NeuroImage 260 (2022) 119448

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Increased or decreased? Interpersonal neural synchronization in group creation

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A R T I C L E I N F O

Keywords:
Group creation
Hyperscanning
fNIRS
Interpersonal neural synchronization

A B S T R A C T

Group creation is the process by which group members collaborate to produce novel and useful ideas or products, including ideas generation and evaluation. However, the interpersonal neural mechanism of group creation during natural communication remains unclear. In this study, two groups of same-sex dyads with similar individual creativity collaborated to complete the Product Improvement Task (creative condition) and the Item Purchase Plan Task (control condition), respectively. Functional near-infrared spectroscopy (fNIRS) was used to record both members' neural activity in the left prefrontal (lPFC) and right temporal-parietal junction (rTPJ) regions during the task. Considering that the role asymmetry of group members may have an impact on interpersonal neural patterns, we identified leaders and followers in the dyads based on participant performance. The results showed that leaders and followers in the creative condition had significantly lower interpersonal neural synchronization (INS) in the right superior temporal gyrus-left superior frontal gyrus, right supramarginal gyrus-left superior frontal gyrus, and right supramarginal gyrus-left middle frontal gyrus than in the control condition. Partial multivariate Granger causality analyses revealed the influence between dyads was bidirectional but was significantly stronger from the leaders to the followers than the other direction. In addition, in the creative task, the INS was significantly associated with novelty, appropriateness, and conflict of views. All these findings suggest that the ideas generation and ideas evaluation process in group creation have poor interpersonal neural activity coupling due to factors such as the difficulty of understanding novel ideas. However, performances may be improved when groups can better integrate views and reach collective understanding, intentions, and goals. Furthermore, we found that there are differences in the dynamics of INS in different brain regions. The INS related to the novelty of the group creation decreased in the early stages, while the INS related to the appropriateness decreased in the middle stages. Our findings reveal a unique interpersonal neural pattern of group creation processes in the context of natural communication.

1. Introduction

Employing small groups to solve problems is critical to modern life (Doboli and Doboli, 2021). Cooperation between members with different knowledge and skills may create novel ideas or products and solve problems creatively, resulting in greater group benefits (Mao et al., 2016; Senaratne and Gunawardane, 2015). Therefore, understanding the mechanisms of group creativity is important for many domains.

Group creativity is defined as a group of members working together to produce novel and useful ideas or products (Ristic et al., 2016; Wang and Zhu, 2011). There are two basic characteristics of group creativity: group structure and creative process. For the group structure, due to differences such as knowledge utilization preferences and individual traits (Ray and Romano, 2013), role asymmetry may exist in the

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https://doi.org/10.1016/j.neuroimage.2022.119448.
Received 29 October 2021; Received in revised form 1 July 2022; Accepted 3 July 2022
Available online 14 July 2022.

interaction process of group creativity. Groups tend to emerge with individuals who are good at generating novel ideas and individuals who are willing to understand and coordinate with others (Bolinger et al., 2009). The former usually gain status in the group and may become leaders who lead ideas. The latter, as followers, exert less influence on others but are also important in promoting creativity (Bolinger et al., 2009). This pattern of collaboration may be relatively stable throughout the process of group creativity (Mayseless et al., 2019). Similarly, in the leaderless group discussions, many studies have also found that individuals may spontaneously form a "leader-follower" relationship (i.e. one person lead the task and the other one follow) in interactions (Jiang et al., 2015; Konvalinka et al., 2014; Selten and Warglien, 2007). This spontaneous asymmetrical interpersonal relationship may be beneficial to group performance (Selten and Warglien, 2007; Wallot et al., 2016). For the creative process, group creativity involves both divergent and convergent thinking, which is similar to individual creativity (Tan, 2015; Ulrich, 2018). The interacting members not only generate ideas (related to divergent thinking) but also evaluate the ideas (related to convergent thinking) of others (Chen et al., 2017; Paulus and Yang, 2000; Ray and Romano, 2013), with the two stages being constantly recursive and iterative (Harvey, 2014; Harvey and Kou, 2013). The former is expected to improve the novelty of ideas and the latter is expected to improve the appropriateness of the group's creative ideas (Paletz and Schunn, 2010; Singh and Fleming, 2010). In addition, due to cognitive diversity and difficulty in understanding the intentions of others' views, members may have a conflict of views during interactions, but creativity tends to develop better when teams are better able to integrate members' views (Harvey, 2014; Kohn et al., 2011; Ristic et al., 2016; Xue et al., 2018).

Since group creation depends on interpersonal interaction, in recent years, researchers have used functional near-infrared spectroscopy (fNIRS) based hyperscanning technique to understand the interaction of creative groups (e.g., Duan et al., 2020; Lu et al., 2019a, 2019b, 2020b; Lu and Hao, 2019; Mayseless et al., 2019). Compared with single-brain studies, hyperscanning aims to measure the brain activity of multiple brains simultaneously to meet the needs of studying the interbrain activity patterns of interactive participants (see (Kelsen et al., 2020; Redcay and Schilbach, 2019; Wang et al., 2018) for further details). Because fNIRS has high temporal and spatial resolution, and high tolerance for physical activity, it has been widely used as a brain signal acquisition modality in hyperscanning studies (Brockington et al., 2018). By analyzing the synchrony of group members' neural activity during the interaction, termed interpersonal neural synchronization (INS), researchers mainly focused on the influencing factors of the process of group creation. Recent evidence suggests that INS in the process of group creation is related to romantic relationships (Duan et al., 2020), communication mode (Lu et al., 2020b), cooperation (Xue et al., 2018), feedback (Lu et al., 2019a). And the stronger INS may indicate better team performance. However, the above-mentioned influencing factors on INS have also been found in other hyperscanning studies of interpersonal interaction (Cui et al., 2012; Liu et al., 2019; Long et al., 2021; Zhu et al., 2021).

To identify the interpersonal neural models specific to group creativity, a direct comparison of group creativity tasks with general tasks (i.e. non-creative tasks) may be needed. Lu et al. (2019b) compared the INS difference between the alternative uses task (AUT, demanding divergent thinking) and the object characteristic task (OCT, not demanding divergent thinking) under the conditions of cooperation. They found that the dyads' INS of right dorsolateral prefrontal cortex (rDLPFC) and right temporal-parietal junction (rTPJ) in the AUT task was stronger than in the OCT task. However, in this study, participants were only asked to continuously generate novel ideas in the turn taking without eventually forming an integrated proposal. So the study focused more on idea generation and less involved idea evaluation in group creativity. In addition, unlike natural communication, turn taking itself is already a cooperative process that may affect interpersonal neural models related to creativity (Mayseless et al., 2019).

To better understand the interactions that occur naturally in the group creativity process and the characteristics of its interpersonal neural mechanism, Mayseless et al. (2019) explored the INS difference between creative tasks (open product design) and control tasks (prescribed 3D model building) in the context of natural communication and its relationship with behavioral indices of creativity. The result suggested that dyads' INS in anterior prefrontal cortex (aPFC)-posterior superior temporal gyrus (pSTG) and aPFC-TPJ in the creative task was significantly greater than in the control task. However, it should be noted that while the creative design task includes the idea generation and idea evaluation, the 3D model building task as the control condition is quite different from it. For example, the 3D model building task requires advanced manual dexterity and spatial skill. However, this interactive process may involve less verbal communication and less complex processing of language and emotions (Li et al., 2021), which may affect the strength of INS (Hasson et al., 2012).

