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RESEARCH ARTICLE

Gender of partner affects the interaction pattern during group creative idea generation

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Abstract
This study aimed to determine how gender composition affects the group creative process. Participants were recruited into dyads with different gender compositions (female–male dyad, F–M; female–female, F–F; male–male, and M–M) to solve two problems. One problem demanded creativity alternative use task (AUT) and the other did not object characteristic task. Functional near-infrared spectroscopy (fNIRS)-based hyperscanning was used to record interpersonal neural responses. Results demonstrated no significant difference in creative performance among the three types of dyads. However, the F–F dyad showed higher levels of cooperative behaviour (i.e. the index of convergence) and collective flexibility than the other dyads. Also, in the fNIRS data, the F–F dyad showed higher interpersonal brain synchronization (IBS) increments in the right posterior parietal cortex during the AUT than the other dyads, which covaried with their creative performance. These findings indicate that while solving a creativity problem together, females are more likely than males to consider others' perspectives. This gender difference might be due to the enhanced IBS increment in the right posterior parietal cortex.

Keywords Group creativity · Gender composition · Hyperscanning · fNIRS · IBS

Introduction

Group creativity can be defined as the capacity of a group to produce novel (original and unique) and useful work (Sternberg and Lubart 1996; Runco and Acar 2012). Gender composition is an inevitable factor in groups. Several studies have initially explored the effect of gender composition (ex. gender diversity and gender fault lines) on group creativity (Pearsall et al. 2008; Lee et al. 2018). However, these studies mainly focused on how gender composition affects final group creative outcomes. How gender composition affects the collaborative creative process, especially the interpersonal neural correlates that underlie the effect, is almost neglected. Imagine that you are solving a problem demanding creativity, together with a female or male partner. Would you use different or equal strategies or manners to interact with your partner according to the gender of your partner? In this study we aimed to, first, explore how different gender compositions affect the collaborative creative process and, second, unveil the interpersonal neural correlates that underlie the effect.

An effective interpersonal interaction is quite necessary to unlock the creative potential in a group (Shin and Zhou 2007; Harvey 2014; Xue et al. 2018; Lu et al. 2019b). With respect to gender differences in interpersonal interaction, several theories have been posited. According to the social-cultural theory, specific social roles in society affect how individuals interact with others (Eagly and Wood 1999). For instance, females were historically expected to be domesticated and communal, thereby displaying sympathetic, amicable and emotionally expressive behaviour (Eagly 2009). Similarly, the self-construal theory also assumes that females are more interdependent, sharing, affiliative, selfless, and emotionally supportive than males (Cross and

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Madson 1997; Eckel and Grossman 1998; Zakriski et al. 2005). However, social–cultural theory suggests that males may be more independent, assertive, ambitious, and dominant than females (Eagly 2009). Accordingly, during the interpersonal interaction process, females may more likely show patience toward partners, attend to partners' ideas, and take partners' perspectives. However, it is still unknown how such attributes of females or males will affect the collaborative creative process.

Consequently, we primarily expected to address two questions. The first question is 'How will gender composition affect the collaborative creative process?' Within that question, using the functional near-infrared spectroscopy (fNIRS)-based hyperscanning technique, we also expected to unveil the interpersonal neural correlates that underlie the effect of gender composition on the group creative process. Therefore, the second question is 'What are the interpersonal neural correlates that underlie the effect of gender composition on the collaborative creative process?'

