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Educational diversity and group creativity: Evidence from fNIRS hyperscanning

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ABSTRACT

Educational diversity is defined as the diversity of educational backgrounds measured by multiple subjects. This study aimed to unveil the interpersonal neural correlates that underlie the effect of group educational diversity on group creativity. One hundred and sixteen college students were assigned to high educational diversity (HD; the members respectively majored in science or social science) or low educational diversity (LD; the members both majored in either science or social science) groups based on their academic majors. They were required to solve two problems that either demanded creativity (alternative uses task, AUT) or not (object characteristics task). We used functional near-infrared spectroscopy (fNIRS)-based hyperscanning to simultaneously record the neural responses of pairs of interacting participants in each group. The LD group showed more AUT fluency and perspective-taking behaviours than the HD group, whereas no group difference was observed for AUT uniqueness. Additionally, collective flexibility was higher in the HD group than in the LD group. The fNIRS results showed that the interpersonal brain synchronisation (IBS) increments at the right angular gyrus and right primary somatosensory cortex were greater in the LD group than in the HD group. These findings indicate that although high educational diversity benefits cognitive flexibility, it does not necessarily lead to a better idea quality or greater idea quantity. The greater IBS increments and perspective-taking behaviours that we observed in the LD group may account for this.

1. Introduction

In line with the present rapid societal globalisation, it has become increasingly common for individuals with different educational backgrounds to work together as a group, a trend that suggests that increasing group educational diversity is inevitable. Educational diversity is defined as the diversity of educational backgrounds measured by multiple subjects Schubert and Tavassoli (2020). Given that group creativity is vital for the development of human society, the impact of educational diversity on group creativity deserves exploration.

With regard to the association between educational diversity and group creativity, relative research findings to date on can be divided into two streams. One line of evidence indicates that a high level of educational diversity can contribute to group creativity Hennessey and Amabile (2010). Within this line of investigation, the Information/Decision-Making Perspective (Williams and O'Reilly, 1998) postulates that a high level of educational diversity can be an informational resource. It is strongly associated with a variety of knowledge, creative thinking and innovation (Bower and Hilgard, 1981; Dahlin et al., 2005). These shapes professional knowledge, skills, and abilities (Hutzschenreuter and Horstkotte, 2013). Therefore, a broader pool of task-relevant resources (i.e., information and perspectives) is accessible to high educational diversity groups, contributing to the quality of group creative outcomes. In line with this perspective, studies have found evidence of a constructive effect of high educational diversity on group creative performance (e.g., Bantel and Jackson, 1989). However, another line of evidence emphasises the role of accessibility to others' ideas in enhancing group creativity (Leggett Dugosh ad Paulus, 2005; Fink et al., 2012; Xue et al., 2018). These studies suggest that when exposed to easy-to-understand ideas, it is easier for individuals to search for potential related semantic connections. In this case, individuals are more likely to generate creative ideas by combining these ideas with their own knowledge. According to this perspective, an increase in group educational diversity may decrease the accessibility of partners' ideas or perspectives and thus impede the formation of relative semantic connections and the use of partners' ideas to generate further ideas.

Nevertheless, the effect of group educational diversity on group creativity remains controversial. Furthermore, the interpersonal neural correlates of group educational diversity effects on group creativity remain unknown. In the current study, we aimed to address three questions:

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(1) How does group educational diversity affect the group's creative outcomes? (2) How does group educational diversity affect the group's creative process (e.g., perspective-taking behaviours)? (3) What are the interpersonal neural correlates that underly any effect of group educational diversity on group creativity? By addressing these questions, we will not only deepen understanding of these effects by adding the dimension of interpersonal neural correlates but also suggest future innovations.

To reveal the interpersonal neural correlates of interest, the hyperscanning technique was adopted. This involves the simultaneous recording of the neural responses of multiple interacting individuals in real time. This has been done previously using functional magnetic resonance imaging (fMRI; Li et al., 2009), electroencephalography (EEG; Dikker et al., 2017), and functional near-infrared spectroscopy (fNIRS; Dai et al., 2018). Many studies have identified neural correlates of different social interaction processes, such as enhanced interpersonal brain synchronisation (IBS) (Gvirts and Perlmutter, 2019; Redcay and Schilbach, 2019). For instance, several studies have examined the brain activity shared between speakers and listeners and found evidence of a role of speaker-listener neural coupling in successful communication (Stephens et al., 2010; Silbert et al., 2014). Recently, researchers have confirmed an association between enhanced IBS and group creativity (Lu et al., 2019a; Lu et al., 2020b; Mayseless et al., 2019; Xue et al., 2018). For instance, Lu et al., (2019a) found enhanced IBS in right dorsolateral prefrontal cortex and temporal parietal junction in the cooperation condition than in the competition condition, and such an IBS enhancement was specific to group creativity. Here, we chose the approach of functional near-infrared spectroscopy (fNIRS)-based hyperscanning because of the following advantages: higher tolerance for motion artifacts, greater ecological validity than EEG or fMRI, and possibility of verbal communication during the scanning process.

A group is defined as two or more individuals who are connected by social relationships Forsyth (2014). In the present study, owing to the limited number of fNIRS detectors and emitters in a practical montage, we could only record simultaneous neural responses in the brain regions of interest of two people (see below). Therefore, the dyadic paradigm was used in this study (Lu et al., 2019b; Mayseless et al., 2019). The participants, who were unknown to each other, were assigned to either high educational diversity (HD) or low educational diversity (LD) two-person groups based on their academic majors. They were required to solve two problems; one demanding creativity (alternative uses task, AUT) and one not (object characteristic task, OCT). During the tasks, we used fNIRS-based hyperscanning to simultaneously scan the neural responses of the participants in each group. Since previous studies have indicated that the prefrontal cortex and right temporal/parietal areas are associated with creative idea generation and social interaction, we focused on these two brain regions in the current study (Fink et al., 2009; Benedek et al., 2014; Zheng et al., 2018; Lu et al., 2019b). According to the Information/Decision-Making Perspective, we would expect the following: (Ia) the high educational diversity (HD) group has better group creative performance than the low educational diversity (LD) group, (IIa) the HD group has more perspective-taking behaviours than the LD group, and (IIIa) the HD group has greater IBS than the LD group. However, from the perspective of knowledge accessibility, we would expect the following: (Ib) the LD group has better group creative performance than the HD group, (IIb) the LD group has more perspective-taking behaviours than the HD group, and (IIIb) the LD group has greater IBS than the HD group.

2. Methods

2.1. Participants

One hundred and sixteen college students (69 females, age: 21.48 ± 2.05 years) were recruited. All participants were full time students of their own academic majors. The major and minor (if any) of each participant both belongs to science or social science. That is, no participants majored in science/social science, but minored in social science/science. Based on the majors that the participants had been studying for 2 years or more prior to the experiment, they were assigned to two groups: LD (the partners both majored in either science or social science) and HD (the partners majored in different domains). Dyads in the LD group were either science-science or social science-social science and those in the HD group were all science-social science. Science majors comprised those in computer science, physics, and chemistry. Social science majors comprised those in psychology and education. Fifty-eight pairs were created (LD, 30; HD, 28). In each pair, the participants were unknown to one another, which was confirmed prior to the experiments. Informed consent was obtained from participants prior to the experiments. Each participant was paid ¥ 37 for participation. The study procedure was approved by the University Committee on Human Research Protection of East China Normal University.

The data of the study were analysed according to a single-factor design, with GROUP (LD, HD) as the between-subject factor. In order to estimate the achieved power in the current study, a post hoc power analysis using G*power 3.1 (Faul et al., 2007) was conducted. The effect size *d* was set to the reported effect size (Cohen's *ds* > 0.63). The calculated power was 0.77 which was acceptable.