Although the above two studies found higher INS in group creation, there is also some evidence that the INS of group creation tasks may be lower than the general tasks. First, the shared neural response may reflect similar representation or thinking (Cetron et al., 2019; Meshulam et al., 2021; Nguyen et al., 2021; Wass et al., 2020). To generate novel ideas, group members often need to inhibit dominant and consensus representations, engage in mental representational change, break the thinking impasses and diverge in different directions (Huang et al., 2019). As a result, the INS of group creation tasks may decrease. Second, due to the heterogeneity of knowledge, skills, and experience, group members in the process of idea evaluation may have difficulty understanding each other's novel ideas and intentions, resulting in disagreements or conflicts (Bodla et al., 2018), which may lead to the INS of group creation tasks lower than general tasks (Fishburn et al., 2018; Lu et al., 2021; van Baar et al., 2021). Finally, Mayseless et al. (2019) found that the originality score in the creative task showed a trend level negative correlation with the INS increase of inferior frontal gyrus (IFG)-pSTG. This seems to imply that the INS may decrease when the interacting members generate some creative responses (Shamay-Tsoory et al., 2019).

The present study used a Product (umbrella) Improvement task as the group creation task (Torrance, 1966). Participants were required to eventually generate a novel and appropriate solution. This process involved both idea generation and evaluation. The item (umbrella) purchase plan task, which requires a similar interaction pattern but does not demand creativity, was used as a general task for control. The similarity of the experimental materials used and interaction patterns in the two tasks better reduced the differences in INS due to excessive differences between experimental tasks. Given the advantages of fNIRS-based hyperscanning techniques, this study used fNIRS to continuously record changes in the cerebral activity of dyads during the interaction. We focused on the rTPJ and lDLPFC to explore the interpersonal neural models between the individuals involved in group creation. The reasons are as follows. First, the rTPJ and lDLPFC have been considered to be key brain regions for cognitive processing in creative tasks (Huang et al., 2021). The rTPJ as a component of the default-mode network (DMN) was considered to be related to the generation of creative ideas, while the lDLPFC as a component of the executive control network (ECN) was considered to be related to the evaluation of creative ideas (Huang et al., 2021; Kleinmintz et al., 2019). Moreover, in the context of social interaction, the TPJ and PFC regions are also considered to be components of the mentalizing system (MS), which is responsible for mentalizing, theory of mind, and other social cognition. The coupling between the two may reflect the state of interaction between individuals (Lu et al., 2021). In addition, previous hyperscanning studies of group creativity have also shown that the lDLPFC and rTPJ are recruited (Lu et al., 2019a; Lu and Hao, 2019).

Role asymmetry has been neglected in previous studies on interpersonal neural mechanisms of group creativity, and members' roles are considered to be equal and symmetrical. The INS of different brain areas was calculated as the average across all group members in any given condition. For example, the INS between lDLPFC and rTPJ was calculated from the average of the INS between lDLPFC (Participant 1) and rTPJ (Participant 2) and the INS between rTPJ (Participant 1) and lDLPFC (Participant 2) (Li et al., 2021). Because role differentiation already exhibits unique interpersonal neural characteristics early in natural communication (Jiang et al., 2015), this calculation method of INS may obscure some important information. In the present study, we assessed individual roles (leader or follower) based on dyads' interactions before data analysis. Then INS was calculated between each channel of the leaders and all channels of the followers in each dyad and was not averaged. This study examined the differences and dynamics of INS between creative condition and control condition, the information flow between roles, and the relationship between INS and behavior indicators.

2. Methods

2.1. Participants

One hundred and twenty-seven college students were recruited. They were asked to complete an AUT task through an online questionnaire before the experiment. The novelty scores of the answers generated by the participants were used as a measure of individual creativity (Runco and Acar, 2012) (see details in the supplementary materials S1).

To avoid the influence of gender and creativity level on group creation (Cheng et al., 2015; Xue et al., 2018), the dyads were made up of two people with the same level of creativity and the same gender (see details in the supplementary materials S1). After excluding participants who disobeyed the experimental instructions (see details in the supplementary materials S1), there were 17 dyads (6 dyads of men and 11 dyads of women) under each experimental condition, for a total of 68 participants (mean age: 20.01 ± 1.91 years old).

The members of each dyad did not know each other before the experiment. All the participants were right-handed, had no brain disease or mental illness, and had normal or corrected-to-normal vision. They were paid a standard experiment participation fee and provided signed informed consent before participation. All experimental protocols were approved by the Ethics Institute Review Board of Central China Normal University.

2.2. Experimental tasks

In the creative condition, dyads were asked to complete the "Product Improvement Task". This task is an item on the Torrance Tests of Creative Thinking (TTCT), which is typically used to measure individual creativity (Wei et al., 2014). We slightly changed the task for use in the dyadic context. To make the task relevant to daily life, we replaced the elephant, the object of the original creative product improvement task, with an umbrella (see Fig. 1A). These dyads were asked to discuss form a novel and appropriate improvement plan for the umbrella. In the control condition, dyads were asked to complete a general task of "Item Purchase Plan". Compared with the creative task, the general task required little creativity. These dyads were asked to discuss to form an appropriate purchase plan for the umbrella (see supplementary materials S2 for task instructions). After the discussion, the team ultimately needed to reach a consensus on the improvement plan or purchase plan and then write down the plan together.

2.3. Experimental procedure

2.3.1. Subjective measurement

Before the general experimental procedure, participants were asked to complete assessments of cooperative preference, the familiarity with umbrellas, and the degree of demand for umbrellas. After the general experimental procedure, participants were asked to complete an assessment of interest in the task (see Supplementary Material S3 for questionnaires).

2.3.2. General experimental procedure

The general experimental procedure consisted of an 8 min resting-state session, 2 min instruction session, and a 20 min task session (see Fig. 1C).

Participants were asked to sit face to face (see Fig. 1B), and the initial 8 min resting-state session served as a baseline. During this session, participants were asked to remain as still as possible, with their eyes closed and their minds relaxed, and don't think about specific problems or fall asleep (Lu et al., 2019b). Next, in the instruction session, the task and requirements were introduced. Then, during the task session, group members cooperated to complete the corresponding experimental tasks through natural communication. This process was recorded with a video camera with audio. fNIRS data were simultaneously collected during both the resting-state session and task session. To ensure the validity of the data, the participants were asked to avoid large-scale movement as much as possible during the experiment. After the discussion, the participants were asked to write down the plan together, and individually rated the degree of conflict of views during the discussion session from 1 (not at all) to 5 (very much) points.

2.3.3. Task performance evaluation and role division

Eight graduate students, who were blind to the group assignment, used the consensus assessment technique (Amabile, 1983) to evaluate the novelty and appropriateness of the problem solution on a Likert scale ranging from 1 (not at all) to 5 (extremely). Four of them evaluated the creative product improvement task and the other four evaluated the purchase plan task. The average of the four scores across two items was used as the final score for group performance. All the inter-rater agreements were satisfactory (ICCs > 0.82).

In addition, three graduate students were invited to watch the video and evaluate the role of each member of the dyad (leader: who always takes the lead, follower: who more or less follows the other) based on the naturally emerging discussion. One member was identified as a leader if two or more raters marked him or her as a leader. The other member of the dyad was marked as a follower. Another four graduate students counted the number of expressed views per individual in each dyad. All graduate students were blind to the purpose of the experiment.

2.4. fNIRS data acquisition

NIRScout (NIRx Medical Technologies, New York) was used to record changes in each participant's oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) concentrations during the experimental task. There were 4 probe sets. Of these, 2 probes had 3 emitters and 4 detectors to form a 3*4 probe set, forming a total of 8 measurement channels. The other 2 probe sets had 5 emitters and 4 detectors to form a 5*4 probe set, forming a total of 12 measurement channels. Thus, there were a total of 20 measurement channels. The distance between each channel was up to 3 cm (fixed with a 3 cm fixing piece).