A fNIRS-based hyperscanning device was used to uncover the underlying interpersonal neural correlates. Hyperscanning can be conducted by functional magnetic resonance imaging (fMRI) (Li et al. 2009), electroencephalogram (EEG) (Dikker et al. 2017), or fNIRS (Dai et al. 2018). Given the higher tolerance for motor artefacts and ecological validity that fNIRS offers (compared to EEG or fMRI), an fNIRS-based approach was adopted in the study. Studies using this technique have successfully identified evidence of interpersonal neural correlates that underlie the effect of gender on basic social cooperative interaction (less complicated than creativity-demanding tasks). For instance, Cheng et al. (2015) selected the bilateral prefrontal cortex as the region of interest and reported enhanced task-related inter-brain correlation in the frontopolar cortex, orbitofrontal cortex, and left dorsolateral prefrontal cortex for the female–male dyad during cooperative interaction. They suggested there may be different neural processes that underlie cooperation between mixed-gender and same-gender dyadic interactions. Based on the similar button-press task and a relatively extended region of interest (the right prefrontal cortex and temporal region), Baker et al. (2016) reported enhanced inter-brain correlation in the right temporal cortex for the female–female dyad, and inter-brain correlation in the right inferior prefrontal cortex for the male–male dyad. They suggested that the lack of significant inter-brain coherence in mixed-gender dyads is indicative of different cognitive strategies employed by males and females during cooperation.

In addition, previous studies have explored the relationship between gender and individual creativity. Using EEG, Fink and Neubauer (2006) observed stronger activation over frontal cortices for females with higher verbal IQ than for those with average verbal IQ, when generating original ideas. However, the opposite was observed for males. Fink and Neubauer (2006) suggested that task-related alpha power changed during creative problem solving and was moderated by verbal IQ and gender. Another fMRI-based neuroimaging study found that while high creativity was associated with greater connectivity and efficiency alongside clustering in fewer brain areas for males, high creativity in females was associated with lower connectivity and efficiency alongside clustering across more brain regions (Ryman et al. 2014). Other neuroimaging studies also reported interactions between creativity and gender on resting state imaging measures (ex. regional homogeneity, functional connectivity, and low frequency fluctuation) (Takeuchi et al. 2017a) and white matter structures (Takeuchi et al. 2017b). These findings indicate a unique topological organization of neural connectivity underlying the generation of novel ideas in males and females. Abraham et al. (2014) also explored gender differences in creativity using fMRI. They found that although the behavioural creative performance of females and males was comparable, quantitative and qualitative gender differences in brain activity occurred during the creative cognitive process. During creative thinking, regions associated with speech processing, social perception, self-referential processing and mental state reasoning are recruited in the female brain in areas such as the medial prefrontal cortices, superior temporal lobe, posterior cingulate and temporoparietal junction. However, regions involved in autobiographical, semantic, episodic and spatial memory are recruited in the male brain in areas such as the amygdala and inferior frontal gyrus (see details in Abraham 2016).

Based on previous neuroimaging studies on social interaction and creativity, the cerebral regions in the bilateral prefrontal cortex (PFC) and the right temporal–parietal junction (r-TPJ) are associated with both social interaction and creative cognition processes. Previous hyperscanning studies have successfully identified interpersonal neural correlates in these regions in the group creative process (Xue et al. 2018; Lu et al. 2019a, b; Mayseless et al. 2019). Accordingly, we expected to determine whether any interpersonal neural correlate underlies the effect of gender on group creative processes. For instance, female dyads might show a higher interpersonal neural correlation in the r-TPJ than male dyads or mixed-gender dyads. Therefore, the bilateral PFC and r-TPJ were chosen as the regions of interest in the present study.

In the present study, participants were assigned into three types of female–male dyads (i.e., F–M dyad, F–F dyad, and M–M dyad) to solve two problems either demanding creativity alternative uses task (AUT), or not object characteristic task (OCT). An fNIRS-based system was used to continuously record the neural activities in the PFC and r-TPJ cerebral regions during tasks. Given that divergent thinking performance is a reliable predictor of creative potential and a key component of creativity, the study mainly focused on the divergent thinking test (Runco and Acar 2012). As such, the OCT was designed merely to reveal the specific interpersonal neural correlate that underlies the effect of gender composition on the group creative process. Although aforementioned reviews may indicate that females are more likely to consider others' perspectives during an interpersonal conversation, how they will behave during a collaborative creativity task is difficult to hypothesize. Therefore, we considered it more proper to posit no precise hypothesis.