2.2. Experimental procedure

Upon arrival, each group's participants were required to sit face-to-face. There were two square tables between them, and the distance between the two participants was 1.6 m (see Fig. 1A). The whole experiment consisted of two 1 min resting sessions, two 1.5 min instruction sessions, and two 5 min task sessions (see Fig. 1B). During the resting session, participants were asked to close their eyes, remain still, and relax. During the instruction session, the rules of brainstorming (i.e., deferment of judgement, quantity breeding quality, encouragement of freewheeling, and seeking combination and improvement) and the task procedures were described in detail Osborn (1957). Participants were asked to take turns reporting ideas and to present only one idea at a time. They could say 'pass' if they could not think of an idea during their turn.

During the sessions, the sequences of the two tasks (AUT versus OCT) were counterbalanced between the groups. During the AUT, the participants were explicitly instructed to be creative and generate as many creative uses for an everyday object as possible (Said-Metwaly et al., 2019). We used 'book' as the target everyday object. Given that the 5 min AUT has been widely used in studies of both individual and group creativity (e.g., Takeuchi et al., 2010a, 2010b; Lu et al., 2019b), the task length was set to 5 min in this study. AUT is a well-established divergent thinking task, a reliable predictor of real-world creativity (Runco and Acar, 2012), and has been widely used in both behavioural and neuroscience studies on individual and group creativity (Fink et al., 2009; Lu et al., 2019b; Lu et al., 2020b; Runco and Okuda, 1991). Besides, AUT is not highly related to one's major. In this case, the results can be less contaminated by the task bias (if the task was highly related to one participant's academic major, the other participant, especially from another different academic major, would suffer an inherent disadvantage). During the OCT, participants were asked to report the characteristics of an everyday object ('fishing rod' was used as the target object). The OCT is a memory-retrieval task that demands no creativity but involves direct stimulus-related information (Binder et al., 2009; Fink et al., 2009; Fink et al., 2010). In previous studies, participants have only been asked to present typical characteristics of the target object during the OCT (Fink et al., 2009). However, the task duration was 5 min in this study, which was longer than that in previous studies. Therefore, participants could present all relevant characteristics of the target object and not only typical ones.

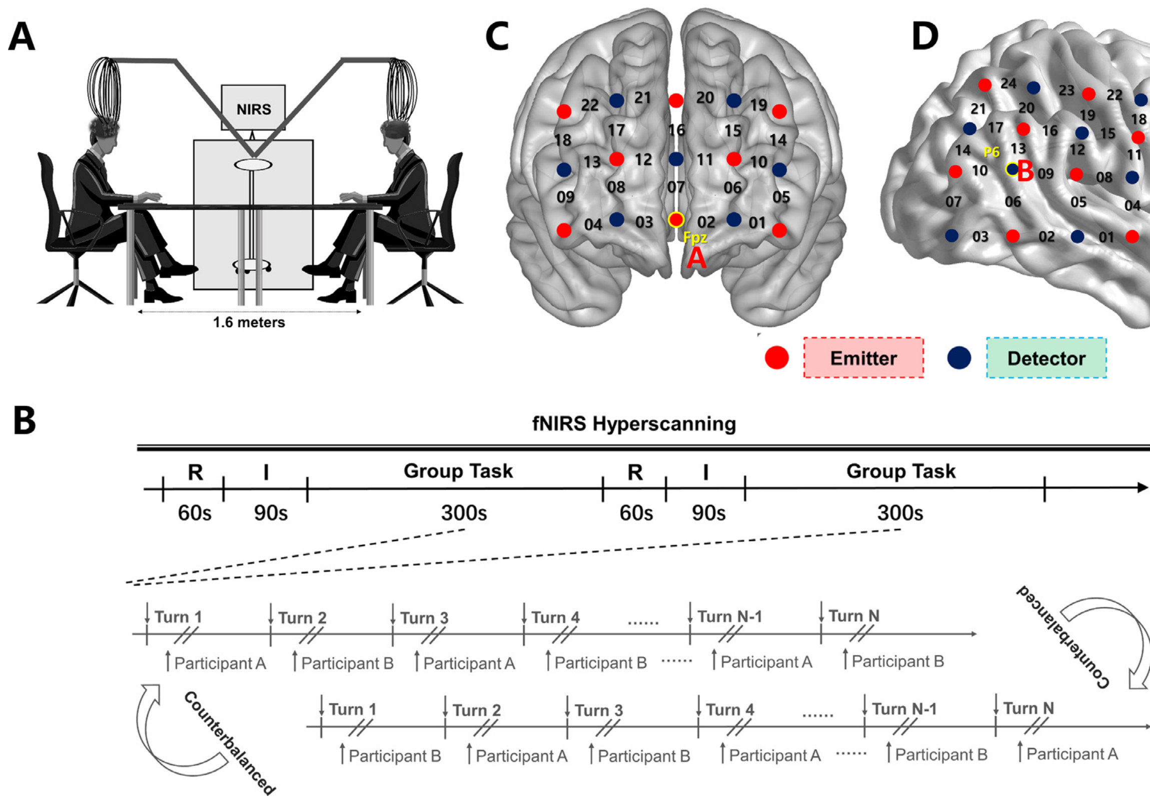

Fig. 1. Experimental design in the study. **(A)** Experimental setup. **(B)** Hyperscanning procedure. R: 60-second resting state session; I: ~90-second instruction introduction session; AUT: 5 min AUT session; OCT: 5-min OCT session. The reporting sequence of the two participants was counterbalanced. **(C)** Optode probe set on the prefrontal cortex. **(D)** Optode probe set on the right temporal parietal regions.

2.3. Behavioural performance assessment

AUT performance was assessed using the fluency and uniqueness of the reported responses (Guilford, 1967; Runco and Acar, 2012). The AUT fluency score was assessed based on the total number of nonredundant responses reported by each group. For instance, if one group presented 10 nonredundant responses, the AUT fluency score was 10. The AUT uniqueness score was assessed using an objective scoring method. Reponses from all groups were first 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 only 5% or fewer participants), it scored ‘1’. All other responses scored ‘0’. Following this procedure, two trained raters independently assessed the AUT uniqueness score for each group. The inter-rater agreement of this method was satisfactory (Cronbach’s α = 0.99). The final AUT uniqueness score for each group was obtained by averaging the scores across the two raters.

To assess the extent to which each group sought responses from different categories during the AUT, collective flexibility was calculated for each group (Lu et al., 2019a). Two trained raters independently assessed the total number of categories to which the reported responses belonged. For instance, the idea of ‘using the book to kill mosquitoes’ and the idea of ‘using the book to kill flies’ would be ideas from the same category. The inter-rater agreement was satisfactory (Cronbach’s α = 0.97). Scores for each group were averaged across raters to give the final flexibility score. In order to control the potential effect of AUT fluency on the collective flexibility score, the final collective flexibility was obtained using the following equation: final collective flexibility = flexibility/fluency. Here, fluency indicates the fluency of the group.

Additionally, researchers have repeatedly demonstrated the importance of informational communication/perspective-taking in group creativity (Hoever et al., 2012; Tang and Naumann, 2016; van Knippenberg, 2017). To assess perspective-taking behaviour during the AUT, the index of convergence (IOC) was calculated (Larey & Paulus, 1999; Lu et al., 2019a). The IOC was assessed as follows: (1) the responses of the two participants were listed in chronological order; (2) from the first idea to the last, when a response pertained to the same category as the previous response, it scored ‘1’, and the number of ideas that scored ‘1’ was counted (i.e., if there were 3 ideas that scored ‘1’, the sum would be ‘3’, which indicates that there were 3 ideas pertaining to the same category as the previous response); (3) the IOC for each group was obtained using the following equation: IOC = Sum/ [Group fluency – Sum]. Here, fluency indicates the fluency score of the group. Two trained raters independently assessed the IOC for each group. The inter-rater agreement was satisfactory (Cronbach’s α = 0.89). The final IOC score for each group was obtained by averaging across raters.

