using the following equation: uniqueness percentage = uniqueness/fluency.

In addition, we calculated the occurrence of the first unique idea in each dyad, which indicates the time at which the first unique response (scored '1' in the AUT uniqueness assessment) was generated (see Supplementary S2).

2.4. Collective communication behaviour

To explore the extent to which the participant combined his/her own responses with his/her partner's in each dyad (perspective-taking behaviour), an adapted index of convergence (IOC) was used (Larey and Paulus, 1999; Lu et al., 2019a). The adapted IOC for each dyad was calculated as follows: (1) Based on the time point, responses were listed sequentially for each dyad. (2) If a response from 'participant 1' was identified as a response from the same category to which the previous response from 'participant 2' belonged, it was scored '1'. The total number of responses scored '1' was used as the Sum (stay). For instance, if there were 13 responses scored '1', the Sum (stay) was '13'. (3) The IOC for each dyad was obtained based on the following equation: IOC = Sum (stay)/[Dyad fluency – Sum (stay)]. Here, 'Dyad fluency' indicates the AUT fluency of the dyad. The IOC for each dyad was assessed independently by two trained raters. The inter-rater agreement was satisfactory (ICC = 0.78). Eventually, the final IOC score for each dyad was obtained by averaging individual ratings from the two raters.

We also calculated the collective flexibility to evaluate the extent to which each dyad sought responses from different categories (Lu et al., 2019a). For each dyad, two trained raters were asked to independently calculate the total number of categories explored. The inter-rater agreement was satisfactory (ICC = 0.96). The final collective flexibility score for each dyad was obtained by averaging individual ratings from the two raters.

It should be noted that the independent raters were blind to experimental conditions. In addition, we calculated the occurrence of the first idea convergence in each dyad, which indicates the time at which the first idea convergence (scored '1' in the IOC assessment) occurred (see Supplementary S2).

2.5. Accumulation of AUT performance and idea convergence

To explore the trajectory of AUT performance and idea convergence, we assessed the accumulations of AUT fluency, AUT uniqueness, and idea convergence (scored '1' in the IOC assessment) over time. The accumulation of AUT fluency was calculated as follows: (1) the 300-s task period was divided into thirty 10-s sessions; (2) the AUT fluency in each 10-s session was calculated; (3) the accumulation of AUT fluency for each session was calculated by summing AUT fluency in this session and previous sessions. For instance, the accumulation of AUT fluency for the second session (i.e. 11 – 20 s) was the sum of AUT fluency in the second (e.g. fluency = 4) and first (e.g. fluency = 1) sessions; therefore, the accumulation of AUT fluency for the second session was 5. The accumulations of AUT uniqueness and idea convergence were calculated based on a similar procedure. However, since AUT uniqueness and IOC were assessed by two independent raters, the accumulations of AUT uniqueness and idea convergence were calculated by averaging the results of the two raters.

2.6. fNIRS data collection

Oxyhaemoglobin (HbO) and deoxyhaemoglobin (HbR) concentrations for both individuals in each dyad were recorded simultaneously using a NIRS system (ETG-7100, Hitachi Medical Corporation, Japan). The obtained NIRS data were converted through NIRS-SPM (Ye et al., 2009). The modified Beer-Lambert law was used to convert the raw optical intensities to the relative HbO and HbR concentrations. The sampling rate for measuring the absorption of near-infrared light (wavelengths: 695 and 830 nm) was 10 Hz. Since previous hyperscanning studies on group creativity have suggested that the PFC and r-TPJ regions were recruited in group creativity (Lu et al., 2019a,b; Xue et al., 2018), we focused on those regions in this study. One 3 × 5 optode probe set (8 emitters and 7 detectors, 3 cm optode separation) consisting of 22 measurement channels (CHs) was placed over each participant's PFC region. According to the international 10–20 system for electroencephalography, the lowest probes were positioned along the Fp1-Fp2 line, with the middle optode placed on the frontal pole middle point (Fpz) (Sai et al., 2014). The middle probe of the patch was aligned precisely along the sagittal reference curve. Additionally, one 4 × 4 optode probe set (8 emitters and detectors, 3 cm optode separation) consisting of 24 measurement CHs was placed over each participant's r-TPJ region. The lowest probe was aligned with the sagittal reference curve, and optode B was positioned on P6. The virtual registration method was used to determine the correspondence between the NIRS CHs and the measurement points on the brain (Singh et al., 2005; Tsuzuki et al., 2007) (see Fig. 1D; the MNI coordinates of CHs of a typical participant are presented in Table S2).

2.7. IBS increments of CHs within the PFC and R-TPJ patch

Given that the HbO signal showed higher sensitivity to changes in cerebral blood flow than the HbR signal, this study only focused on the HbO signal (Cui et al., 2012; Hoshi, 2007; Jiang et al., 2012).