Method

Participant

One hundred and thirty-six college students (77 females, age: 21.23 ± 2.91 years old) were recruited. Based on gender, participants were assigned into three types of dyads: female–female (F–F) dyads, female–male (F–M) dyads, and male–male (M–M) dyads. Two dyads were excluded because the participants disobeyed the experimental instructions. Consequently, a total of 66 dyads remained (26 F–F dyads, 22 F–M dyads, and 18 M–M dyads). Participants in each dyad were unknown to each other, as confirmed prior to the experiment. No significant difference in age composition was observed among the three conditions, $F\ (2, 63) = 0.14$, $P > 0.05$, $\eta_p^2 = 0.00$. Participants provided informed consent and were each paid ¥ 37 for their participation. The study procedure was approved by the University Committee on Human Research Protection of East China Normal University.

A two-factor mixed experimental design was used, with GENDER (F–F, F–M, and M–M) as the between-subject factor and TASK (AUT and OCT) as the within-subject factor.

Experimental procedure

Upon arrival, participants were asked to sit face-to-face. The spatial distance between two participants was 1.6 m (see Fig. 1a). The experimental procedure consisted of two 1-min resting-state sessions, two 1.5-min instruction sessions, and two 5-min task sessions (see Fig. 1d). The resting-state session between the two tasks served as the baseline session. During this session, participants were asked to remain as still as possible, with their eyes closed and mind relaxed.

Following each resting-state session, brainstorming rules (i.e. deferred judgement, quantity breeds quality, encouraged freewheeling, and combination and improvement) and task instructions were introduced in detail during the instruction session (Osborn 1957). Participants were asked to report one idea at a time while taking turns. They were allowed to say 'pass' if they failed to present an idea during their respective turn.

During the AUT, participants were explicitly instructed to be creative and generate as many creative uses for an everyday object as possible (Said-Metwaly et al. 2020). Here, 'book' was used as the target everyday object. The AUT is a well-established divergent thinking task and a reliable predictor of real-world creative performance (Runco and Acar 2012). It has been widely used in behavioural and neuroscience studies on creativity (Runco and Okuda 1991; Fink et al. 2009; Lu et al. 2019b). During the OCT, participants were asked to report typical characteristics of an everyday object (Fink et al. 2009). Here, 'fishing rod' was used as the target everyday object. The OCT is broadly a memory-retrieval task that demands no creativity but involves direct stimulus-related information (Binder et al. 2009; Fink et al. 2009, 2010). Here, the OCT was designed merely to reveal a specific interpersonal neural correlate that underlies the