OCT performance was assessed using the fluency of the reported responses only (Fink et al. 2009; Fink et al. 2010; Lu et al., 2019b; Xue et al., 2018). The calculation of the OCT fluency was similar to that of the AUT fluency.

2.4. Trajectory of behavioural performance during the AUT

To uncover the effect of educational diversity on the group creative process in a dynamic manner, the behavioural performances were tracked over task time. We equally split the whole task period into three epochs (i.e., EPOCH1, EPOCH2, and EPOCH3) for each group (Wang et al., 2019) and estimated AUT fluency, AUT uniqueness, collective flexibility, and IOC during each epoch. Two-way mixed design ANOVAs using EPOCH as the within-subject factor and GROUP as the between-subject factor were performed on these indices.

2.5. fNIRS data collection

The oxyhaemoglobin and deoxyhaemoglobin concentrations of the two individuals in each pair were recorded simultaneously using an NIRS system (ETG-7100, Hitachi Medical Corporation, Japan) as the absorption of near-infrared light at wavelengths of 695 and 830 nm. The sampling rate was 10 Hz. The modified Beer–Lambert law was used to convert the raw optical intensities to the relative oxyhaemoglobin and deoxyhaemoglobin concentrations. Since previous studies have indicated that the prefrontal cortex and right temporal/parietal regions are associated with creative idea generation and social interaction, we mainly focused on these brain regions in this study (Fink et al., 2009; Benedek et al., 2014; Zheng et al., 2018; Lu et al., 2019b). One 3×5 optode probe set (8 emitters and 7 detectors, 3 cm optode separation) consisting of 22 measurement channels (CHs) was placed over the prefrontal cortex of each participant. According to the international 10–20 system for electroencephalography, the lowest probes were positioned along the Fp1-Fp2 line, with the middle optode (optode A) placed on the frontal pole middle point (Fpz) (Sai et al., 2014; see Fig. 1C). In addition, the middle probe of the probe set was aligned precisely along the sagittal reference curve. Meanwhile, one 4×4 optode probe set (8 emitters and detectors, 3-cm optode separation) consisting of 24 measurement CHs was placed over the right temporal and parietal regions of each participant. The lowest probe was aligned with the sagittal reference curve, and optode B was positioned at P6. The optode probe sets were positioned using individualised caps made from swimming caps, which increases the consistency of the signals across variations in head size (Chen et al., 2020; Wang et al., 2019). Additionally, to determine the correspondence between the NIRS CHs and the measurement points on the brain, we used the virtual registration method (Singh et al., 2005; Tsuzuki et al., 2007; see Fig. 1D) and recorded the Montreal Neurological Institute (MNI) coordinates of the CHs of a typical participant (see Table S1).

2.6. IBS Increment between the Corresponding CHs

During data pre-processing, a principal component spatial filter algorithm was used to remove the global components in the raw fNIRS data for each participant (Zhang et al., 2016). Meanwhile, a correlation-based signal conditioning method was used to correct motion artifacts (Cui et al., 2010; Pan et al., 2018). With the correlation-based signal improvement method, the oxyhaemoglobin and deoxyhaemoglobin signals are assumed to be negatively correlated and thus the corrected deoxyhaemoglobin is solely the corrected oxyhaemoglobin multiplied by a negative coefficient (Cui et al., 2010; see Fig. 2B). Therefore, the subsequent analyses mainly focused on oxyhaemoglobin signals.

Next, a total of 12 regions of interest (ROIs) were created based on shared source localisations according to the MNI coordinates of the CHs. One CH was associated to one ROI only if more than 70% of the CH areas belonged to that ROI. For instance, since more than 70% of the areas of CH2, CH3, CH6, CH7, CH8, CH11, and CH12 (in the optode probe patch over the prefrontal cortex) belonged to the frontopolar area (ROI1), ROI1 consisted of the abovementioned CHs. The ROIs were the (1) frontopolar cortex, (2) left dorsolateral prefrontal cortex (l-DLPFC), (3) right dorsolateral prefrontal cortex (r-DLPFC), (4) left inferior frontal gyrus (l-IFG), (5) right inferior frontal gyrus (r-IFG), (6) right middle temporal gyrus (r-MTG), (7) right superior temporal gyrus (r-STG), (8) right primary somatosensory cortex (r-PSC), (9) right angular gyrus (r-AG), (10) right supramarginal gyrus (r-SG), (11) right motor cortex (r-Motor), and (12) right somatosensory association cortex (r-SAC; see Fig. 2A; see details in Appendix S1).

The data collected from these ROIs during the two tasks were used for analysis of IBS. To obtain steady-state data, the data from the initial and final 30 seconds of the task were removed, leaving 240 s of data for each task. Next, wavelet transform coherence (WTC) was used to assess the relationship between the oxyhaemoglobin time series from the corresponding ROIs of the two participants in each group (i.e., IBS; see Fig. 2A; Grinsted et al., 2004). WTC assesses the cross-correlation between two time series as a function of time and frequency Torrence and Compo (1998), which can reveal a locally phase-locked behaviour that may not be uncovered by traditional time series analysis such as Pearson's correlation (Grinsted et al., 2004). WTC has been widely used in recent hyperscanning studies (Dai et al., 2018; Yang et al., 2020). The WTC of the oxyhaemoglobin signals i (k) and j (k) was defined as follows:

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

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

To assess the IBS increment specific to group creation, we subtracted the time-averaged IBS of the OCT session from that of the AUT session. The reason for choosing OCT as a baseline rather resting are listed as follows: (1) creativity researchers typically reveal neural substrates specific to creative cognition by comparing neural responses during AUT to that during OCT (Fink et al. 2009; Fink et al. 2010; Sun et al. 2016); (2) participants during resting were resting with their mind relaxed and eyes closed, whereas participants during OCT were thinking with eyes open (more similar to the AUT session). Therefore, we suggested the neural difference of 'AUT vs. OCT' is more specific to group creativity than that of 'AUT vs. resting.' In further analyses, the IBS increments were converted to Fisher z-statistics (Chang and Glover, 2010).

To identify the frequency band of interest that was specifically associated with group creation, one-sample t-tests using '0' as the testing value were performed on the IBS increments across all 12 ROIs across the full frequency range (0.015–0.7 Hz; 68 frequencies) for each group (LD, HD). Data above 0.7 Hz were not considered, thereby excluding high-frequency noise such as cardiac activity (0.8–2.5 Hz) (Barrett et al., 2015; Tong et al., 2011). Data below 0.015 Hz were not considered because enhanced an IBS has often been 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). This high pass filtering can also remove very low-frequency fluctuations, which are mostly noise and which have often been excluded in previous hyperscanning studies featuring WTC analysis (e.g., Dai et al., 2018; Zheng et al., 2018). The resulting P values were corrected using the false discovery rate method ($P < 0.05$). The total number of resulting P values was $12 \times 68 = 816$.

To determine whether IBS increments were specific to the interacting participants (actual groups), we performed a validation test (Jiang et al., 2015; Reindl et al., 2018). (1) The oxyhaemoglobin time series of all participants were randomly re-paired. We named these re-paired groups as 'nominal groups.' (2) Similar IBS analyses were then conducted for the nominal groups. This permutation process was repeated 1000 times.

Next, IBS increments within the frequency band of interest was averaged for further analyses. Independent-sample t-tests were used to compare the frequency-averaged IBS increments of the two groups across all ROIs. The resulting P values were corrected using the false discovery rate method ($P < 0.05$). The corrected results yielded two t maps. The MNI coordinates and t values of the t maps were converted into XXX.img files using xjView (nirs2img.m, http://www.alivelearn.net/xjview). The resulting XXX.img files were then rendered over the 3D brain model using BrainNet Viewer (Pan et al., 2018; Xia et al., 2013).