During the data pre-processing, CHs with poor signals were replaced with the averaged HbO time series of the most adjacent CHs (e.g. if CH7 in the PFC patch was a bad CH, the time series was replaced with the averaged HbO time series of CH2, CH3, CH11, and CH12). The CH with 'poor signal' was determined based on the following two steps: (1) during the hyperscanning, the experimenter recorded the CHs with poor signals (i.e. the CHs with poor SNR); (2) after the hyperscanning, the wavelet transform plot was used to check the signal of CHs. If the heart beat signals (a bright brand in the frequencies around ~1 Hz) were not captured, it was identified as a CH with 'poor signal'. Due to extremely poor signals (more than half of the CHs had poor signals), the fNIRS data from four dyads were excluded from further analysis. Next, a principal component spatial filter algorithm (Zhang et al., 2016) was used to remove global components in the raw fNIRS data of each participant. Meanwhile, a correlation-based signal improvement method was applied to remove motion artefacts (Cui et al., 2010; Pan et al., 2018).

Data collected during the baseline session and three task sessions were entered into further interpersonal brain synchronisation (IBS) analyses. Meanwhile, to obtain data within the period of steady state, the data from the initial and final 30 s of the task session were removed, leaving 240 s of data for each task session. Next, wavelet transform coherence (WTC) was used to assess the relationship between HbO time series from the corresponding CHs of both participants in each dyad (i.e. IBS) (Grinsted et al., 2004). The WTC of HbO signals $i(k)$ and $j(k)$ was defined as follows:

$$\mathrm{WTC}\left(k,b\right) = \frac{\left|b^{-1}W^{ij}(k,b)\right|^2}{\left|b^{-1}W^{i}(k,b)\right|^2\left|b^{-1}W^{j}(k,b)\right|^2}$$

In the formula, k denotes the time and b the wavelet scale; $\langle\cdot\rangle$ indicates a smoothing operation in time and scale; W denotes the continuous wavelet transform.

The IBS increment for each task session was calculated by subtracting the time-averaged IBS during the baseline session from that during the task session. For further analysis, the IBS increments were converted to Fisher z-statistics (Chang and Glover, 2010; Cui et al., 2012).

One-way repeated measures ANOVAs using CONDITION as the within-subject factor were conducted on the IBS increment of each CH (a total of 46 CHs) along the full frequency range (0.015–0.7 Hz). Data above 0.7 Hz were not considered so as to exclude higher frequency noise such as cardiac activity (0.8–2.5 Hz) (Barrett et al., 2015; Tong et al., 2011). Additionally, significant IBS increments were often observed at frequencies above 0.015 Hz in previous hyperscanning studies on group creativity (Lu et al., 2019b; Mayseless et al., 2019; Xue et al., 2018). Data below 0.015 Hz were not considered, which also helped to remove very low-frequency fluctuations. All resulting P–values (generated by ANOVAs) were corrected using the false discovery rate (FDR) method ($P < 0.05$). There were 68 total frequencies within the full frequency range (0.015–0.7 Hz) and 46 CHs. Therefore, the total number of resulting P values was 46*68 = 3128. All of these P values were FDR corrected at one time. Next, Bonferroni-corrected post hoc tests were conducted to reveal the group difference in IBS increments (i.e. Bonferroni correction was used to account for multiple comparisons in post hoc tests). Eventually, we performed bivariate Pearson correlations to reveal the relationships between IBS increments and behavioural performance (i.e. AUT fluency, AUT uniqueness, IOC, collective flexibility).

We also explored the trajectory of significant IBS increments over time. Since the time series of IBS increments were non-stationary, the trajectory analysis on IBS increments was not based on a mixed model that incorporated time as a continuous variable. We split the remaining 240 s-task period equally into three epochs (i.e. EPOCH1, EPOCH2, EPOCH3) in each condition (Wang et al., 2019). A one-way repeated measures ANOVA using EPOCH (EPOCH1, EPOCH2, EPOCH3) as the within-subject factor was performed on IBS increments (showing significant group differences) for each condition.

2.8. IBS increments of CH combinations between the PFC and R-TPJ patch

To examine whether communication mode affected IBS increments of both corresponding CHs within and different CH combinations between the PFC and r-TPJ patch, we also calculated the IBS increments at the frequencies showing significant differences by condition in the previous IBS analysis for different CH combinations between the PFC and r-TPJ patch. Given that the report sequences of both participants in the dyads were random, the IBS increments of CH combinations between the PFC (participant 1) and r-TPJ (participant 2) and that between the PFC (participant 2) and r-TPJ (participant 1) were averaged for further analysis. There were 528 total CH combinations ($22_{\text{(number of CHs within the PFC patch)}} * 24_{\text{(number of CHs within the r-TPJ patch)}} = 528$). Next, similar IBS analyses were conducted on the IBS increments of 528 CH combinations.

2.9. Validation analysis

To determine whether such group difference in IBS increments was specific to the effect of CONDITION on the interacting participants (actual dyads) in a dyad, we performed a validation test (Jiang et al., 2015; Reindl et al., 2018): (1) The HbO time series of all 46 participants were randomly re-paired (no HbO time series of two participants from the identical actual dyad were re-paired), which we named it 'random dyads'. Note that time series from the same communication mode were paired. (2) Similar IBS analyses were then conducted for the random dyads. This permutation process was repeated 1000 times.