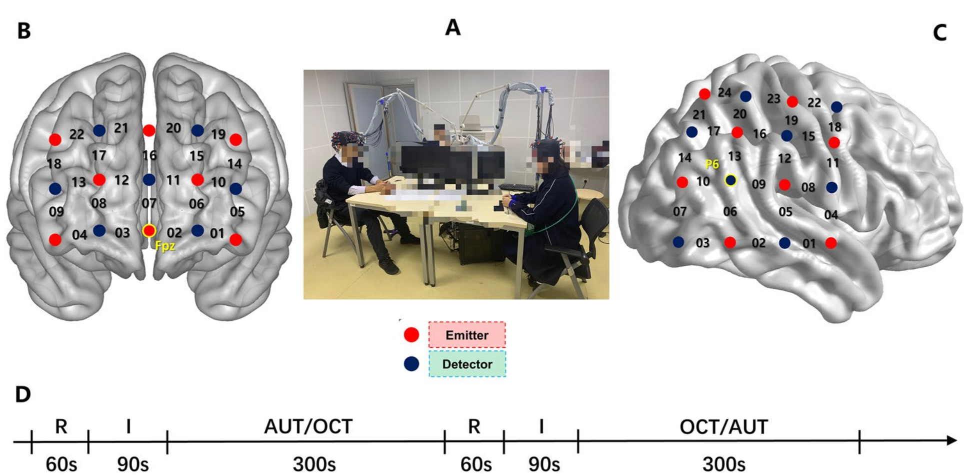

Fig. 1 Experimental design. **a** Experimental setup. **b** Optode probe set. The probe patch is placed on the PFC. **c** Optode probe set. The probe patch is placed on the r-TPJ. **d** Hyperscanning procedure. R: 60-s resting state session; I: ~ 90-s instructions introduction session; AUT/OCT or OCT/AUT: 5-min task session. The sequence of these two tasks was counterbalanced

effect of gender composition on a group creative process. The sequence of tasks was counterbalanced among different dyads.

Assessment of performance on the AUT and OCT

Participants' AUT performance was assessed using the fluency, uniqueness, and feasibility of their generated ideas (Guilford 1967; Runco and Okuda 1991). The fluency score was based on the total number of ideas generated by each dyad. The uniqueness score was assessed using an objective method whereby generated ideas from all dyads were collected into a comprehensive lexicon. Synonyms were then identified and ideas collapsed accordingly. If an idea was statistically infrequent (i.e. 5% or fewer participants in the sample reported the idea), it scored '1'. All other responses scored '0'. Two trained raters followed this procedure to independently assess the uniqueness score of each participant. The inter-rater agreement of this method was satisfactory [internal consistency coefficient (ICC) = 0.99]. To determine the uniqueness scores, individual participant ratings from each of the two raters were averaged. The final uniqueness score for each dyad was obtained by summing the uniqueness scores of the participants in the dyad. The feasibility score was assessed using a subjective method. Five trained raters independently rated the feasibility of each generated idea on a 5-point Likert-type scale ranging from 1 'not feasible at all' to 5 'highly feasible'. The inter-rater agreement was satisfactory (ICC = 0.82). Individual ratings from 5 raters were combined into a single feasibility score for each response. The final feasibility score for each dyad was calculated by averaging the feasibility scores of all ideas generated during the task.

Participants' performance on the OCT was assessed using the fluency of generated responses only, as explained previously.

Collective communication behaviours during the AUT

To assess the extent to which each dyad sought ideas from different categories, the collective flexibility was calculated for each dyad (Lu et al. 2019a). Two trained raters independently assessed the total number of categories explored for each dyad. The inter-rater agreement was satisfactory (ICC = 0.96). Individual ratings for each dyad from these two raters were averaged into a single collective flexibility score.

To assess the extent to which each dyad combined their ideas with others, the index of convergence (IOC) was calculated (Larey and Paulus 1999; Lu et al. 2019a). The IOC for each dyad was assessed as follows: (1) based on the time point, the responses from the two participants were listed sequentially; (2) from the first idea to the last, once a response was identified as a response from the same category as the previous response, it scored '1'. The total number of ideas that scored '1' was calculated as the Sum (stay). 'Stay' means both the current and previous idea stayed in the same category. Namely, if 33 ideas scored '1', the Sum (stay) would be '33', indicating 33 ideas were identified as responses from the same category; (3) eventually, the IOC for each dyad was obtained by the following equation: IOC = Sum (stay)/[Dyad fluency − Sum (stay)]. Here, the dyad fluency indicates the fluency of the dyad. Two trained raters independently assessed the IOC for each dyad. The inter-rater agreement was satisfactory (ICC = 0.94). The final IOC score for each dyad was obtained by averaging the ratings from the two raters.