Further, a mixed model that incorporated time as a continuous variable was also used to examine the trajectory of significant IBS increments over time. However, we found that the time series of IBS increments were non-stationary (see Fig. 4F, G, H), in which case such an analysis could be problematic. Therefore, we equally split the remaining 240-second task period into three epochs (i.e., EPOCH1, EPOCH2, and EPOCH3) in each group and performed two-way mixed design ANOVAs

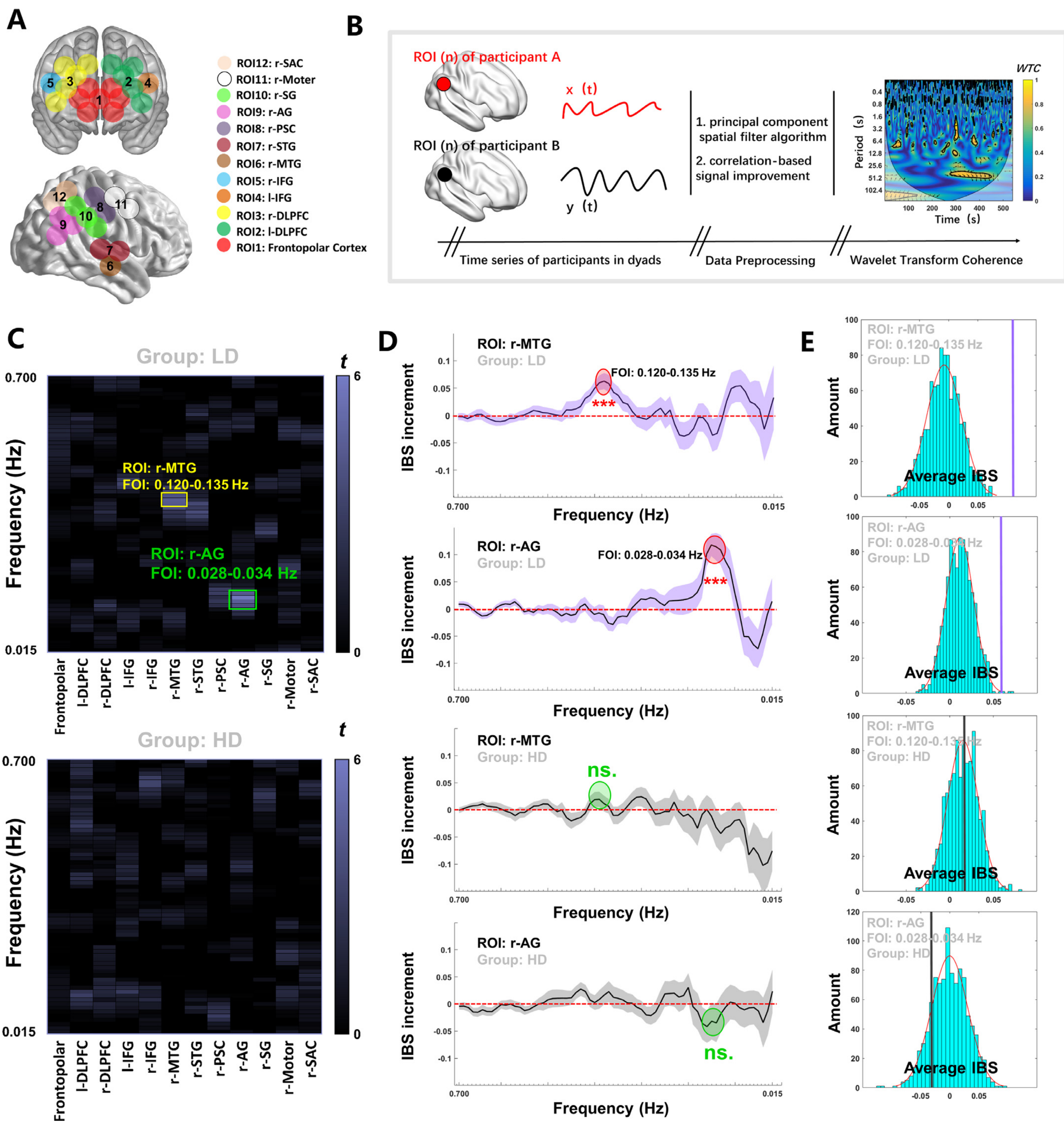

Fig. 2. Regions of interest and the selection of frequency of interest. **(A)** Regions of interest. **(B)** Data preprocessing and the estimation of interpersonal brain synchronisation. **(C)** The heatmap of the *t* values for independent-samples *t*-tests using GROUP as the between-subject factor on the IBS increment of all ROIs along the full frequency range (0.015–0.7 Hz). The colour bar denotes the *t* values. The vertical axis denotes individual frequencies and the horizontal axis denotes ROIs. The yellow/green rectangles indicate the GROUP effect on the IBS increment of the right middle temporal gyrus (r-MTG)/ right angular gyrus (r-AG) at the frequency band of 0.120–0.135 Hz / 0.028–0.034 Hz survived the false discovery rate correction in the LD group. **(D)** The IBS increments of the r-MTG and r-AG is plotted against the frequencies (x-axis) for different groups (shaded areas: 95% confidence interval). Note that the above resulting *P* values were already corrected using the false discovery rate method (threshold: $P < 0.05$). **(E)** The distributions of average IBS increment values from 1000 permutation. The vertical axis indicates the amount of the occurrence of the corresponding average IBS increment values. The purple/black lines denote the positions of the actual IBS increment values of the actual groups in the LD/HD group.

with EPOCH as the within-subject factor and GROUP as the between-subject factor, to compare IBS increments among the three epochs.

2.7. Pre- and post-experiment assessment

Prior to the experiment, individual creative potential was measured using the Runco Ideational Behaviour Scale (Runco et al., 2016). It contains 19 items that are scored on a 5-point Likert scale ranging from 0 (never) to 4 (just about every day). The Runco Ideational Behaviour Scale focuses on ideation that may occur in daily life (e.g., 'How often do you have ideas for rearranging the furniture in your home'?). The internal consistency reliability of the Runco Ideational Behaviour Scale in the study was satisfactory (Cronbach's $\alpha = 0.85$). In addition, participant preference for teamwork was measured using the Group Preference Scale Larey and Paulus (1999). The Group Preference Scale contains 10 items that are scored on a 5-point Likert scale ranging from 1 (not at all) to 5 (very much). For example, 'I try to look at everybody's side of a disagreement before I make a decision.' The internal consistency of the Group Preference Scale in this study was satisfactory (Cronbach's $\alpha = 0.84$). Further, participants completed the Perspective-Taking Scale, which assesses individual perspective-taking tendencies Davis (1983). It contains 7 items (e.g., whether individuals like to take the perspectives of others into consideration while making a decision), which are scored on a 5-point Likert-type scale ranging from 0 ('does not describe me well') to 4 ('describes me very well'.) The internal consistency of the Perspective-Taking Scale in this study was satisfactory (Cronbach's $\alpha = 0.72$). Finally, participant openness to experience was assessed using the openness subscale of the NEO-PI-R (Costa and McCrae 1992). The Chinese revised NEO Personality Inventory was used (Dai et al. 2004). It contains 48 items that are scored on a 5-point Likert scale ranging from 0 ('not at all') to 4 ('very much'). For instance, 'I often try new foods.' The internal consistency of openness in this study was satisfactory (Cronbach's $\alpha = 0.64$).

Immediately after the experiment, participants were asked to rate their tendency to perspective-taking (i.e., we tended to complete the task by considering each other's perspectives), task enjoyment, and liking for collaboration with their partner during the tasks using a 5-point Likert-type scale ranging from 1 ('not at all') to 5 ('very much').