2.10. Post-experiment assessment

Immediately after the experiment, participants were asked to rate the task difficulty and communication mode effectiveness, how they liked the communication mode, how they liked collaborating with their partner, their tendency towards perspective-taking (i.e. 'we tended to complete the task by taking perspectives from each other during the task'), and task enjoyment. A 5-point Likert type scale was used for this assessment, ranging from 1 = not at all to 5 = very much (see results in Supplementary S3).

3. Results

3.1. AUT performance in different conditions

A one-way repeated-measures ANOVA using CONDITION as the within-subject factor was performed on AUT uniqueness. Results showed a significant main effect of CONDITION on AUT uniqueness, F (2, 52) = 4.90, $P = 0.011$, $\eta_p^2 = 0.16$. Post hoc tests (Bonferroni) showed that AUT uniqueness was significantly higher in the T condition ($M = 8.96$, $SD = 3.28$) than in the E condition ($M = 6.75$, $SD = 3.23$; $P = 0.018$) (see Fig. 2A).

In addition, a one-way repeated-measures ANOVA using CONDITION as the within-subject factor was performed on AUT uniqueness percentage. Results also showed a significant main effect of CONDITION on AUT uniqueness percentage, F (2, 52) = 4.88, $P = 0.011$, $\eta_p^2 = 0.16$. Post hoc tests (Bonferroni) showed that AUT uniqueness percentage in the E condition ($M = 0.34$, $SD = 0.13$) was marginally lower than in the T condition ($M = 0.40$, $SD = 0.09$; $P = 0.053$) and significantly lower than in the N condition ($M = 0.44$, $SD = 0.15$; $P = 0.038$) (see Fig. 2B).

Moreover, a similar one-way repeated-measures ANOVA using CONDITION as the within-subject factor was performed on AUT fluency. No significant main effect was observed, F (2, 52) = 1.86, $P > 0.05$, $\eta_p^2 = 0.07$ (see Fig. 2C).