Moreover, we also calculated the occurrence of the first unique idea, occurrence of the first idea convergence, and duration of idea convergence during the AUT for each dyad (See details in the supplementary materials S2).

fNIRS data collection

The oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentration for each dyad was recorded simultaneously using a NIRS system (ETG-7100, Hitachi Medical Corporation, Japan). The sampling rate for the measurement of the absorption of near-infrared light (wavelengths: 695 and 830 nm) was 10 Hz. Previous hyperscanning studies on group creativity suggested that the PFC and r-TPJ regions were recruited in group creativity (Xue et al. 2018; Lu et al. 2019a, b). Accordingly, the PFC and r-TPJ were selected as regions of interest in this study. One 3×5 optode probe set (eight emitters and seven detectors, 3-cm optode separation) consisting of 22 measurement channels (CHs) was placed over the bilateral PFC region of each participant (see Fig. 1b). Based on the international 10–20 system for electroencephalography, the lowest probes were positioned along the Fp1–Fp2 line, with the middle optode placed on the frontal pole middle point (Fpz) (Sai et al. 2014). The middle probe of the patch was aligned precisely along the sagittal reference curve. Meanwhile, one 4×4 optode probe set (eight emitters and detectors, 3-cm optode separation) consisting of 24 measurement CHs was placed over the r-TPJ region of each participant (see Fig. 1c). The lowest probe was aligned with the sagittal reference curve and the optode B was positioned on P6. To determine the correspondence between the NIRS CHs and the measurement points on the cerebral cortex, the virtual registration method was used (Singh et al. 2005; Tsuzuki et al. 2007).

Interpersonal brain synchronization (IBS)

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

To remove the global components in the fNIRS data, the raw fNIRS data of each participant was preprocessed using a principal component spatial filter algorithm (Zhang et al. 2016). Data collected during the baseline session and two task sessions were entered into the IBS analyses. Meanwhile, to obtain data within the period of steady state, the data in the initial and ending 30 s periods of the task session were removed, leaving 240 s of data for the task session. Next, wavelet transform coherence was conducted to assess the relationship between HbO time series from the corresponding CHs of the two participants in each dyad (i.e. IBS; Grinsted et al. 2004). The IBS increment was calculated by subtracting the time-averaged IBS during the baseline session from that during the task session. For further analyses, the IBS increment was converted to Fisher z-statistics (Chang and Glover 2010; Cui et al. 2012).

One-way ANOVAs using GENDER as the between-subject factor was conducted on the IBS increment (during the AUT) at each CH along the full frequency range (0.01–0.15 Hz; Nozawa et al. 2016). Data below 0.01 Hz were not considered to remove very low-frequency fluctuations. Data above 0.15 Hz were also considered to exclude noises such as cardiac activity (~0.8–2.5 Hz) and respiratory activity (~0.15–0.3 Hz) (Guijt et al. 2007; Tong et al. 2011; Barrett et al. 2015). The resulting P values were corrected using the false discovery rate (FDR) method across all CHs and all frequencies ($P < 0.05$). The number of P values is 46 (CHs) *47 (frequencies) = 2162. All of these P values were FDR corrected at one time. The results yielded several F maps (each frequency had a F map). The MNI coordinates and F values of F maps were converted into *.img files by using xjView (nirs2img.m, https://www.alivelearn.net/xjview). The obtained *.img files were then rendered over the 3D brain model using BrainNet Viewer (Xia et al. 2013). If a significant main effect of GENDER was observed, a follow-up post hoc test with Bonferroni correction was performed. Finally, bivariate Pearson correlations were used to reveal relationships between the significant IBS increments and behavioral performance (i.e. AUT fluency, AUT uniqueness, AUT feasibility) or communication behaviours (i.e. IOC, collective flexibility).

To determine whether the observed significant GENDER effect was specific to group creative process, we conducted a mixed ANOVA with the TASK (AUT, OCT) as the within-subject factor and GENDER as the between-subject factor on the significant IBS increments.

Furthermore, as an exploratory analysis to examine the trajectory of the observed significant IBS increment over time in different dyads, two-way mixed-design ANOVAs using GENDER as the between-subject factor and EPOCH (the task period were equally divided into three epochs: EPOCH1, EPOCH2, EPOCH3) as the within-subject factor were conducted on the IBS increment at the significant CHs during the AUT and OCT.