In dyads, each participant had two probe sets on the head: a 3*4 probe set on the left forehead and a 5*4 probe set on the right temporal-parietal joint area. The probe was placed according to the 10-20 international system. The emitters on the left forehead covered FP1, AF3, and F5, with detectors located at FPz, AFz, AF7, and F3. The emitters on the right temporal-parietal joint area were located at P8, T8, CP6, P4, and C4, with detectors at TP8, P6, C6, and CP4. The positions of the probes are shown in Fig. 1D. The brain region corresponding to the channel was positioned using a three-dimensional locator (NIRx Medical Technologies, New York), which to determine the Nz, Cz, Iz, AL, AR points and probe positions. The probabilistic registration method was used to register the fNIRS channel position with the Montreal Neurological Institute (MNI) space coordinates to obtain the corresponding

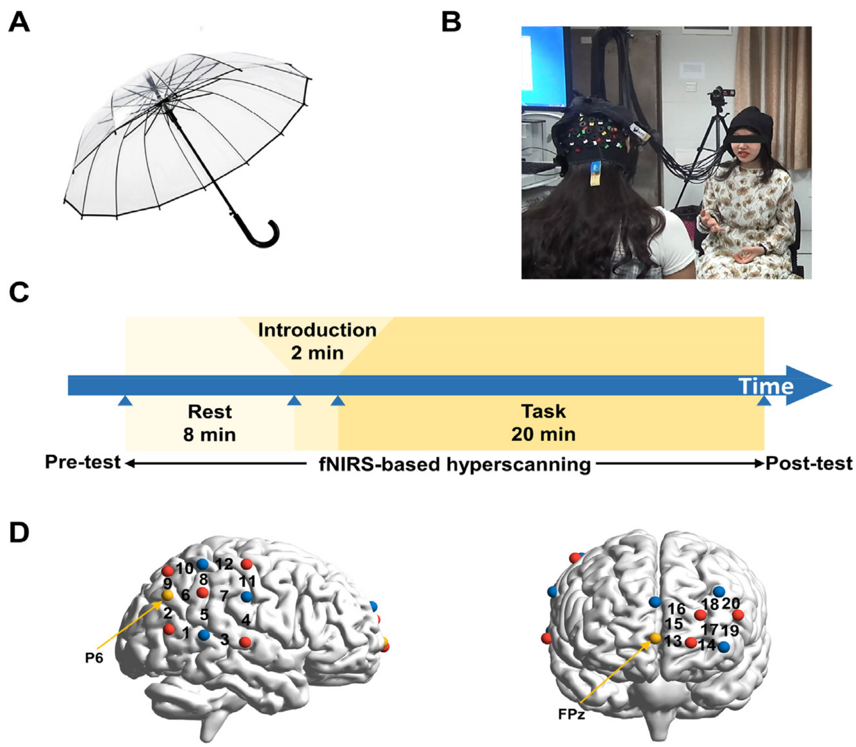

Fig. 1. Experiment procedure. (A) Umbrella prototype. (B) Participants' seating arrangement. (C) Experiment flow chart. (D) Cap configuration. Red circles indicate emitters; Blue circles indicate detectors. The measurement channels are marked by numbers. Measurement channels covered the frontal, temporal, and parietal cortices.

relationship with the Brodmann area and automatic anatomical labels (AAL) area (Tsuzuki et al., 2012).

The absorption of near-infrared light at two wavelengths (785 and 830 nm) was measured with a sampling rate of 7.8125 Hz. Based on the modified Beer-Lambert law, changes in the HbO and HbR concentrations were obtained by measuring changes in absorption of fNIRS light after its transmission through the tissue. Previous studies have shown that HbO was a sensitive indicator of change in regional cerebral blood flow (Zheng et al., 2018). Thus, this study focused on the HbO concentrations only.

2.5. *Behavioral data analysis*

2.5.1. *Correctness check of role division*

Since the leaders may express more views (Wickham and Walther, 2007), we conducted a 2 (between-group variable: Task Type: creative task vs. general task) * 2 (within-group variable: Role: leader vs. follower) mixed ANOVA on the number of expressed views to verify the correctness of the role division. In addition, the communication skills and competence of members were further evaluated to ensure the correctness of the role division (see Supplementary material S4 for details).

2.5.2. *Task performance*

Before conducting a comparison of task performance between the two tasks, we first tested the control of extraneous variables in the experiment. A 2 (between-group variable: Task Type: creative task vs. general task) * 2 (within-group variable: Role: leader vs. follower) mixed ANOVA was conducted for each of the following dependent variables: individual creativity, cooperative preference, familiarity with umbrellas, the degree of demand for umbrellas, and interest in the task.

As extraneous variables obtained by subjective measurement might have affected task performance, one-way ANCOVA was conducted to exclude possible effects of extraneous variables on task performance. We separately averaged the five extraneous variables in dyads. For that analysis, the Task Type (a categorical variable) was an independent variable and the five extraneous variables at the pair level (continuous variables) were covariates.

2.6. *fNIRS data analysis*

2.6.1. *Pair-level analysis*

The fNIRS data collected during the rest session and task session were analyzed. Data from the first 60 s and last 60 s were deleted during preprocessing. Thus, data within the period of steady state were analyzed. During preprocessing, no filtering or detrending procedures were applied (Cui et al., 2012). In addition, we did not perform any artifact corrections at the single-subject level, as wavelet transform coherence (WTC) normalizes the amplitude of the signal according to each time window and thus was not vulnerable to the transient spikes induced by movements (Nozawa et al., 2016).

We employed WTC analysis to estimate INS. A Matlab package was used to perform WTC (Grinsted et al., 2004) as a way to assess the cross-correlation between the two fNIRS time series generated by each pair of participants as a function of frequency and time (Torrence and Compo, 1998). For the two participants in one dyad, HbO values were obtained in two time series of equal length and aligned. Then, WTC was applied to these two aligned time series to find regions in the time frequency space where the two time series co-varied. For more thorough information about wavelet coherence, please see Grinsted et al. (2004) and Chang and Glover (2010). Because there were 20 measurement channels for each participant (leader or follower), 400 (20*20) pairs of time series were generated for each dyad, and WTC was thus conducted 400 times (Zheng et al., 2020, 2018). The coherence values were time-averaged across the rest and discussion periods, and converted into Fisher z-values.

Consistent with previous studies (Dai et al., 2018; Jiang et al., 2012), we focus on the relative enhancement of INS during the task session compared to the resting-state session. Thus, we subtracted the coherence value of the resting-state session from that of the task session to obtain an index of time-aligned INS increase (Grinsted et al., 2004). At this stage, no specific frequency ranges were selected.

Since the group creativity process requires members to continuously generate and evaluate ideas through verbal communication, this process involves neurocognitive processing of members' mutual understanding. The neural coupling between two persons in verbal interaction may not be limited to time alignment. Previous studies have shown that in the process of information comprehension, listeners' neural response may lag behind speakers, resulting in a time-lag INS (Jiang et al., 2021; Liu et al., 2017; Stephens et al., 2010). Therefore, we added various time-lags to the computation of INS increases to obtain the time-lagged INS increases (Long et al., 2021; Zheng et al., 2018). For the selection of time windows, we referred to previous interpersonal neural studies on verbal comprehension (Jiang et al., 2021; Liu et al., 2020, 2017; Stephens et al., 2010). Specifically, the time course of the leaders' brain activity (i.e., HbO) was shifted forward or backward relative to that of the followers' brain activity by 1–6 s (step = 1 s).

2.6.2. Group-level analysis (time-aligned INS)

2.6.2.1. Task type-related differences in time-aligned INS. The following analyses were conducted to identify the difference in the INS increase between the two tasks. First, to identify the frequency ranges that were specifically associated with the task style, independent sample t-tests were conducted on the time averaged coherence value of each CH (channel) combination (400 in total) along the full frequency range (0.01–0.7 Hz). Following previous studies (Dai et al., 2018; Jiang et al., 2012), data above 0.7 Hz were not included to avoid aliasing of higher frequency physiological noise, such as cardiac activity (0.8–2.5 Hz). Data below 0.01 Hz were also not used, to remove very low frequency fluctuations. Finally, data within the frequency range of respiratory activity (0.15–0.3 Hz) were not considered. The t-test results were threshold at $p < 0.0005$. No further corrections were applied because this analysis was used to identify the pattern along the frequency range rather than to obtain the final results (Zheng et al., 2018). It was finally found that the frequency range of interest was 0.315–0.445 Hz, and the coherence values within this frequency range were averaged. Independent samples t-tests (creative task vs. general task) were performed on the time-aligned INS increase of all channels in this band, and FDR correction was performed (Zheng et al., 2020, 2018). The channel combinations exhibiting significant condition-related INS increase differences were defined as significant CH combinations.