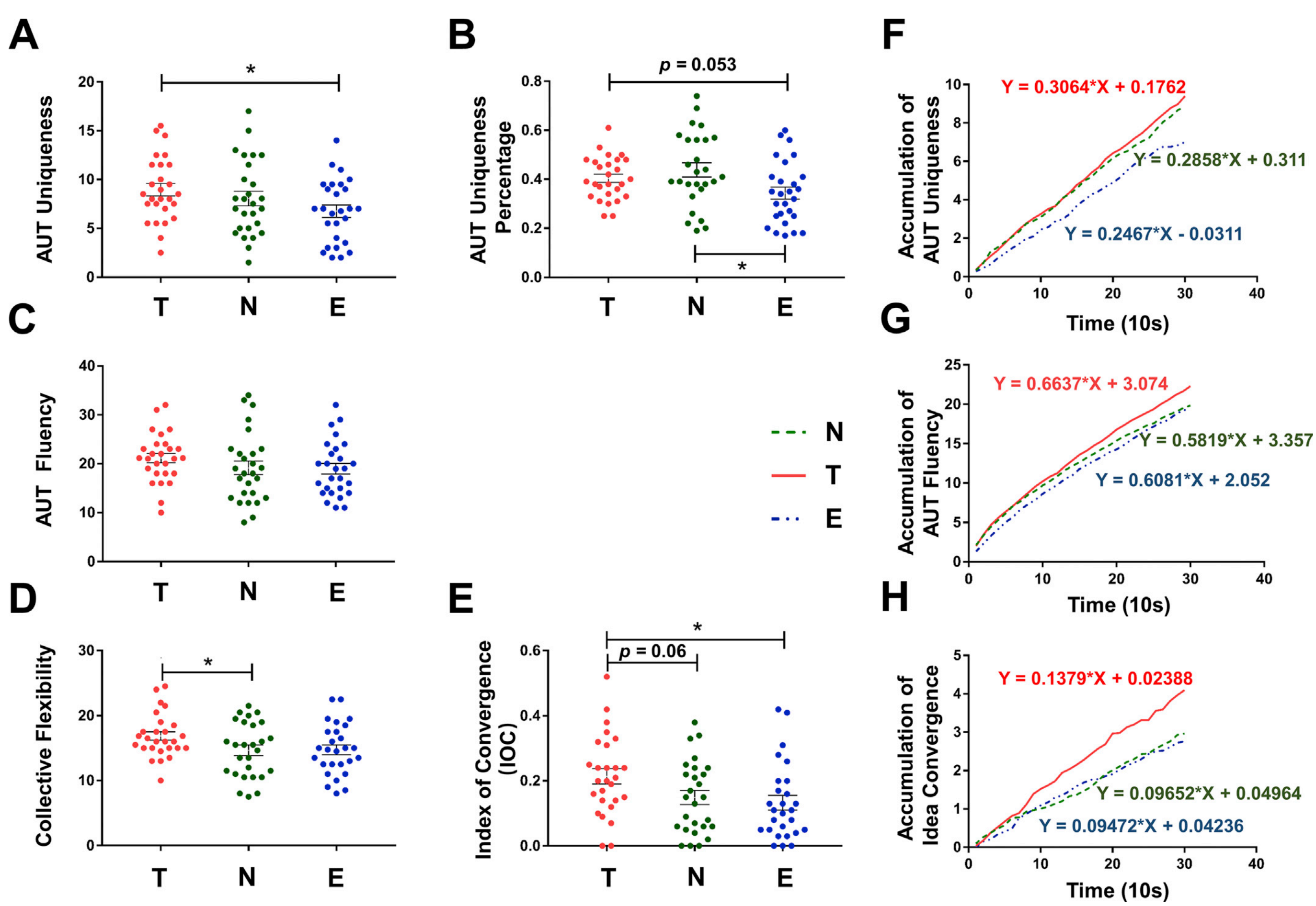

Fig. 2. Behavioral performance. (A) AUT uniqueness. (B) AUT uniqueness percentage. (C) AUT fluency. (D) Collective flexibility. (E) Index of convergence. Error bars indicate standard errors of the mean. $*P < 0.05$, $**P < 0.01$. (F) The accumulation of AUT uniqueness of each dyad (y-axis) is plotted against the time (the time interval between two points is 10 s) for different communication modes. (G) The accumulation of AUT fluency of each dyad (y-axis) is plotted against the time for different communication modes. (H) The accumulation of idea convergence of each dyad (y-axis) is plotted against the time for different communication modes.

3.2. Collective behaviour in different conditions

A one-way repeated-measures ANOVA using CONDITION as the within-subject factor was performed on collective flexibility. Results showed a significant main effect of CONDITION on collective flexibility, $F(2, 52) = 4.02$, $P = 0.024$, $\eta_p^2 = 0.13$. Post hoc tests (Bonferroni) showed that collective flexibility was significantly higher in the T condition ($M = 16.86$, $SD = 3.36$) than in the N condition ($M = 14.67$, $SD = 4.22$; $P = 0.037$) (see Fig. 2D).

A one-way repeated-measures ANOVA using CONDITION as the within-subject factor was also performed on the IOC. Results showed a significant main effect of CONDITION on IOC, F (2, 52) = 4.13, $P = 0.022$, $\eta_p^2 = 0.14$. Post hoc tests (Bonferroni) showed that IOC in the T condition ($M = 0.21$, $SD = 0.12$) was marginally higher than in the N condition ($M = 0.15$, $SD = 0.11$; $P = 0.060$) and significantly higher than in the E condition ($M = 0.13$, $SD = 0.12$; $P = 0.049$) (see Fig. 2E).

3.3. Trajectory of AUT performance and idea convergence in different conditions

We examined the trajectory of the accumulations of AUT uniqueness, AUT fluency, and idea convergence over time. Linear regression using TIME as the independent factor was performed on the accumulations of AUT uniqueness, AUT fluency, and idea convergence in each of the three conditions. The principle results are as follows: (1) TIME significantly positively predicted the accumulation of AUT uniqueness in the T ($\beta = 0.31$, $P < 0.0001$, $R^2 = 0.9991$; 95% confidence interval (CI) = [0.3029, 0.3099]), N ($\beta = 0.28$, $P < 0.0001$, $R^2 = 0.9982$; 95% CI = [0.2811, 0.2905]), and E conditions ($\beta = 0.25$, $P < 0.0001$, $R^2 = 0.9962$; 95% CI = [0.2407, 0.2526]) (see Fig. 2F). Since the 95% CIs of the three conditions differed from each other, the increase in AUT uniqueness over time in the T condition was the fastest, and that in the N condition was the second fastest. (2) TIME also significantly positively predicted the accumulation of AUT fluency in the T ($\beta = 0.66$, $P < 0.0001$, $R^2 = 0.9917$; 95% CI = [0.6403, 0.6872]), N ($\beta = 0.58$, $P < 0.0001$, $R^2 = 0.9855$; 95% CI = [0.5545, 0.6093]), and E conditions ($\beta = 0.61$, $P < 0.0001$, $R^2 = 0.9917$; 95% CI = [0.5865, 0.6296]) (see Fig. 2G). Since the 95% CI of the T condition differed from that of the other two conditions, the increase in AUT fluency over time in the T condition was the fastest among the three conditions. (3) TIME also significantly positively predict the accumulation of idea convergence in the T ($\beta = 0.14$, $P < 0.0001$, $R^2 = 0.9945$; 95% CI = [0.1339, 0.1418]), N ($\beta = 0.10$, $P < 0.0001$, $R^2 = 0.9938$; 95% CI = [0.0936, 0.0995]), and E conditions ($\beta = 0.09$, $P < 0.0001$, $R^2 = 0.9892$; 95% CI = [0.0909, 0.0985]) (see Fig. 2H). Since the 95% CI of the T condition differed from that of the other two conditions, the increase in idea convergence over time in the T condition was the fastest among the three conditions.