Pre- and post-experiment assessment

Prior to the experiment, participants' preference for teamwork was measured using Group Preference Scale (GPS) scores (Larey and Paulus 1999). The GPS contains 10 items (e.g., 'I like teamwork'), which are scored on a 5-point Likert-type scale ranging from 1 'not at all' to 5 'very much'. Higher scores predict higher levels of preference for teamwork. The reliability of GPS in the present study was satisfactory (Cronbach's $\alpha = 0.84$). To exclude the potential contamination of individual creative potential and perspective-taking tendency (i.e. whether individuals like to take the perspectives of others into consideration while making a decision) on the observed effect, the Runco Ideational Behavior Scale (RIBS) (Runco et al. 2016) and Perspective Taking Scale (PTS) (Davis 1983) were used to measure individual creative potential and perspective-taking tendency. The RIBS focuses on ideation that may occur in daily life (e.g. 'how often do you have ideas for rearranging the furniture in your home?'). It contains 19 items, which are scored on a 5-point Likert-type scale ranging from 0 'never' to 4 'just about every day'. The reliability of RIBS in the present study was satisfactory (Cronbach's $\alpha = 0.85$). The PTS contains seven items, which are scored on a 5-point Likert-type scale ranging from 0 'does not describe me well' to 4 'describes me very well'. For instance, 'I try to look at everybody's side of a disagreement before I make a decision'. The reliability of PTS in the present study was acceptable (Cronbach's $\alpha = 0.71$).

To examine whether the observed effects were independent from individual task enjoyment, tendency for perspective taking during the task, and like for their partner, participants were asked to rate their task enjoyment, tendency for perspective-taking (i.e. we tended to complete the task by taking the perspectives from each other during the task), and like for collaboration with their partner during the tasks. Participant ratings were completed on a 5-point Likert-type scale, ranging from 1 'not at all' to 5 'very much' immediately after the experiment.

Results

Task performance on the AUT and OCT

One-way ANOVAs using GENDER as the between-subject factor was conducted on AUT fluency, AUT uniqueness, AUT feasibility, and OCT fluency. No significant main effect for GENDER was observed on AUT fluency [F (2, 63) = 0.52, $P > 0.05$, $\eta_p^2 = 0.23$], AUT feasibility [F (2, 63) = 1.61, $P > 0.1$, $\eta_p^2 = 0.05$], or OCT fluency [F (2, 63) = 2.00, $P > 0.05$, $\eta_p^2 = 0.06$], and AUT uniqueness [F (2, 63) = 2.70, $P > 0.05$, $\eta_p^2 = 0.08$] (see Fig. 2).

As an exploratory analysis to examine the trajectory of task performance over time in different dyads, a two-way mixed-design ANOVA and further simple effect analyses using GENDER as the between-subject factor and EPOCH (the task period were equally divided into three epochs: EPOCH1, EPOCH2, and EPOCH3) as the within-subject factor were conducted on AUT fluency, AUT uniqueness, AUT feasibility, and OCT fluency (see details in the supplementary materials S1).

Collective communication behaviours in different dyads

We found that the data distribution of IOC is not normal. Hence, to normalize the data, the data were converted into sqrt (n) values (i.e. square root calculations). Next, a one-way ANOVA using GENDER as the between-subject factor was performed on the sqrt (n) data. The results showed a significant main effect for GENDER on sqrt (IOC), F (2, 63) = 5.46, $P = 0.007$, $\eta_p^2 = 0.15$. Post hoc tests revealed that sqrt (IOC) was significantly higher in the F–F dyad ($M = 0.32$, SD = 0.11) than in the F–M dyad ($M = 0.24$, SD = 0.07; $P = 0.008$, Cohen's $d = 0.87$) and M–M dyad ($M = 0.23$, SD = 0.15; $P = 0.006$, Cohen's $d = 0.68$) (see Fig. 2d).