2.6.2.2. Validation of the INS differences between task types through a permutation test. To verify that the group difference in INS increase was specific to the original pairing of the leaders and followers, a validation approach (i.e., a permutation test) was used (Lu et al., 2020b). For each condition, all participants were randomly assigned to new dyads to recompute the INS and perform a series of independent sample t-tests on the newly formed two sets of data. This permutation process was repeated 1000 times to yield a distribution (*t* value) of all CHs, which was then compared with the original pairing data.

2.6.2.3. Linking task performances with time-aligned INS. To determine the behavioral significance of leader-follower neural coupling, we examined the correlation between INS increase of significant CH combinations and the task performances, separately, under different conditions. Since creativity level, cooperative preference, and interest in the task may affect the correlation between INS and task performance (Kelsen et al., 2020; Lu et al., 2019b; Xue et al., 2018; Zhu et al., 2019), we separately averaged the three extraneous variables in dyads. Then, a Pearson's partial correlation analysis was applied, which controlled for the potential effect of the three extraneous variables (creativity, cooperative preference, and interest in the task), and FDR correction was performed.

2.6.2.4. Dynamics of the time-cumulative time-aligned INS analysis. To identify the earliest time-point where the INS increase differed among conditions, we conducted a time accumulation INS analysis to significant CH combinations respectively (Liu et al., 2019). First, we normalized the discussion session of each dyad into 200 epochs. For each dyad, the time-cumulative INS at epoch n was calculated as the sum of the INS ranging from the first epoch to the nth epoch. Second, we performed independent samples t-tests at 200 epochs to compare the difference of INS increase between the two conditions. Finally, the resulting *p* values were FDR corrected.

2.6.2.5. Coupling directionality. We further estimate the magnitude of bidirectional information flow between the leaders and the followers in the two tasks by conducting partial multivariate Granger causality analyses (PMGCA). Tradition Granger causality analysis (GCA) uses vector autoregressive models to measure the causal relationship between time series in brain data. Since the Granger causality value may indicate the strength of the interpersonal influence during the social interaction (Cheng et al., 2019), it provides a neurobiological suggestion of coupling directionality, i.e., which individual was more actively driving another (Barnett and Seth, 2014). However, the exogenous and endogenous influences such as common external stimulus-induced neural responses or similar intrinsic neural responses may confound the Granger causality between individuals and lead to spurious causal inference (Guo et al., 2008; Roelstraete and Rosseel, 2012; Youssofzadeh et al., 2016). PMGCA can better mitigate potentially confounding effects on causal inference by modifying the traditional GCA by adding terms based on residual correlations between the predicted and the conditional variables (see more details in (Guo et al., 2008; Roelstraete and Rosseel, 2012, 2011).

Consistent with previous studies (Hou et al., 2020; Pan et al., 2021, 2018), our PMGCA was based on normalized HbO signals of significant CH combinations during the discussion periods. The main steps of the PMGCA are as follows: First, in each channel, we converted the HbO signals of the task session into z-scores using the mean and the standard deviation of the signals recorded during the resting-state session (Chen et al., 2020; Cheng et al., 2019; Pan et al., 2021). Second, for each individual, the z-scored time series of significant channels in the same brain regions were averaged. Third, to mitigate the impact of exogenous or latent variables, the time series of the leader corresponding follower's significant channel and the time series of the follower corresponding leader's significant channel were used as moderating variables (see 3.2.5 for details). Fourth, an R package (FIAR; download from https://github.com/cran/FIAR) was used to calculate the partial multivariate Granger causalities in two directions (Roelstraete and Rosseel, 2011): from the leaders to the followers and from the followers to the leaders. Finally, we used a one-sample t-test to compare the differences between each direction and zero in each condition, and then the effect of Task Type and Direction was examined by mixed ANOVA.

2.6.3. Group-level analysis (time-lagged INS)

2.6.3.1. Task type-related differences in time-lagged INS. To examine whether there are differences in time-lagged INS between the two tasks, a series of independent samples t-tests (creative task vs. general task) was applied to each time lag (i.e., -6s (follower precede) to +6s (leader precede)) in 0.315–0.445 Hz frequency range, and FDR correction was performed (Long et al., 2021; Zheng et al., 2020).

2.6.3.2. Linking conflict of views with time-lagged INS. Since the level of time-lagged INS was considered to represent the degree of individual understanding of information in the communication (Jiang et al., 2021; Liu et al., 2017; Stephens et al., 2010), it might be related to the conflict of views perceived by the individual during the task (Harvey, 2014). To test this hypothesis, we averaged the degree of conflict of views in dyads, then a Pearson's correlation analysis was adopted to analyze the relationships between the degree of conflict of views and the time-lagged INS of significant CH combinations, separately, under different task conditions, and FDR correction was performed.

Table 1
Specific brain areas involved in the INS between leaders and followers.

CH Combinations(leader-follower)	Leader	Follower
CH3-CH14	right Superior temporal gyrus (rSTG)	left Superior frontal gyrus (lSFG)
CH3-CH15	right Superior temporal gyrus (rSTG)	left Superior frontal gyrus (lSFG)
CH3-CH16	right Superior temporal gyrus (rSTG)	left Superior frontal gyrus (lSFG)
CH7-CH16	right Supramarginal gyrus (rSMG)	left Superior frontal gyrus (lSFG)
CH7-CH18	right Supramarginal gyrus (rSMG)	left Middle frontal gyrus (lMFG)
CH15-CH20	left Superior frontal gyrus (lSFG)	left Middle frontal gyrus (lMFG)

3. Result

3.1. Behavioral result

3.1.1. Correctness check of role division

The mixed ANOVA results on the number of expressed views revealed a significant main effect of Role, F (1, 32) = 76.79, $p < 0.001$, $\eta^2_{partial} = 0.71$, the leaders (27.71 ± 1.45) expressed more views than the followers (22.50 ± 1.31). In addition, there was a significant interaction between Task Type and Role, F (1, 32) = 4.96, $p = 0.033$, $\eta^2_{partial} = 0.13$. The simple effect for Role at creative task was significant, F (1, 32) = 60.40, $p < 0.001$, $\eta^2_{partial} = 0.65$, the leaders (28.88 ± 2.05) expressed more views than the followers (22.35 ± 1.85). The simple effect for Role at general task was also significant, F (1, 32) =21.35, $p < 0.001$, $\eta^2_{partial} = 0.40$, the leaders (26.53 ± 2.05) expressed more views than the followers (22.65 ± 1.85). That is, the difference in the number of expressed views between leaders and followers was greater in the creative task compared to the general task. The main effect for Task Type was not significant, F (1, 32) = 0.15, $p = 0.705$. The results suggested that the evaluators' judgment on the role of participants is reasonable.

3.1.2. Task performance

There was no significant main effect or interaction effect for individual creativity, cooperative preference, familiarity with umbrellas, the degree of demand for umbrellas, and interest in the task (*ps* > 0.05).

The ANCOVA results showed a significant main effect of Task Type on novelty score (F (1, 27) = 15.95, $p < 0.001$, $\eta^2_{partial} = 0.37$). Specifically, the novelty score of dyads in the creative task (3.06 ± 0.81) was higher than that of the general task (2.29 ± 0.78). The main effect of Task Type on appropriateness score was not significant (F (1, 27) = 3.43, $p = 0.075$; creative task (3.06 ± 0.52), general task (3.57 ± 0.55)).