3.4. IBS increments within the PFC and R-TPJ patch in different conditions

One-way repeated-measures ANOVAs using CONDITION as the within-subject factor were conducted on the IBS increment of each CH (a total of 46 CHs) along the full frequency range (0.015–0.7 Hz). The resulting P–values were corrected by the FDR method at $P < 0.05$ (the number of ANOVAs for correction is 46*68 = 3128; i.e. 46 CHs and 68 frequencies). Hereafter, Pn indicates CHn in the PFC probe and Tn indicates CHn in the r-TPJ probe (i.e. P8 indicates CH8 in the PFC probe; T24 indicates CH24 in the r-TPJ probe).The results only showed significant main effects of CONDITION on the IBS increments of T17 (see Fig. 3C) at the frequency of 0.48 Hz (F (2, 44) = 13.13, $P < 0.0001$, $P_{corr} = 0.035$, $\eta_p^2 = 0.37$) and T17 at the frequency of 0.43 Hz (F (2, 44) = 13.21, $P < 0.0001$, $P_{corr} = 0.050$, $\eta_p^2 = 0.38$) (see Fig. 3A and B). However, no other significant effect survived the FDR correction ($P_{corr} > 0.05$). It should be noted that these two frequencies were adjacent and only

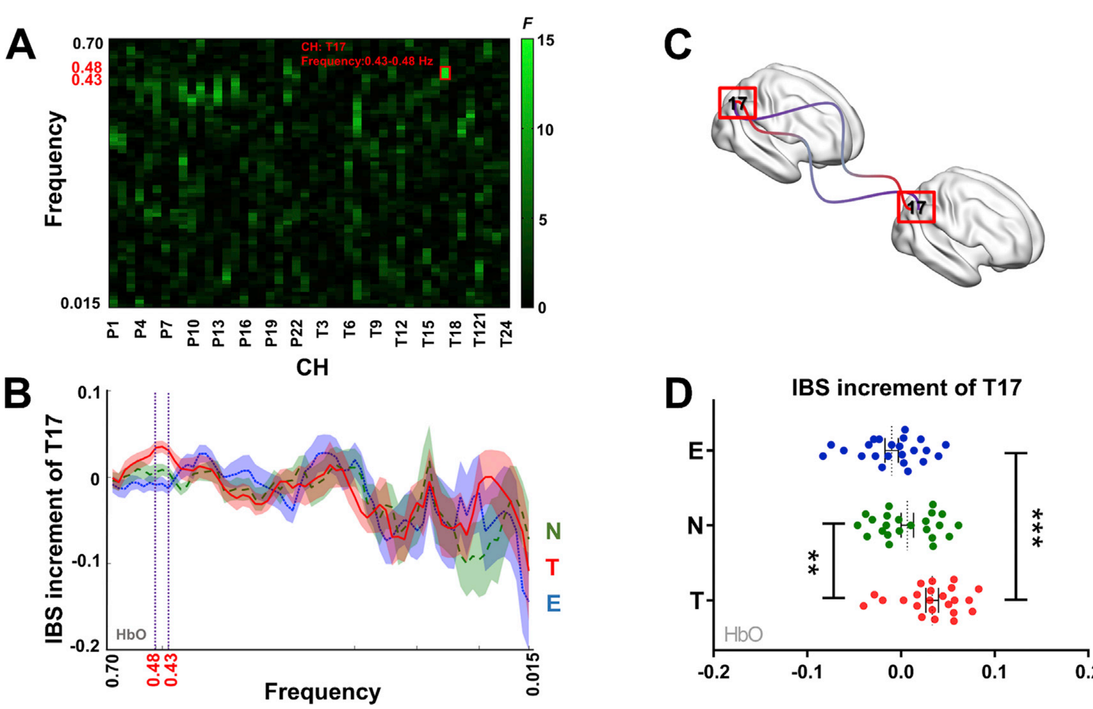

Fig. 3. IBS increments of HbO signals. (A) Heatmaps of the F values for the one-way repeated measures ANOVAs using CONDITION as the within-subject factor were conducted on the IBS increment of each CH (a total of 46 CHs) along the full frequency range (0.015–0.7 Hz). The colour bar denotes the F values. The red rectangle indicates that the main effect of CONDITION on the IBS increments of the corresponding CHs and frequencies survived the FDR correction. The vertical axis denotes individual frequencies and the horizontal axis denotes CHs. Note that T17 at the frequencies of 0.48 and 0.43 Hz had significant main effect (FDR corrected). (B) The IBS increments at T17 of each dyad is plotted against the frequencies (x-axis) for different communication modes (shaded areas: 95% confidence interval). Significant main effect of CONDITION was observed at the frequencies of 0.43 and 0.48 Hz. (C) The location of T17 on the cerebral cortex. (D) The amplitude of IBS increments of T17 at the frequency band of 0.43–0.48 Hz. Error bars indicate standard errors of the mean. **$P < 0.01$, ***$P < 0.001$.

separated by one frequency (i.e. 0.45 Hz), where the main effect of CONDITION on the IBS increment of T17 was also significant before FDR correction (F (2, 44) = 13.36, P < 0.0001, P_{corr} > 0.05,η_p^2 = 0.38). Therefore, we averaged the IBS increments of T17 at these three frequencies (equal the IBS increments at the frequency band of 0.43–0.48 Hz). Next, the IBS increment of T17 at the frequency band of 0.43–0.48 Hz were used for further analysis.