3. Results

3.1. Groupwise analyses of gender composition and pre- & post-experiment assessments

No significant difference in age composition was observed between the two groups (t [56] = 0.19, $P > 0.10$). There were 7 and 8 male–male pairs, 14 and 10 female–female pairs, and 9 and 10 female–male pairs in the LD and HD groups, respectively. Hence, the gender composition of the two groups was also comparable.

A series of independent-sample t-tests were performed on the scores of the Runco Ideational Behaviour Scale, Perspective-Taking Scale, Group Preference Scale, openness, task enjoyment, tendency to perspective-taking, and liking for collaboration with their partner during the AUT or OCT. The results showed no significant group difference (Ps > 0.05; see details in Table S2 in the Appendix).

3.2. Behavioural Performance

Independent-sample t-tests using GROUP as the between-subject factor were performed on AUT fluency, AUT uniqueness, and OCT fluency. The results only demonstrated a significant group difference in AUT fluency, t (56) = 2.38, $P = 0.021$, Cohen's $d = 0.63$. The LD group showed a significantly higher AUT fluency ($M = 27.66$, $SD = 7.14$) than the HD group ($M = 23.37$, $SD = 6.53$; see Fig. 3A). However, no significant group difference was observed for AUT uniqueness (t [56] = 1.22, $P > 0.05$; see Fig. 3B) or OCT fluency (t [56] = 1.30, $P > 0.05$).

Independent-sample t-tests using GROUP as the between-subject factor were also performed on collective flexibility and IOC. Significant group differences were observed for collective flexibility (t [56] = -3.65, $P < 0.001$, Cohen's d = 0.94). Collective flexibility was significantly higher in the HD group ($M = 0.74$, $SD = 0.09$) than in the LD group ($M = 0.66$, $SD = 0.08$; see Fig. 3C). Additionally, the results also showed a significant group difference in IOC (t [56] = 3.21, $P = 0.002$, Cohen's $d = 0.84$). IOC was significantly higher in the LD group ($M = 0.34$, $SD = 0.14$) than in the HD group ($M = 0.23$, $SD = 0.12$; see Fig. 3D).

3.3. Groupwise comparison of trajectories of behavioural performance over time

Two-way mixed design ANOVAs using EPOCH as the within-subject factor and GROUP as the between-subject factor were performed on AUT fluency, AUT uniqueness, collective flexibility, and IOC (see detailed statistic in Table S3 in the Appendix).

Specifically, regarding AUT fluency, the interaction effect of EPOCH × GROUP was marginally significant (F [1.74, 97.62] = 3.14, $P = 0.055$, $\eta_p^2 = 0.05$). Further simple effect analysis (Bonferroni-corrected) showed that, in the LD group, AUT fluency significantly decreased over time (EPOCH1 > EPOCH2, $P < 0.001$, Cohen's $d = 0.88$; EPOCH1 > EPOCH3, $P < 0.001$, Cohen's $d = 1.81$; EPOCH2 > EPOCH3, $P < 0.001$, Cohen's $d = 0.85$). However, in the HD group, no difference was observed between the EPOCH2 and EPOCH3 (EPOCH1 > EPOCH2, $P < 0.001$, Cohen's $d = 0.98$; EPOCH1 > EPOCH3, $P < 0.001$, Cohen's $d = 1.42$). Additionally, significant group difference was observed during the EPOCH1 (LD > HD, $P = 0.018$, Cohen's $d = 0.64$) and EPOCH2 (LD > HD, $P = 0.01$, Cohen's $d = 0.70$). No other significant difference was observed.

Regarding AUT uniqueness, neither the main effect of EPOCH (F [2, 112] = 0.66, $P = 0.94$, $\eta_p^2 = 0.00$) nor the interaction effect of EPOCH × GROUP was significant (F [2, 112] = 1.84, $P = 0.16$, $\eta_p^2 = 0.03$).

Regarding collective flexibility, the interaction effect of EPOCH × GROUP was significant (F [2, 112] = 6.11, $P = 0.003$, $\eta_p^2 = 0.10$). Further simple effect analysis (Bonferroni-corrected) showed that, in the LD group, collective flexibility was significantly lower during the EPOCH2 ($P < 0.001$, Cohen's $d = 1.27$) and EPOCH3 ($P < 0.001$, Cohen's $d = 1.45$) than during the EPOCH1. However, in the HD group, results only showed that collective flexibility was significantly lower during the EPOCH2 than during the EPOCH1 ($P < 0.001$, Cohen's $d = 1.19$). Additionally, significant group difference was observed during the EPOCH3 (LD < HD, $P < 0.0001$, Cohen's $d = 1.10$). No other significant difference was observed.

Regarding IOC, the interaction effect of EPOCH × GROUP was significant (F [1.23, 69] = 6.99, $P = 0.007$, $\eta_p^2 = 0.11$). Further simple effect analysis (Bonferroni-corrected) showed that, in the LD group, IOC significantly increased over time (EPOCH1 < EPOCH2, $P = 0.005$, Cohen's $d = 0.72$; EPOCH1 < EPOCH3, $P < 0.001$, Cohen's $d = 0.92$; EPOCH2 < EPOCH3, $P = 0.002$, Cohen's $d = 0.68$). However, in the HD group, results only showed that IOC was significantly lower during the EPOCH1 than during the EPOCH2 ($P < 0.001$, Cohen's $d = 1.21$).Additionally, significant group difference was observed during the EPOCH3 (LD > HD, $P = 0.006$, Cohen's $d = 0.69$). No other significant difference was observed.

3.4. Groupwise Differences in IBS increments in the frequency bands of interest

The frequency band analyses showed that in the LD group, the right middle temporal gyrus had significantly enhanced IBS increments at frequencies 0.120–0.135 Hz. Additionally, the right angular gyrus had significantly enhanced IBS increments at frequencies 0.028–0.034 Hz (see Fig. 2C, D). However, no significant IBS increment was observed in the HD groups (see Fig. 2C, D). The resulting P values were already corrected

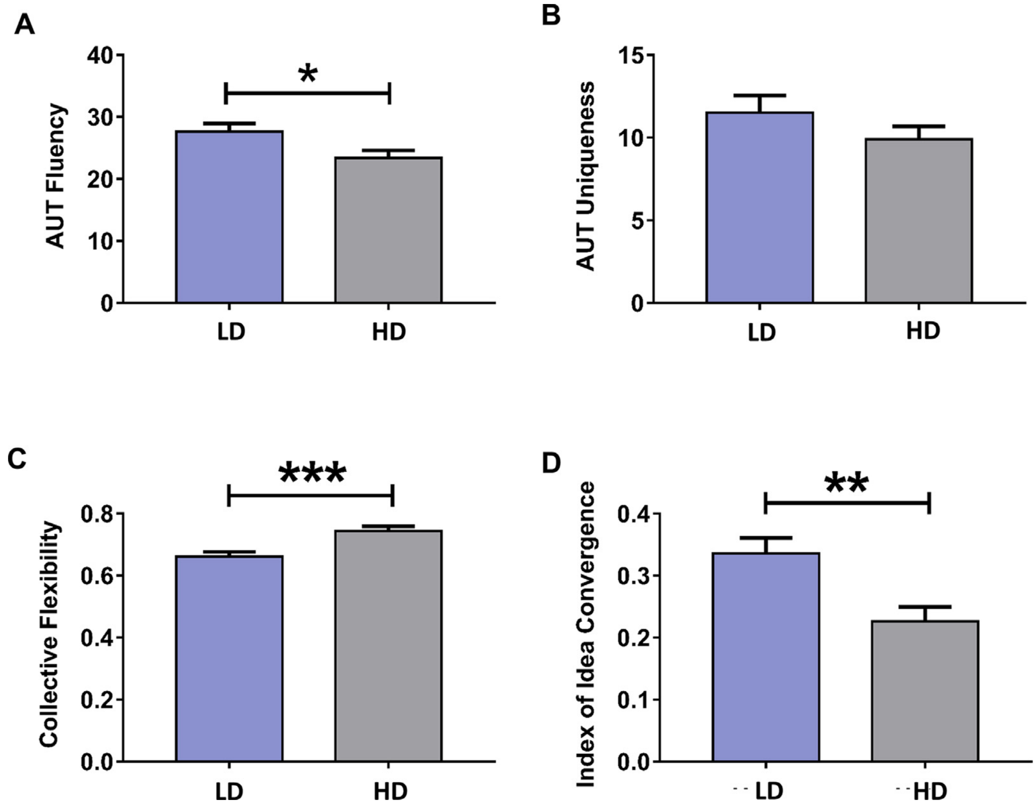

Fig. 3. Behavioural performance. **(A)** AUT fluency. **(B)** AUT uniqueness. **(C)** Index of idea convergence. **(D)** Collective flexibility. Error bars indicate standard errors of the mean. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