3.2. Time-aligned INS result

3.2.1. Task type-related differences in time-aligned INS

The differences between the conditions on the time-aligned INS increase of all channel combinations in the 0.315–0.445 HZ frequency were tested. The results of t-tests showed that the INS for the channel combinations (leader-follower) of CH3-CH15 (t (32) = -4.10, corrected $p = 0.026$, Cohen's $d = 1.41$), CH3-CH16 (t (32) = -4.40, corrected $p = 0.020$, Cohen's $d = 1.51$), CH7-CH16 (t (32) = -4.75, corrected $p = 0.016$, Cohen's $d = 1.63$) and CH7-CH18 (t (32) = -4.30, corrected $p = 0.020$, Cohen's $d = 1.47$) under the creative condition were significantly lower than under the control condition (see Fig. 2A, B). These four channel combinations are defined as significant CH combinations for subsequent analysis, and the specific brain they involved are shown in the Table 1.

3.2.2. Validation of the INS differences between task types

After random permutation, the results did not show any significant group differences in time-aligned INS increase for any CH combination at the 0.315–0.445 Hz frequency. Validation results (t-values) for the 4 significant CH combinations from the 1000 permutations are shown in Fig. 2C. Compared with the distribution generated by the permutation procedure, the t-values of the actual dyads were in the 1% areas of the distribution generated by the permutation procedure. These results suggest that the significant INS increase was specific to the original dyads.

3.2.3. Relationship between task performances and INS

A significant positive correlation was found between the time-aligned INS increase of CH3-CH16 (rSTG-lSFG) and the novelty score under the creative condition (partial $r = 0.62$, corrected $p = 0.027$) (see Fig. 2D). There was also a significant positive correlation found between the INS increase of CH7-CH18 (rSMG-lMFG) and the appropriateness score under the creative condition (partial $r = 0.64$, corrected $p = 0.026$) (see Fig. 2E). The correlation between INS and task performances was not found in the general task (corrected *ps* > 0.05).

3.2.4. Dynamic INS difference between two tasks

The time accumulation INS analysis explored how time-aligned INS dynamically changes over the course of tasks. The result showed that from the 5th epoch (about 23-29s), the INS increase of CH3-CH15 and CH3-CH16 showed a continuous and stable significant difference among conditions (corrected *ps* < 0.05). Starting from the 57th (about 319–324s) epoch and the 60th (about 336–342s) epoch, respectively, the INS increase of CH7-CH16 and CH7-CH18 showed continuous and stable significant differences among conditions (corrected *ps* < 0.05) (see Fig. 3).

3.2.5. Coupling directionality

PMGCA was used to measure the directional information flow between two members. Leaders contain two time series: rSTG (CH3) and rSMG (CH7), and followers contain two time series: lSFG (the average of CH15 and CH16) and lMFG (CH18). In addition, two time series of lSFG (the average of CH15 and CH16) and lMFG (CH18) from leaders and two time series of rSTG (CH3) and rSMG (CH7) from followers were used as condition variables.

In creative condition, the G-causalities of both directions were significantly higher than zero: from the leaders to the followers (t (16) = 10.29, $p < 0.001$) and from the followers to the leaders (t (16) = 17.80, $p < 0.001$). The PMGCA result of the control condition was similar to the creative condition, with both directions identified significant increases in the G-causality relative to zero: from the leaders to the followers (t (16) = 8.88, $p < 0.001$) and from the followers to the leaders (t (16) = 12.26, $p < 0.001$).

Mixed ANOVA revealed a significant main effect of Task Type, F (1, 32) = 4.82, $p = 0.036$, $\eta^2_{partial} = 0.13$, with the larger G-causalities in the control condition (0.0049 ± 0.0020) compared to the creative condition (0.0038 ± 0.0013) (see Fig. 4). This result suggested that a stronger interpersonal influence between group members in the general task condition. The main effect of Direction was also significant, F (1, 32) = 4.62, $p = 0.039$, $\eta^2_{partial} = 0.13$. G-causalities from the leaders to the followers (0.0047 ± 0.0021) was significantly greater than that from the followers to the leaders (0.0040 ± 0.0013). How-

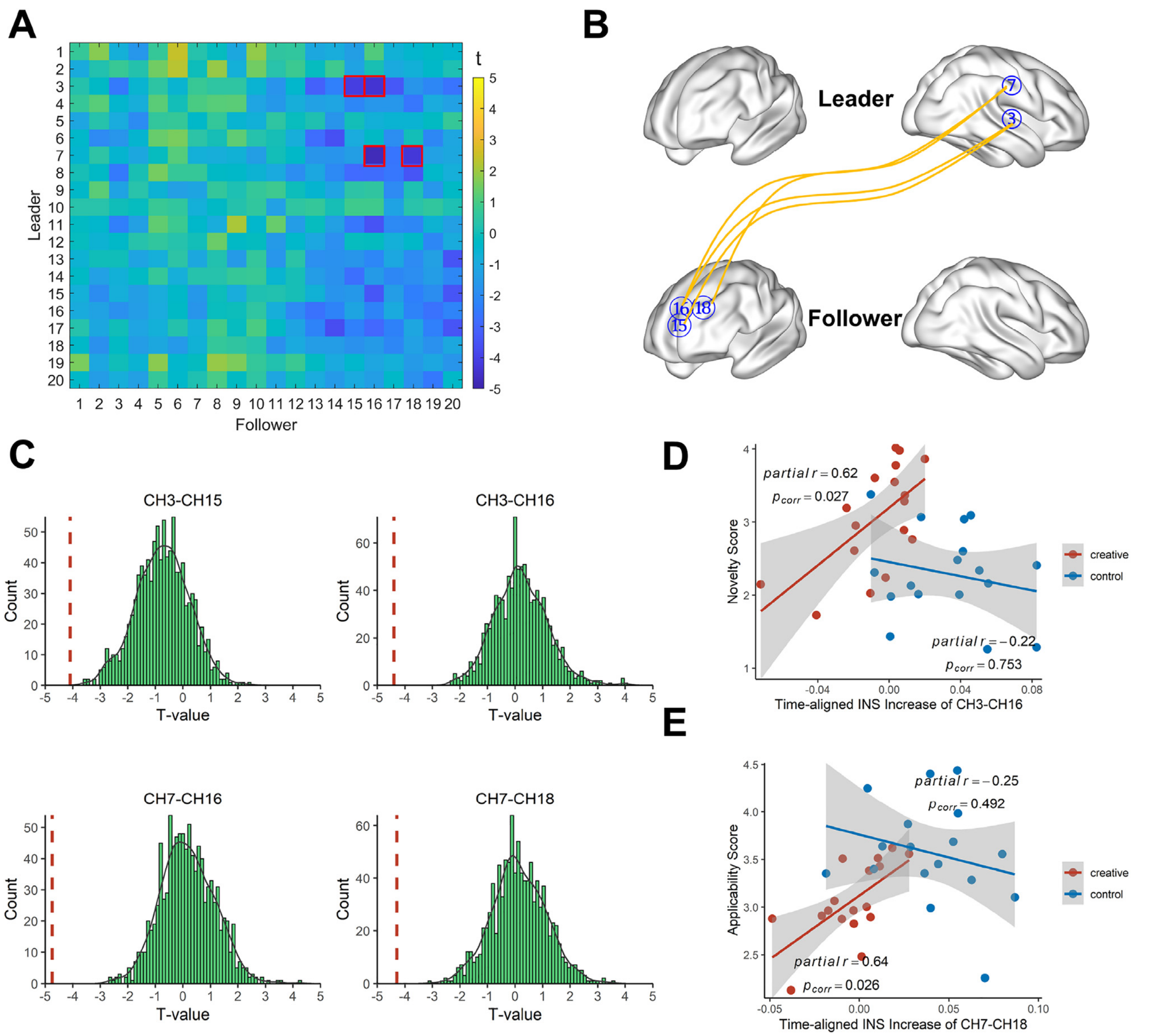

Fig. 2. Time-aligned INS result. (A) Time-aligned INS matrix at 0.315–0.445 HZ. The color indicates the *t* value. The significantly different CH combinations are marked by the red frames. (B) The location of significant CH combinations on the cerebral cortex. (C) The distribution of the *t* value was calculated by 1000 random dyads for the significant CH combinations. The dotted lines denote the positions of the *t* values on the actual dyads. (D) The partial correlation between time-aligned INS increase of CH3-CH16 and novel score. (E) The partial correlation between time-aligned INS increase of CH7-CH18 and appropriateness score.

ever, we did not find a significant interaction effect, F (1, 32) = 0.01, p = 0.914.