Specifically, the main effect of CONDITION on the IBS of T17 at the frequency band of 0.43–0.48 Hz was significant, (F (2, 44) = 16.25, P < 0.0001,η_p^2 = 0.42). Post hoc tests (Bonferroni) showed that the IBS increment of T17 were significantly higher in the T condition (M = 0.03, SD = 0.03) than in the N (M = 0.01, SD = 0.03; P = 0.006, Cohen's d = 0.83, Bonferroni-corrected) or E condition (M = −0.01, SD = 0.03; P < 0.0001, Cohen's d = 1.30, Bonferroni-corrected) (see Fig. 3D). A similar significant difference among the three conditions was also observed at each of the three frequencies (i.e. 0.43, 0.45, 0.48 Hz). We considered it reasonable and acceptable to use the IBS increment of T17 at the frequency band of 0.43–0.48 Hz for further analysis.

One-way repeated measures ANOVAs using EPOCH (EPOCH1, EPOCH2, EPOCH3) as the within-subject factor were respectively performed on the IBS increment of T17 for each condition. The results showed no significant main effect of EPOCH (E: F (2, 44) = 2.75, P = 0.08,η_p^2 = 0.11; N: F (2, 44) = 0.36, P = 0.70,η_p^2 = 0.02; T: F (2, 44) = 0.37, P = 0.70,η_p^2 = 0.02).

3.5. IBS increments between the PFC and R-TPJ patch in different conditions

One-way repeated-measures ANOVAs using CONDITION as the within-subject factor were conducted on the IBS increments across all CH combinations (528 CH combinations). The resulting P values were corrected using the FDR method at P < 0.05. However, the results showed no significant main effect of CONDITION (Ps > 0.05).

3.6. Validation analysis of significant IBS increments

The validation tests showed no significant group difference in IBS increments for any CH or frequency. Fig. 4A shows the results of one typical validation test. Validation results (F values) for T17 at the 0.43, 0.45, and 0.48 Hz frequencies from the 1000 permutations are shown in Fig. 4B, C, and D. Note that the F-values of the actual dyads were in the 1% areas and larger than any of the 1000 F-values at these three frequencies. Accordingly, we suggest that the IBS increment of T17 in the T condition was specific to the effect of CONDITION on the actual dyads.

3.7. IBS-behaviour relationship

Bivariate Pearson correlation analyses were performed on the IBS increment of T17 in the 0.43–0.48 Hz frequency range and on behavioural performance during the AUTs. Since there were five behavioural task performances, the correlation analyses were conducted five times. The multiple comparisons (five correlation analyses) were corrected using the FDR method (P < 0.05). Results showed that the IOC was significantly positively correlated with the IBS increment (r = 0.37, P_{corr} = 0.0085) (see Fig. 4E). However, no significant correlation was observed for other behavioural performances ($P_{corr}s$> 0.05).

4. Discussion

In this study, we investigated the effects of communication modes on creative idea generation within a group and revealed their underlying interpersonal neural correlates using an fNIRS-based hyperscanning technique. Participants were randomly assigned to dyads to solve three AUTs using three communication modes. Regarding creative outcomes, no significant difference in AUT fluency was observed. The results showed higher AUT uniqueness in the T condition than in the E condition and higher AUT uniqueness percentages in the T and N conditions than in