using the false discovery rate method (threshold: $P < 0.05$). Note that we chose the frequency bands that showed significant IBS increment in the 'Task vs. baseline' contrast, regardless of grouping. That is, we didn't choose the frequency bands that showed significant IBS increments in the HD group and neglect those in the LD group. It was the finding that FDR-corrected results only showed significant IBS increments in the LD group that drove the subsequent analysis). This analysis protocol is not a double-dipping analysis and widely accepted in recent publications (see examples in Lu et al., 2019a and Pan et al., 2018).

The validation results for IBS increments in the right middle temporal gyrus at frequencies 0.120–0.135 Hz and in the right angular gyrus at frequencies 0.028–0.034 Hz are presented in Fig. 2E. The figure shows the distribution of the average IBS increments from 1000 permutations. Note that in the LD group, the average IBS increments of the actual groups were in the 1% areas and larger than most average IBS increments in the nominal groups. However, no similar result was observed in the HD group. Based on these results, we suggest that the enhanced IBS increments at frequencies 0.120–0.135 Hz and 0.028–0.034 Hz in the LD group were specific to interaction, namely the actual groups. Accordingly, the frequency bands of interest in the study were 0.120–0.135 Hz (frequency band of interest 1) and 0.028–0.034 Hz (frequency band of interest 2).

Regarding frequency band of interest 1, independent-sample *t*-tests with GROUP as the between-subject factor were used to compare IBS increments of the two groups across all ROIs. The resulting *P* values were corrected using the false discovery rate method ($P < 0.05$). No significant group difference in IBS increment was observed ($P > 0.05$; see Fig. 4A, C).

Regarding frequency band of interest 2, independent-sample *t*-tests with GROUP as the between-subject factor were also performed on IBS increments of the two groups across all ROIs. The resulting *P* values were corrected using the false discovery rate method ($P < 0.05$). A significant difference was observed in the IBS increment in the right angular gyrus (t [56] = 3.88, $P = 0.0003$, $P_{corr} = 0.003$, Cohen's $d = 1.04$). The IBS increment was significantly greater in the LD group ($M = 0.11$, $SD = 0.11$) than in the HD group ($M = -0.03$, $SD = 0.16$; Fig. 4B, D). A significant difference was also observed for the IBS increment in the right primary somatosensory cortex (t [56] = 3.02, $P = 0.004$, $P_{corr} = 0.02$, Cohen's $d = 0.81$). The IBS increment was significantly greater in the LD group ($M = 0.06$, $SD = 0.11$) than in the HD group ($M = -0.05$, $SD = 0.15$; see Fig. 4B, E).

A channel-wise analysis was also conducted on the IBS increments in these two frequency bands of interest. Please see details in the appendix (Table S4).

3.5. Groupwise comparison of trajectories of IBS increments over time

Two-way mixed design ANOVAs with EPOCH (EPOCH1, EPOCH2, EPOCH3) as the within-subject factor and GROUP as the between-subject factor were performed on IBS increments for the right angular gyrus and right primary somatosensory cortex in frequency band of interest 2.

Regarding the IBS increment in the right angular gyrus, the main effect of EPOCH was marginally significant (F [2, 112] = 3.02, $P = 0.053$, $\eta_p^2 = 0.05$). Bonferroni-corrected post hoc tests showed no significant difference ($Ps > 0.05$). The interaction effect of EPOCH × GROUP is not significant (F [2, 112] = 2.52, $P = 0.085$, $\eta_p^2 = 0.04$). Further simple effect analysis is not appropriate. However, since we observed that the mean values of IBS increments of EPOCH2 and EPOCH3 were obviously greater than that of EPOCH1 in the LD group (see details in Table S3), we further conducted a one-way repeated measures ANOVAs with EPOCH as the within-subject factor on this IBS increment. Bonferroni-corrected post hoc tests showed that the IBS increment was greater during EPOCH3 ($P = 0.055$, Cohen's $d = 0.69$) and EPOCH2 ($P = 0.008$, Cohen's $d = 0.71$) than during EPOCH1.