3.3. Time-lagged INS result

3.3.1. Task type-related differences in time-lagged INS

The time-lag results showed that the INS increase of CH3-CH14 (t (32) = -4.70, corrected p = 0.019, Cohen's d =1.66) and CH15-CH20 (t (32) = -4.22, corrected p = 0.038, Cohen's d = 1.49) were significantly lower in the creative condition than in the control condition when the leaders' brain activity preceded that of the followers by 1s. In addition, when the leaders' brain activity preceded that of the followers by 2s, the INS increase of CH3-CH14 (t (32) = -4.42, corrected p = 0.043, Cohen's d = 1.56) was significantly lower in the creative condition than in the general task condition. See Table 1 for specific brain areas involved in the CH3-CH14 and CH15-CH20. No significant results were found when the followers' brain activity preceded that of the leaders at any time-lags, at any CH combinations (corrected p > 0.05) (see Fig. 5A-5D).

3.3.2. Relationship between conflict of views and time-lagged INS

When the brain activity of the leaders precedes the followers, the correlation analysis found that the INS increase of the CH3-CH14 at 1s and 2s time lags was significantly negatively correlated with the degree of conflict of views in the creative condition (1-s time lag: $r_{CH3\text{-}CH14}$ = -0.73, corrected $p_{CH3\text{-}CH14}$ = 0.002; 2-s time lag: $r_{CH3\text{-}CH14}$ = -0.71, corrected $p_{CH3\text{-}CH14}$ = 0.002) (see Fig. 5E, 5F). The correlation between time-lagged INS increase and conflict of views was not found in CH15-CH20 or the general task (corrected ps > 0.05).

4. Discussion

The present study explored the difference between the group creativity task and the general task and unveiled the underlying interpersonal neural correlates, using the fNIRS-based hyperscanning technique.

Our findings first confirm that the "leader-follower" role asymmetry occurred spontaneously in groups during natural communication. Leaders expressed more views, and there was a greater information flow

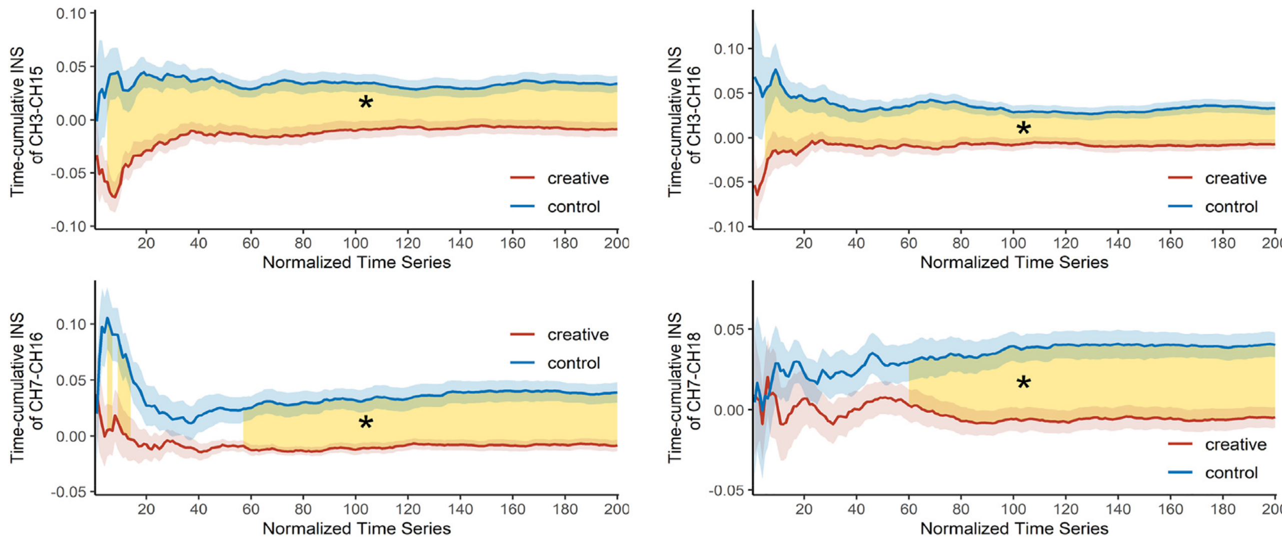

Fig. 3. The dynamics of the time-cumulative INS. The time-cumulative INS increase of 200 normalized epochs in the creative condition and control condition. The red and blue shaded areas denote the standard error at each epoch. The yellow color indicates the INS significant difference between these two conditions, $^{*}p < 0.05$, FDR corrected.

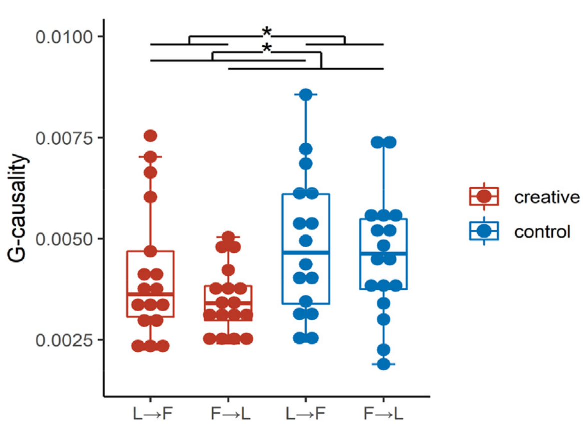

Fig. 4. The G-causalities from leader (L) to follower (F) were significantly greater than vice versa. The G-causalities of the creative condition were significantly weaker than the control condition. * $p < 0.05$.

from the leaders to the followers. Moreover, we reveal the unique interpersonal neural models of group creation. The time-aligned INS and time-lagged INS between leaders and followers in the creative condition were significantly lower than in the control condition, and the former positively predicted the performances of group creation, and the latter negatively predicted the conflict of views in the group creation. In addition, differences between groups emerged earlier for INS related to novelty and later for INS related to appropriateness.

4.1. Role asymmetry in group creation

Leadership is a universal feature of social species (Jiang et al., 2015). Leader-follower relationships emerge spontaneously among participants in leaderless group discussions, even though they have no differences in natural or social status (Jiang et al., 2021, 2015). However previous interpersonal neural studies on group creativity did not take into account group structure (i.e. role asymmetry). In this study same-sex pairs of college students who had similar individual creativity scores worked on either a group creativity task or a general task. Based on their interactions, one member was identified as the leader and the other as the follower.

Research on the emergence of leadership has found that the higher a member's participation and contribution, the greater the chance of being considered a leader (Barge, 1989). That is, the amount of communication predicts becoming a leader (Van Vugt, 2006). Our behavioral results also confirm the above views. Individuals evaluated as leaders in creative tasks and general tasks expressed more views than individuals evaluated as followers. In addition, we found that the difference in the number of views expressed by leaders and followers was greater in creative tasks compared to general tasks, which suggests that more novel ideas may be proposed by leaders in creative tasks.

GCA was originally used to track the direction of information flow between different areas within a brain, and recently has been expanded to track the direction of information flow across interlocutors' brains during social interactions (Schippers et al., 2010). The G-causalities could be used as an indicator of the influence exerted by one individual on another individual at the brain level (Cai et al., 2018). Consistent with previous interpersonal communication research (Jiang et al., 2015), our PMGCA results firstly showed that the influence between individuals in each dyad was bidirectional. However, the influence from the leaders to the followers was significantly stronger than the other direction. That is, although the leaders and followers were mutually influenced, the primary information flow was from leaders to followers. Specifically, the past neural activity of the leaders' rSTG and rSMG can better predict the future neural activity of the followers' lSFG and lMFG. These results may suggest that although both participants were actively engaged in the interaction, the leaders may entrain the followers' neural activity more during the interaction (Pan et al., 2018).