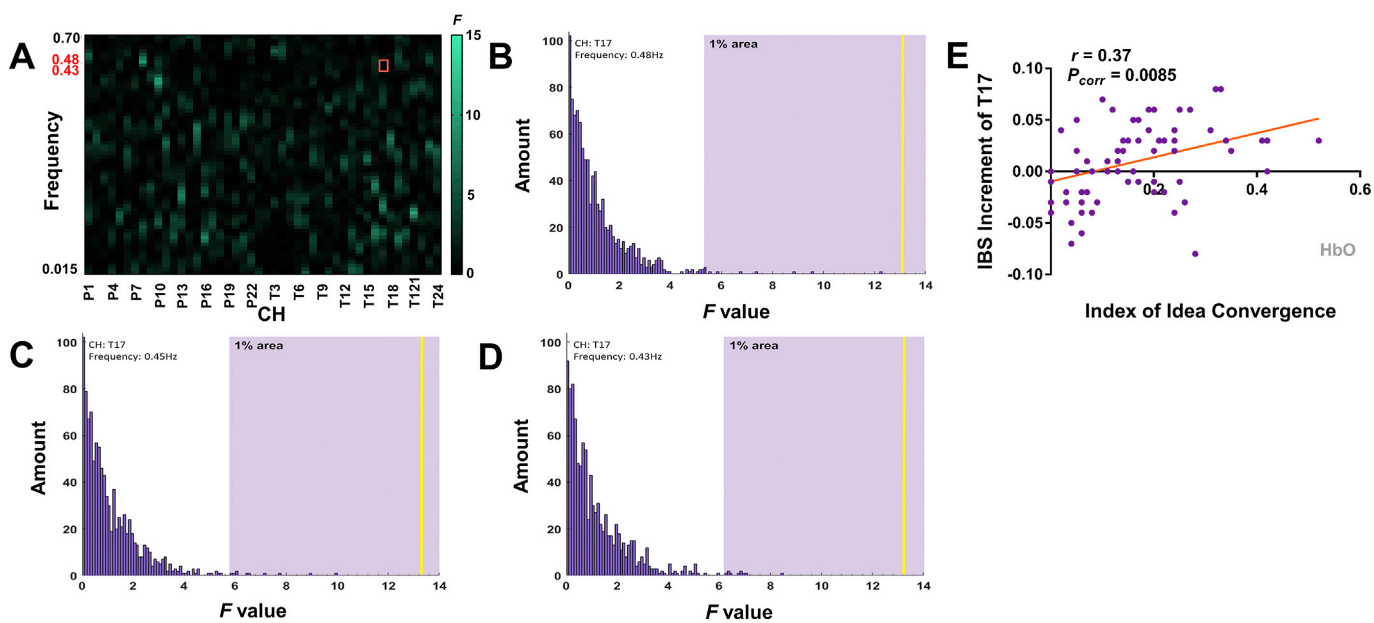

Fig. 4. Results of validation analysis and IBS-behaviour relations. (A) A typical heatmaps of the F values for the one-way repeated measures ANOVAs using CONDITION as the within-subject factor were conducted on the IBS increment of each CH (a total of 46 CHs) along the full frequency range (0.015–0.7 Hz) (IBS increments of random dyads). The colour bar denotes the F values. Note that no significant main effect of CONDITION was observed for T17 at the frequencies of 0.43 Hz or 0.48 Hz. (B–D) The distribution of F values from one-way repeated measures ANOVAs using CONDITION as the within-subject factor on the IBS increment of T17 at the frequency of 0.48 Hz, 0.45 Hz, 0.43 Hz (1000 one-way repeated measures ANOVAs on 1000 samples consisting of 23 random dyads). The vertical axis indicates the amount of the occurrence of the corresponding F values. The 1% upper areas are highlighted by purple rectangles. The yellow lines denote the positions of the F values of the ANOVAs on the actual 23 dyads. Note that the F values of the actual dyads were in the 1% areas and larger than any of the 1000 F values at these three frequencies. (E) The correlation between IOC and IBS increment of T17 at the frequency band of 0.43–0.48 Hz.

the E condition. With regard to the creative process, results showed that IOC was higher in the T condition than in the other conditions. In addition, AUT fluency, uniqueness, and idea convergence increased over time faster in the T condition than in the other conditions. The fNIRS results revealed a higher IBS increment of CH17 (roughly located at the right angular gyrus) in the 0.43–0.48 Hz frequency band in the T condition than in the other two conditions. Meanwhile, the IBS increments were significantly positively correlated with perspective-taking behaviours between individuals during the group creativity tasks.

Specifically, AUT uniqueness was observed to be significantly higher in the T condition than in the E condition. In the T condition, participants were asked to take turns reporting. Thus, participants were supposed to pay attention to others' ideas. Consequently, the participants might be more likely to be stimulated by their team partners' ideas in the T condition than in the E condition. Previous studies have suggested that ideas from others can be cognitively stimulating (Nijstad and Stroebe, 2006; Paulus and Brown, 2007). Accordingly, we supposed that the enhanced interpersonal interaction between individuals in the T condition might stimulate the dyads' creative performance compared to the E condition, regardless of the production blocking effect. However, another possibility should be considered: In comparison to verbal speaking, reporting ideas by typing might suffer from a reduction in communication speed. Although no significant group difference in AUT fluency (the number of reported ideas) was observed, this possibility should be addressed carefully. Moreover, although the aforementioned advantage of turn-taking was absent in the N condition, no significant difference in AUT uniqueness performance was observed between the T and N conditions. This might be explained as follows (1) since no external constraint (i.e. turn-taking): was placed on individuals in the N condition, they might feel freer to generate unique ideas, contributing to their creative performance; and (2) although no strict turn-taking was required in the N condition, participants needed to listen as their partners reported, during which the interpersonal interaction between the team members might be also enhanced. In addition, the AUT uniqueness percentage was observed to be significantly higher in the N condition than in the E condition. This finding suggests that face-to-face interpersonal verbal communication might be more conducive to group creative idea generation than computer-mediated communication, perhaps due to the enhanced interpersonal interaction during the 'listening to the partner' section.

With respect to the creative process, we found IOC to be higher in the T condition than in the other conditions. This might have resulted from the turn-taking setting because participants had to attend to their partners' idea and await their own turn in the T condition. In other words, the extra interpersonal interaction resulting from turn-taking stimulated a higher IOC in the T condition than in the other conditions. Moreover, others' ideas lead individuals to search for additional ideas not only in the same category but also pertaining to other categories (Nijstad and Stroebe, 2006; Paulus and Brown, 2007). This may explain why the collective flexibility was higher in the T condition than in the N condition. The trajectories of group creative performance and idea convergence were also analyzed in different conditions. Results showed that the accumulations of AUT fluency and AUT uniqueness increased faster over time in the T condition than in the other conditions (see Fig. 2F and G). The accumulation of idea convergence also increased faster over time in the T condition than in the other conditions (see Fig. 2H), suggesting that the enhanced interpersonal interaction in the T condition could lead to faster increases in both group creative performance and interpersonal perspective-taking behaviours.