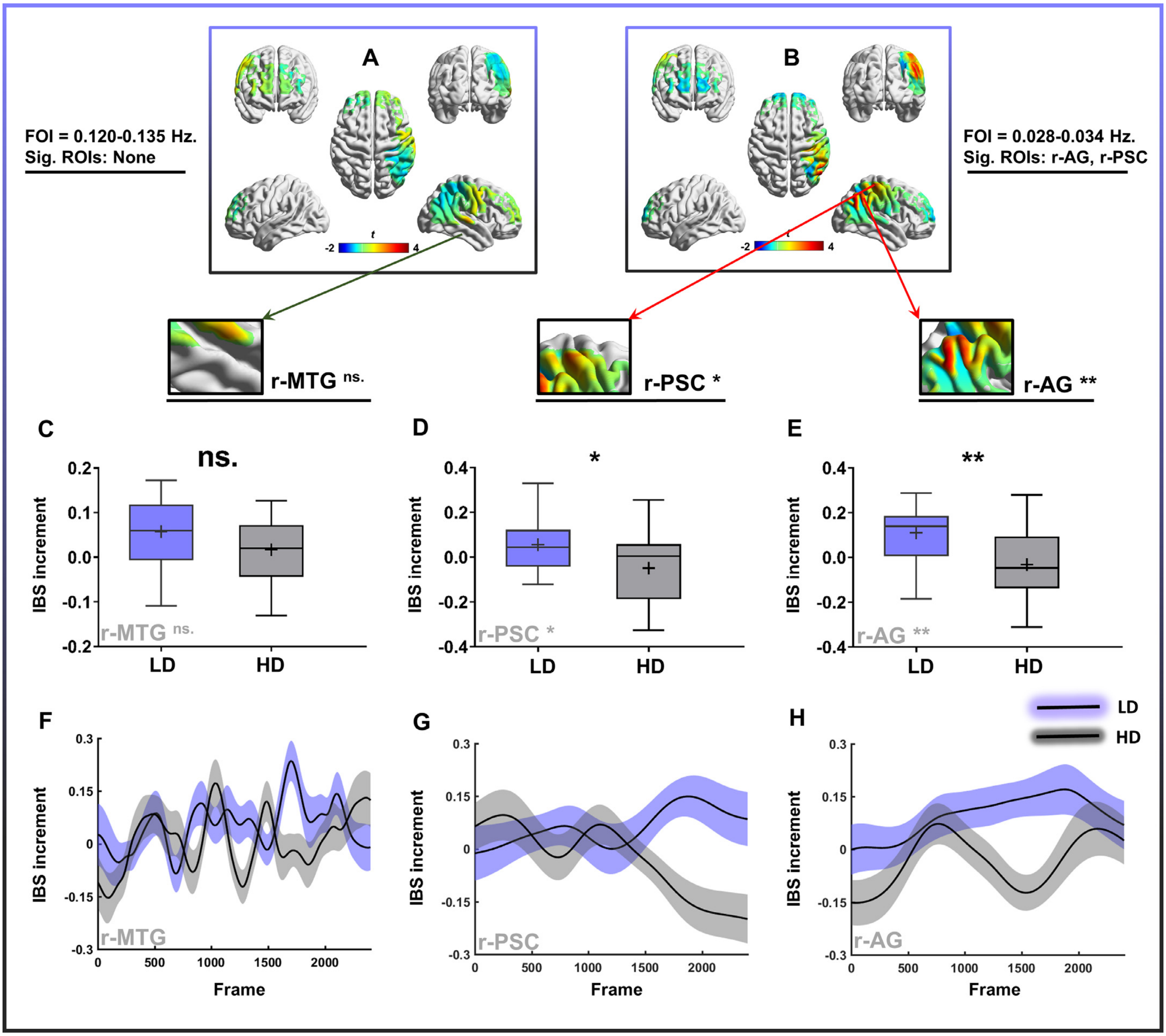

Fig. 4. Interpersonal brain synchronisation (IBS). **(A)** The *t*-map for independent-samples t-tests using GROUP as the between-subject factor on the IBS increment of all ROIs at the frequency band of interest 1 (FOI1). No significant group difference was observed. **(B)** The *t*-map for independent-samples t-tests using GROUP as the between-subject factor on the IBS increment of all ROIs at the frequency band of interest 2 (FOI2). Significant group difference was observed at the right angular gyrus (r-AG) and right primary somatosensory cortex (r-PSC, false discovery rate corrected). Note that the above resulting *P* values were already corrected using the false discovery rate method (threshold: $P < 0.05$). **(C)** The amplitude of IBS increment of the right middle temporal gyrus (r-MTG) at FOI1. **(D)** The amplitude of IBS increment of r-PSC at FOI2. **(E)** The amplitude of IBS increment of the r-AG at FOI2. Error bars indicate standard errors of the mean. $^{*}P < 0.01$, $^{**}P < 0.01$. **(F)** The trajectory of IBS increment of r-MTG at FOI1. **(G)** The trajectory of IBS increment of r-PSC at FOI2. **(H)** The trajectory of IBS increment of the r-AG at FOI2.

Regarding the IBS increment in the right primary somatosensory cortex, the main effect of EPOCH was not significant (F [2, 112] = 1.82, $P = 0.17$, $\eta_p^2 = 0.31$). The interaction effect of EPOCH × GROUP is significant (F [2, 112] = 6.76, $P = 0.002$, $\eta_p^2 = 0.11$). Further simple effect analysis (Bonferroni-corrected) showed that IBS increment was significant greater in the LD group than in the HD group during EPOCH3 ($P < 0.001$, Cohen's $d = 1.10$). However, no group difference was observed during EPOCH2 or EPOCH1. Additionally, the IBS increment was significantly greater during EPOCH1 ($P = 0.006$, Cohen's $d = 1.04$) and EPOCH2 ($P = 0.018$, Cohen's $d = 0.93$) than during EPOCH3. However, no significant difference was observed for the LD group ($Ps > 0.1$; see details in Table S3).

3.6. IBS-behaviour relationships

A series of bivariate Pearson correlations was performed between the IBS increments at the right angular gyrus and right primary somatosensory cortex in frequency band of interest 2 and behavioural performance during the AUT (i.e., AUT fluency, AUT uniqueness, collective flexibility, IOC). The resulting *P* values were corrected using the false discovery rate method (threshold: $P < 0.05$). However, no significant correlation was observed ($Ps > 0.05$).

In order to examine the relationship between the evolution of behavioral performance and IBS increments over time, a series of bivariate Pearson correlations was performed on the above IBS increments and behavioural performance (i.e., AUT fluency, AUT uniqueness, collective flexibility, IOC) during three epochs. The resulting P values were corrected using the false discovery rate method (threshold: $P < 0.05$). Regarding the right angular gyrus, the IBS increment during the EPOCH2 significantly, positively predicted IOC during the EPOCH3 ($r = 0.36$, $P_{corr} = 0.036$) and negatively predicted collective flexibility during the EPOCH3 ($r = -0.36$, $P_{corr} = 0.036$); the IBS increment during the EPOCH3 negatively predicted collective flexibility during the EPOCH3 ($r = -0.34$, $P_{corr} = 0.03$). Regarding the right primary somatosensory cortex, the IBS increment during the EPOCH1 significantly, negatively predicted IOC during the EPOCH2 ($r = -0.36$, $P_{corr} = 0.036$); IBS increment during the EPOCH3 negatively predicted collective flexibility during the EPOCH3 ($r = -0.30$, $P_{corr} = 0.043$).

In addition, a series of bivariate Pearson correlations was performed between the above IBS increments and scores on scales and questionnaires (i.e. perspective-taking tendency, openness, etc.). The resulting P values were corrected using the false discovery rate method (threshold: $P < 0.05$). Results showed no significant correlation (Ps > 0.05).

4. Discussion

In this study, participants who were unknown to each other were assigned to HD or LD groups based on their academic majors. Each group was instructed to perform the AUT and OCT, which differ in whether the task demands creativity. During task performance, we used fNIRS-based hyperscanning to simultaneously record the neural responses of the participants. To the best of our knowledge, this is the first study to tentatively unveil the interpersonal neural correlates underlying the effect of group educational diversity on group creativity. The results showed that the LD group had higher AUT fluency and IOC than the HD group, whereas no significant group difference was observed for AUT uniqueness. However, we observed that collective flexibility was significantly higher in the HD group than in the LD group. The neuroimaging results showed that significantly higher IBS increments evoked in the right angular gyrus and right primary somatosensory cortex in the LD group than in the HD group.

We observed higher AUT fluency in the LD group than in the HD group but comparable AUT uniqueness for the two groups. Accordingly, hypothesis (Ib) is partly supported. This may suggest that a high level of educational diversity is detrimental rather than beneficial to group creative performance, especially in terms of idea quantity. Additionally, the results showed that IOC was significantly greater in the LD group than in the HD group, which indicates that the level of perspective-taking behaviour is higher in the LD group than in the HD group and supports hypothesis (IIb). Previous studies have emphasised the role of accessibility to others' ideas in improving creativity (Leggett Dugosh and Paulus, 2005; Fink et al., 2012; Xue et al., 2018). These studies suggest that when exposed to easy-to-understand ideas, it is easier for individuals to search for potentially related semantic connections. Consequently, individuals could generate more creative ideas by improving others' ideas or by combining these ideas with their own knowledge. In the current study, compared with the educational background of participants in the HD group, since the participants in the LD group had a similar educational background, the ideas they were exposed to might have been easier for them to understand. Therefore, creative idea generation and perspective-taking behaviours would have been stimulated.

Intriguingly, the results showed higher collective flexibility in the HD group than in the LD group. As argued by the Information/Decision-Making Perspective (van Knippenberg and Mell, 2016), a high level of educational diversity can involve diverse knowledge, information, etc (Bower and Hilgard, 1981; Dahlin et al., 2005). Therefore, a broader pool of task-relevant resources (i.e., information and perspectives) is accessible to the HD groups and contributes to group creative performance. In this case, it seems that high group educational diversity did involve diverse information and a broader pool of potential task ideas from different categories (higher collective flexibility). However, the theoretical benefits of high group educational diversity for AUT fluency and AUT uniqueness did not emerge. We suggest that the low level of perspective-taking behaviours occurring during the task in the HD group might have led to this outcome. Recent studies have suggested that knowledge exchange and perspective-taking are important for the relationship between group knowledge diversity and group creativity (Hoever et al., 2012; Tang and Naumann, 2016; van Knippenberg, 2017). In other words, even if one group has more abundant task-relevant resources (potential information or perspectives), this does not necessarily lead to higher idea quantity or quality in the absence of a high level of perspective-taking behaviour by the group members.