The above results provide further evidence of role asymmetry in group creation of natural communication. Since the INS may reflect the role relationship within the group (Zheng et al., 2020), the previous calculation form of averaging between the two directions in the dyads may lose valuable information, and likely hinder us from exploring the interpersonal neural mechanisms of group creation at a finer granularity. (Hamilton, 2021; Jiang et al., 2021).

4.2. INS characteristics of group creation

The present study used a product improvement task that included ideas generation and ideas evaluation phases as the group creation task and the item purchase task that did not require creativity as the control condition. The former required dyads to end up with novel and appropri-

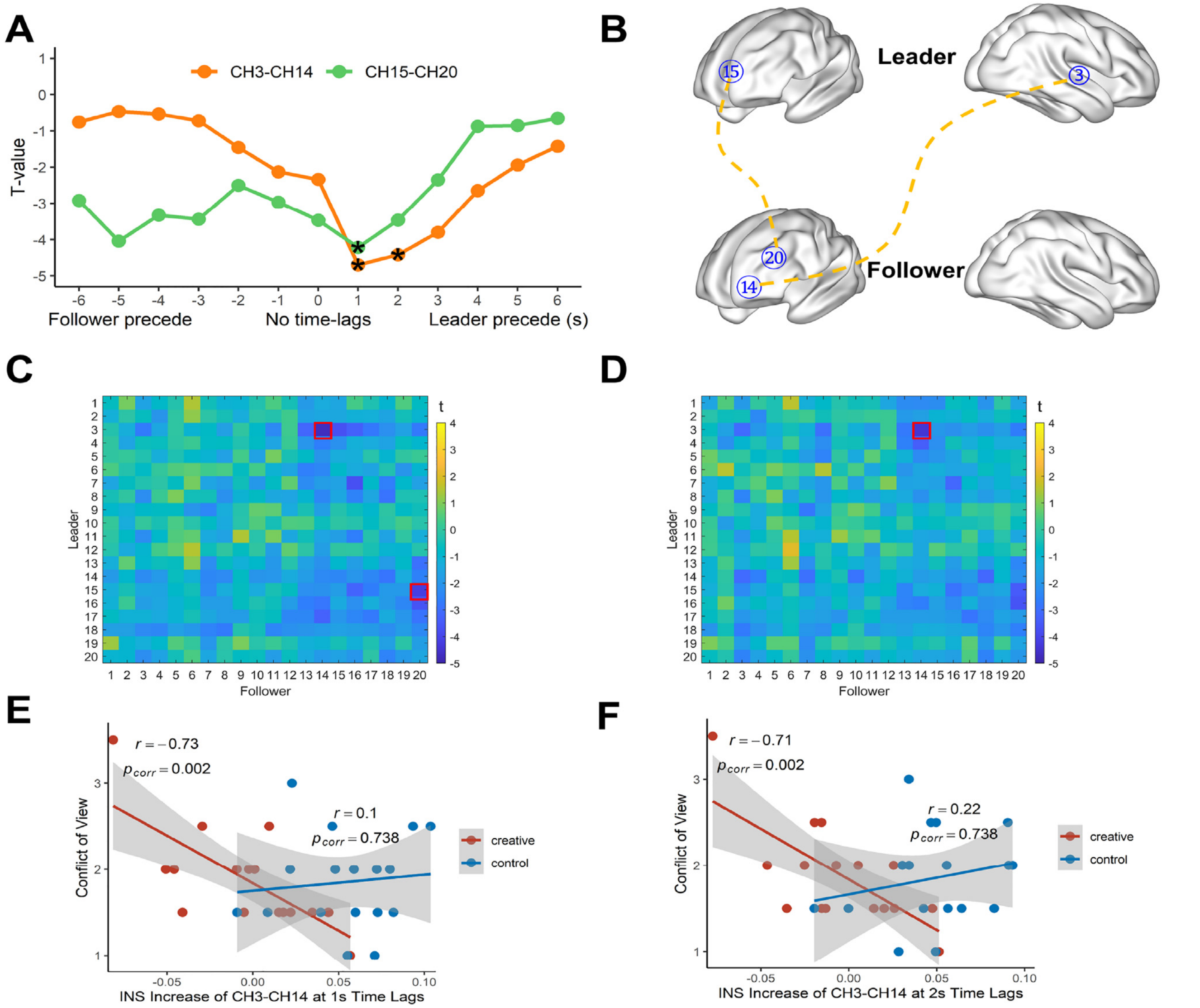

Fig. 5. Time-lagged INS result. (A) Time course of the INS increase of CH3-CH14 and CH15-CH20 from -6s (follower precede) to +6s (leader precede). The y-axis shows the *t* value (i.e., independent sample t-tests on the INS increase, two-tailed), $^{*}p < 0.05$. (B) The location of significant CH combinations on the cerebral cortex. (C, D) Time-lagged INS matrix at 0.315–0.445 HZ, when the leaders' brain activity preceded that of the followers by 1s and 2s. The color indicates the *t* value. The significantly different CH combinations are marked by the red frames. (E) The correlation between INS increase of CH3-CH14 at 1s time lags and conflict of view score. (F) The correlation between INS increase of CH3-CH14 at 2s time lags and conflict of view score.

ate solutions, while the latter only required dyads to end up with appropriate solutions. After controlling for extraneous factors, the behavioral results showed that the novelty score of the creative task was significantly higher than the general task, while the appropriateness score was not significantly different between the two tasks. This result is consistent with the performance characteristics of both creative and general tasks and demonstrates the validity of our experimental manipulation.

The fNIRS results showed significant differences in the time-aligned INS of rSTG-lSFG, rSMG-lSFG, and rSMG-lMFG between the creative condition and control condition. The STG and SMG belong to the DMN (Abe et al., 2019; Marron et al., 2018), which are considered to be the core brain regions for creativity and are related to novel association, idea generation, and divergent thinking (Benedek et al., 2014; Huang et al., 2021; Kleibeuker et al., 2017; Wei et al., 2014; Wu et al., 2016). The lSFG and lMFG are located in lDLPFC (Kikinis et al., 2010), a key node in the ECN (Huang et al., 2021). The lDLPFC is associated with working memory and verbal comprehension (Klaus and Schutter, 2018; Kleinmintz et al., 2019), and was found to be recruited during the evaluation of ideas (Ellamil et al., 2012; Huang et al., 2021). These results may reflect a unique pattern of synergistic activation between DMN and ECN among leaders and followers during group creation (Li et al., 2021).

Compared with the traditional single-brain functional connectivity analysis, the functional correlations between subjects (e.g., INS) have a higher signal-to-noise ratio and interpersonal interaction sensitivity (Pan et al., 2020). According to the cross-brain functional integration hypothesis of INS, INS may 'reflect a reciprocal and dynamic interplay between the neural states of socially interacting conspecifics' (Holroyd, 2022). This hypothesis holds that multiple brains can come together to act jointly as a functional unit, much like modules within a single brain can coordinate their activities to accomplish tasks (Holroyd, 2022; Valencia and Froese, 2020). The coupling between DMN and ECN has been widely found in the study of individual creativity (Beaty et al., 2016, 2015; Ellamil et al., 2012; Kleinmintz et al., 2019; Pinho et al., 2015), which seems to reflect that the ECN can top-down monitor and direct the DMN's idea generation process in the form of idea evaluation to meet the task goals (Beaty et al., 2016). Thus, when the ideas generation and ideas evaluation of individual creation is mapped to group creation, it may manifest as the interpersonal coupling of DMN and ECN.