The fNIRS results showed significantly a higher IBS increment at the right angular gyrus (T17) in the T condition than in the other conditions. Previous studies have shown that IBS increments are interpersonal neural marks for mutual social interaction (Dai et al., 2018; Dikker et al., 2017). We supposed that the enhanced IBS increment observed in the T condition might also be associated with the interpersonal communication process between individuals in each dyad. The angular gyrus is the one of the main areas in the r-TPJ. The r-TPJ (especially the angular gyrus) is involved in socially cognitive processes such as reading characters' minds (Saxe and Powell, 2006), perspective-taking (Santiesteban et al., 2015), and theory of mind (Schurz et al., 2017; Filmer et al., 2019). The angular gyrus is also quite sensitive to creative cognition (Berkowitz and Ansari, 2010; Fink et al., 2010; Jung et al., 2010; Benedek et al., 2014). Moreover, previous hyperscanning studies of group creativity have reported a positive association between the IBS increment of the angular gyrus and social cognition during a group creative activity (Xue et al., 2018; Lu et al., 2019b). More importantly, we found that such an IBS increment positively predicted perspective-taking behaviours between individuals during the group creativity tasks. Accordingly, the IBS increment at the right angular gyrus might be associated with social cognition during group creativity, such as understanding partners' ideas, mentalising, and perspective-taking, which might contribute to the group's creative performance. Certainly, the exact meaning of the IBS increment of angular gyrus between individuals during group creative process requires further investigation.

An intriguing finding was that the IBS increment of T17 was negative in the E condition. In addition, we found this negative IBS increment of T17 within the low frequencies in all conditions. In fact, a negative IBS increment has been widely observed in previous studies (Jiang et al., 2012; Pan et al., 2017; Lu et al., 2019a). However, no interpretation of this has been posited. We suggest two possible interpretations: (1) In traditional individual neuroimaging studies, a positive neural increment indicates brain activation, whereas a negative neural increment indicates brain deactivation. In light of this, given that a significant positive IBS increment indicates interpersonal information exchange, a negative IBS increment may indicate that the interpersonal information exchange process is quite poor, or that individuals are thinking about different things. (2) The occurrence of a negative IBS increment might be a normal fluctuation. For instance, although the IBS increment of T17 in the E condition within the frequency band (0.43–0.48 Hz) was negative, it was not significantly lower than 0, $t\,(22) = -1.38$, $P = 0.18$. However, the IBS increment of T17 in the T condition within the same frequency band was significantly higher than 0, $t\,(22) = 4.99$, $P < 0.0001$. Note that interpretation (2) is limited to the significant IBS increment within the abovementioned frequency band. With regard to the lower frequencies (especially near 0.015 Hz), the IBS increment was significantly lower than 0. However, the IBS increment within these frequencies was not associated with the effect of communication mode on group creativity. Since WTC can offer signals from a wide range of frequencies, we suggest that signals from some frequencies might be meaningless. In sum, social interaction and the underlying neural substrate are quite complex. Concerning the limited findings of existing hyperscanning studies, it is quite hard to interpret the negative IBS increment, especially in the current study. The exact meanings of negative IBS increments should be determined in future studies.

Several limitations should be noted in the current study. First, it has been indicated that group size can affect a group's creativity (Paulus et al., 2013). Due to the device limitation, we only focused on two-person groups. The group size's potential effect on the relationship between communication mode and group creativity, as well as the underlying interpersonal neural correlates, should be explored in future studies. Moreover, whereas the task duration was limited to 5 min in this study, longer task durations are often used in daily creative activities. Hence, the potential impact of task duration on the relationship between communication mode and group creativity could also be an interesting topic for future studies. Furthermore, in addition to the difference in turn-taking setting between the T and N modes, indirectly confirmed by the findings in S1 (Ratios of One-Idea Turns in Three Conditions; see details in S1 in the supplementary materials), something else might have differed between these two modes. For instance, the structured group communication (turn-taking mode) reduces the free-riding effect by forcing participants to engage in the creativity task. Namely, individual creative motivation and task engagement can be stimulated by reducing the free-riding effect, which may lead to enhanced creative performance.

Therefore, it would be better to interpret the findings while taking this possibility into consideration. Meanwhile, the production blocking can also occur in the N mode, which may adversely impact the performance in the N mode and warrants future research. One solution can be, for example, asking the participants to press a button once a new idea emerges and then comparing the number of buttons pressed vs. the number of ideas expressed. Baker et al. (2015) reported that gender composition affects IBS and cooperation behaviours. Although the dyads were mostly female-female, there were a few male-male dyads in our study. We found a group difference in behavioural performance (but not an IBS increment) in male-male dyads that did not follow the similar trends of the whole group. Although there were only five male-male dyads, which might affect the robustness of this finding, future studies should explore whether the effect of communication mode on group creativity is moderated by gender composition.

Author contributions

K.L., and N.H. conceived the experiment. K.L., and T.Y. performed the research. K.L., and T.Y. analyzed the data. K.L., T.Y., and N.H. wrote the paper.

Data availability statement

Data is only available upon reasonable request.

Declaration of competing interest

The authors have nothing to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuroimage.2020.117025.

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