We also examined the trajectory of behavioural performance over time and did group-wise comparisons. An interesting finding was that IOC tended to increase over time in both groups, whereas this tendency is more distinct in the LD group than in the HD group (LD: EPOCH3 > EPOCH2 > EPOCH1; HD: EPOCH2 > EPOCH1). Similarly, collective flexibility tended to decrease over time in both groups, whereas this tendency is more distinct in the LD group than in the HD group (LD: EPOCH1 > EPOCH2 & EPOCH3, EPOCH2 = EPOCH3; HD: EPOCH1 > EPOCH2). Meanwhile, group difference in collective flexibility (EPOCH1 & EPOCH2: LD = HD; EPOCH3: LD < HD and IOC (EPOCH1 & EPOCH2: LD = HD; EPOCH3: LD > HD) became more and more distinct as the task proceeded. These may indicate that various levels of educational diversity lead group creation in different directions: high educational diversity leads group creation to a 'flexibility' pathway, whereas low education diversity leads group creation to a 'convergent/persistence' pathway.

The neuroimaging results showed that the IBS increment at the right angular gyrus was significantly greater in the LD group than in the HD group. This finding supports hypothesis (IIIb). As shown in previous studies, IBS increments occurring between individuals are thought to be a marker for interpersonal information exchange (Nozawa et al., 2016; Dai et al., 2018; Pan et al., 2020). The IBS increment observed in the LD group might also indicate that the group members were mutually engaged in the information exchange process. The right angular gyrus is one of the pivotal areas of the right temporal-parietal junction. Previous studies have confirmed that the right angular gyrus is strongly associated with social cognition, including perspective-taking and theory of mind (Santiesteban et al., 2015; Schurz et al., 2017; Filmer et al., 2019). Accordingly, IBS increments at the right angular gyrus in the LD group might mean that the group members were mutually engaged in understanding the partners' mind so that information/perspectives could be exchanged, communicated, and integrated. This is supported by the fact that there were significantly more perspective-taking behaviours in the LD group than in the HD group (see Fig. 3D). Likewise, the lower IBS increment in the HD group might mean that participants in the HD group mostly generate ideas on themselves rather than considering others' perspectives, which might have resulted from hard-to-understand perspectives or ideas in this group. In addition, previous studies have confirmed the close association between the right angular gyrus and spatial and semantic attentional orienting (Chambers et al., 2004; Cristescu et al., 2006). Considering that shared attention (i.e., orienting attention toward a similar perspective) is necessary for interpersonal communication and may even stimulate perspective-taking behaviour, the IBS increment we observed at the right angular gyrus may mean that participants were orienting their attention to similar perspectives or semantic categories. When participants orient their attention similarly, information exchange and perspective-taking behaviour are more likely to emerge. Above all, researchers usually revealed neural substrates specific to creative cognition by comparing neural responses during the AUT to that during the OCT (Fink et al. 2009; Fink et al. 2010; Sun et al. 2016). In this study, the IBS increment was calculated by subtracting the time-averaged IBS of the OCT session from that of the AUT session, thereby the observed significant IBS increment might indicate the IBS increment specific to group creation. Also, previous research repeatedly proved the close association between the right angular gyrus and creative thinking

(Fink et al., 2010; Jung et al., 2010; Lu et al., 2019b). Accordingly, a prudent interpretation for the observed IBS increment at the right angular gyrus could be that, it indicated the complex interpersonal information exchange process during group creation. This complex social interaction process comprised of behaviours such as orienting attention to easy-to-understand perspectives or semantic categories, taking others' perspectives into consideration, etc., all of which occurred in the scenario of group creation and served the purpose of generating creative ideas. Nevertheless, the exact meaning of these IBS increments requires further investigation.

The neuroimaging results also showed that the IBS increment at the right primary somatosensory cortex was significantly greater in the LD group than in the HD group. The right primary somatosensory cortex is widely recognized as a critical region for processing somatosensory input and contributes to the integration of sensory and motor signals. Previous evidence has also found that the primary somatosensory cortex is associated with attention performance (Wei et al., 2014). When participants were generating alternative uses for the target object, they firstly needed to construct an image for this object and operate it in their mind. Given participants in the LD group had a more similar knowledge background than those in the HD group, the sensory signals emerged during the above imagery process might be more similar in the LD group than in the HD group. Therefore, one interpretation might be that IBS increment at the right primary somatosensory cortex reflected that participants' imagery process for the target object is more similar in the LD group than in the HD group. Nevertheless, the exact implications of IBS increments at the right angular gyrus and right primary somatosensory cortex requires further investigation.

Recent hyperscanning studies on group creativity have confirmed a strong association between IBS increments at right angular gyrus and interpersonal information exchange during group creativity (Xue et al., 2018; Lu et al., 2019b; Lu et al., 2020b). In this study, findings of higher IBS increment at right angular gyrus in the LD group may provide further evidence for such an association. However, this study didn't replicate the previous findings that IBS was enhanced in right dorsolateral prefrontal cortex during group creativity (Xue et al., 2018; Lu et al., 2019b). This may indicate that, although group educational diversity affects the accessibility of partners' ideas, it does not impair individual interests in cooperating with the partners (the lower level of perspective-taking behaviours might merely result from the hard-to-understand ideas) (Xue et al., 2018; Lu et al., 2019b). This can be supported by that no significant group difference was observed for the self-rating scores on tendency to perspective-taking, and liking for collaboration with their partner (see details in Table S2 in the Appendix).

We found that there were also some differences between the ROI-wise and CH-wise results. We suggest it may be more proper to use the ROI-wise analysis rather than the CH-wise analysis in future fNIRS studies. First, since channel-wise results should be corrected to reduce the risk of false positive results, separately analyzing data from multiple channels from the same cerebral region (e.g., a total of 7 channels belong to ROI in this study) may increase the risk of false negative results. Second, given the spatial resolution of fNIRS is not high, combining channels from the same cerebral region as one ROI in fNIRS analysis may be more proper.

Several limitations of the study should be noted. First, during dyadic interaction, it is easy to notice similarities or dissimilarities between any two persons (e.g., gender, social habits, etc.). For instance, previous studies have shown that gender difference can affect interpersonal interaction (Baker et al., 2016; Cheng et al., 2015; Lu et al., 2020a). One's academic major is not one of the most salient features to notice. Thus, we cannot rule out the possibility that the effect of educational diversity on group creativity is confounded by these more salient features such as gender. Future studies should take these features into consideration. Second, although we found no significant group differences in individual creative potential, perspective-taking tendency, or preference for teamwork, we cannot rule out an influence of other factors that might explain the observed differences between the HD and LD groups. For instance, individuals with the same major may be similar in many ways, which can be education-independent (e.g., individual major selection) and education-dependent (e.g., reading hobbies, logistic thinking). This possibility should be further explored in future studies. Third, in the current study, participants in each pair were strangers and had only 5 min to collaboratively solve a creativity task. In such a scenario, new knowledge from the partner can be hard to understand, which may also have impeded the information exchange process and thus the creative performance of the HD group. The effect of team longevity on the relationship between group educational diversity and group creative cognition deserves further investigation. Finally, differences in individual head size or brain area size are a common technical limitation of fNIRS. Although we used several approaches to avoid as many contamination effects as possible, we could not fully exclude the contamination effects of brain size variation. Future studies should use other strategies to exclude the contamination effects of variation in brain area size and head size on fNIRS results .

Declaration of Competing Interest

The authors have nothing to disclose.

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Author Contributions

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

Data and code availability statement

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2021.118564.

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