Unlike previous studies, we found that the INS of the creative condition was significantly lower than the control condition. One possible explanation for the results may be that the ideas generated by the leaders in the creative tasks were more novel and unique than the general tasks, and it might be difficult for the followers with different knowledge and experience to understand their intentions or form shared representation. And many group creation studies have indeed found that group members may react negatively when evaluating the novel ideas of others (Harvey, 2014; Harvey and Kou, 2013; Mueller et al., 2012). The above factors might lead to the difficulty of good cooperation between the DMN and ECN in dyads, resulting in lower INS (Fishburn et al., 2018; Jiang et al., 2021). In addition, the PMGCA results show that the G-causalities of creative tasks are also significantly lower than the control condition, which seems to indicate that the interpersonal influence between leader and follower is lower in the creative task than in the general task for the above reasons (Cheng et al., 2019).

However, there are other possible explanations (not necessarily alternative) for the above results. Although we consider the STG and SMG as being in the DMN and the SFG and MFG as being within the ECN, it does not imply in any way that these regions contribute exclusively to those networks. For example, STG and SMG are also subcomponents of rTPJ, which is related to social cognitive processes such as perspective taking, mentalization, and theory of mind (Lu et al., 2020). The rTPJ and the dlPFC (i.e., where SFG and MFG are located) together form the MS. This system can help individuals understand others' intentions based on gestures, behaviors, and facial expressions (Mayseless et al., 2019; Wang et al., 2018). Thus, another possible explanation for these results is that because of the novelty of the ideas talked about in the creative task, it may be more difficult for group members to figure out each other's intentions.

Consistent with previous research (Duan et al., 2020; Lu et al., 2019a), we also found that INS in group creation was positively correlated with final task performance (i.e., novelty and appropriateness). Due to factors such as the heterogeneous structure of the group and cognitive diversity, groups may generate different views during the creation process. The dialectical model of group creativity argues that when groups are able to actively process the ideas of others and creatively synthesize opposing views, they may have the opportunity to achieve high-quality creative solutions (Harvey, 2014). The integration of views emphasized by this theory is a process of building similarities within different perspectives and shaping collective attention and collective understanding, which may improve INS (Cirelli, 2018; Fishburn et al., 2018; Gvirts and Perlmutter, 2020). Therefore, if leaders and followers integrate their views into a shared view in a cyclical generation-evaluation process, the DMN and ECN between the two may be better coupled, which will help the group develop a good goal directed and improve task performance (Harvey, 2014; Huang et al., 2021; Paulus et al., 2012; Paulus and Brown, 2007).

Previous hyperscanning studies have found that the brain activity of listeners tends to lag behind that of speakers (Liu et al., 2020; Stephens et al., 2010; Zheng et al., 2018). This delay phenomenon of INS is explained by the fact that interactive speech processing between individuals takes a certain amount of time to reach mutual understanding, and the strength of the time-lagged INS is also considered as the level of understanding (Jiang et al., 2021). Our results found that the time-lagged INS of rSTG-lSFG was significantly lower in the creative condition than in the control condition when the leaders' brain activity was preceded by 1s or 2s to the followers. This may indicate that followers had difficulty understanding when evaluating the novel ideas generated by the leaders. Interpersonal incomprehension has long been considered an important factor in the generation of conflict in group creation (Hu et al., 2017). This view is also confirmed by our findings that the time-lagged INS of rSTG-lSFG was significantly and negatively correlated with the conflict degree of views in the creative condition.

We did not find significant results of time-lagged INS when the follower's brain activity preceded that of the leaders. The results suggest that the leaders played a dominant role in the interaction during group creation. In this case, the brain activity of the leaders might always be ahead of the followers in time (Jiang et al., 2015).

4.3. *Temporal dynamics of INS in group creation*

The INS may not be temporal stationarity during measurements (Li et al., 2021). We examined the INS dynamics of the creative task. Since cumulative INS may be a better dynamic indicator than moment-to-moment INS (Jiang et al., 2015), we used cumulative INS to assess the time point at which INS differences emerged between the creative and control conditions. The results of the time-course analysis showed that about half a minute after the beginning of the problem-solving process, the difference in time cumulative INS of rSTG and lSFG between the two conditions became significant and persisted until the end of the interactive process. However, the stable difference in the time cumulative INS of rSMG-lSFG and rSMG-lMFG between the two conditions appeared later, about 5–6 minutes after the beginning of the problem-solving process.

Our results found that the INS of rSTG-lSFG was related to novelty and the INS of rSMG-lMFG was related to appropriateness. The difference in the temporal dynamics of INS may reflect the characteristics of the group creation process. In the early stages of group creation, unconstrained divergent thinking is a key factor of group creativity (Rosing et al., 2018). Since the group has not yet determined the direction of a novel solution, members can explore a variety of different approaches and directions. The group tends to generate more unique and original ideas during this process, and these initial novelty ideas generated often influence the novelty of the final solution (Puccio et al., 2020). Therefore, the novelty-related INS (e.g., rSTG-lSFG) showed inter-condition differences earlier. As the discussion progresses, beginning in the middle to late stages of group creation, members may gradually begin to consider the implementation of creative solutions, focusing on their feasibility (Rosing et al., 2018). At this point, the group may consider whether the solution is appropriate when developing its ideas. Therefore, the appropriateness-related INS (e.g., rSMG-lMFG) showed inter-condition differences later.

4.4. *Limitations*

The study has several limitations. First, gender may affect interpersonal interaction (Cheng et al., 2015), and the participants in this study were all same-sex dyads. In the future, researchers should consider exploring the cooperation mechanism in group creation of opposite-sex members, as leadership and cooperation with the group may vary by gender (Lu et al., 2020a; Mu et al., 2018). Second, in addition to the generation and evaluation of novel ideas, DMNs and ECNs have multiple functions. For example, the DMN also has the role of making social predictions in interpersonal interactions (Barrett, 2016). This implies that there may not be only one interpretation for our findings and further detailed exploration is needed in the future. Third, the interpersonal neural activity of group creativity may not be limited to rTPJ and lDLPFC, and future research should study more brain areas.

5. Conclusion

In the present study, we identified the roles in the leaderless group discussion and found that leaders expressed more views and influenced followers more. Compared with the control condition, the interpersonal influence between leaders and followers in the creative condition was weaker, and the time-aligned INS between leaders' DMN and followers' ECN was lower. However, when these two brain regions of the dyads could be better coupled, the task performances of group creation would be improved. The time-lagged INS, in which the leaders' brain activity was preceded to the followers, was lower in the creative condition than the control condition, and it may reflect the creative groups' conflict of views. In addition, the INS related to the novelty of the group creation decreased in the early stages, while the INS related to the appropriateness decreased in the middle stages. Our findings provide interpersonal neural evidence for group creative interactions in the context of natural communication and increase our understanding of the nature of group creativity.

Credit authorship contribution statement

Zheng Liang: Conceptualization, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Songqing Li:** Conceptualization, Investigation, Data curation, Project administration, Writing - original draft. **Siyuan Zhou:** Methodology, Formal analysis, Writing - original draft. **Shi Chen:** Investigation, Writing - review & editing. **Ying Li:** Investigation, Writing - review & editing. **Yanran Chen:** Methodology, Formal analysis. **Qingbai Zhao:** Supervision, Writing - review & editing, Funding acquisition. **Furong Huang:** Supervision, Writing - review & editing. **Chunming Lu:** Supervision. **Quanlei Yu:** Supervision, Writing - review & editing. **Zhijin Zhou:** Supervision, Writing - review & editing.

Ethics statement

All experimental protocols were approved by the Ethics Institute Review Board of Central China Normal University.

Data and code availability statement

The data and code that support the findings of this study are not publicly available due to research data sharing restrictions from the university, but can be available from the corresponding author by submitting a formal project outline.

Funding

This study was supported by Self-Determined Research Funds of CCNU from The Central Colleges' Basic Research and Operation of MOE (Grant No. CCNU19TD019 and CCNU19ZN022).

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Declaration of Competing Interest

The authors declare no conflict of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2022.119448.

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