Likewise, a one-way ANOVA was conducted on collective flexibility. The results showed a significant main effect for GENDER on collective flexibility, F (2, 63) = 4.34, $P = 0.017$, $\eta_p^2 = 0.12$. Post hoc tests showed that collective flexibility was significantly lower in the M–M dyad ($M = 13.38$, SD = 2.14) than in the F–F dyad ($M = 15.48$, SD = 2.66; $P = 0.011$, Cohen's $d = 0.87$), and F–M dyad ($M = 15.55$, SD = 2.91; $P = 0.011$, Cohen's $d = 0.85$) (see Fig. 2e).

The main effects of GENDER on the aforementioned communication behaviours remained significant after the GPS, PST, and RIBS scores were added to the aforementioned ANOVA models as covariates (Ps < 0.05).

To further examine the trajectory of communication behaviours over time in different dyads, a two-way mixed-design ANOVA and further simple effect analyses were conducted, using GENDER as the between-subject factor and EPOCH as the within-subject factor, on IOC and collective flexibility, respectively (see details in the supplementary materials S2).

Analyses on post-experiment assessment

One-way ANOVAs using GENDER as the between-subject factor was conducted on task enjoyment, tendency for perspective taking, and like of partner collaboration during the AUT or OCT, respectively. Results showed no significant main effect (Ps > 0.05).

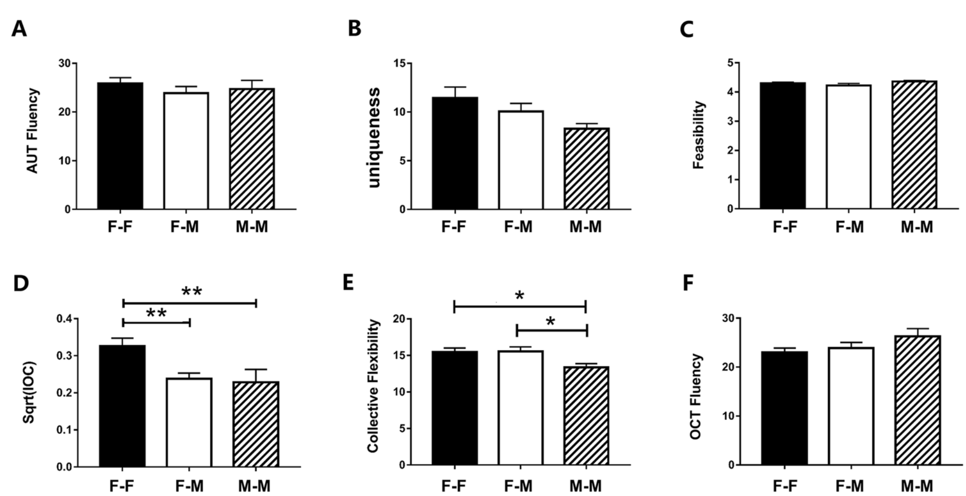

Fig. 2 Task performance and collective communication behaviour. **a** AUT fluency in different dyads. **b** AUT uniqueness in different dyads. **c** AUT feasibility in different dyads. **d** IOC in different dyads. **e** Collective flexibility in different dyads. **f** OCT fluency in different dyads. Error bars indicate standard errors of the mean. *$P < 0.05$, **$P < 0.01$

Interpersonal brain synchronization in different dyads

One-way ANOVAs using GENDER as the between-subject factor was conducted on the IBS increment at each CH along the full frequency range during the AUT (0.01–0.15 Hz). The resulting P values were corrected using the FDR method across all CHs and frequencies ($P < 0.05$). Hereafter, Pn indicates CHn in the PFC and Tn indicates CHn in the r-TPJ (i.e. P2 = CH2 in the PFC probe

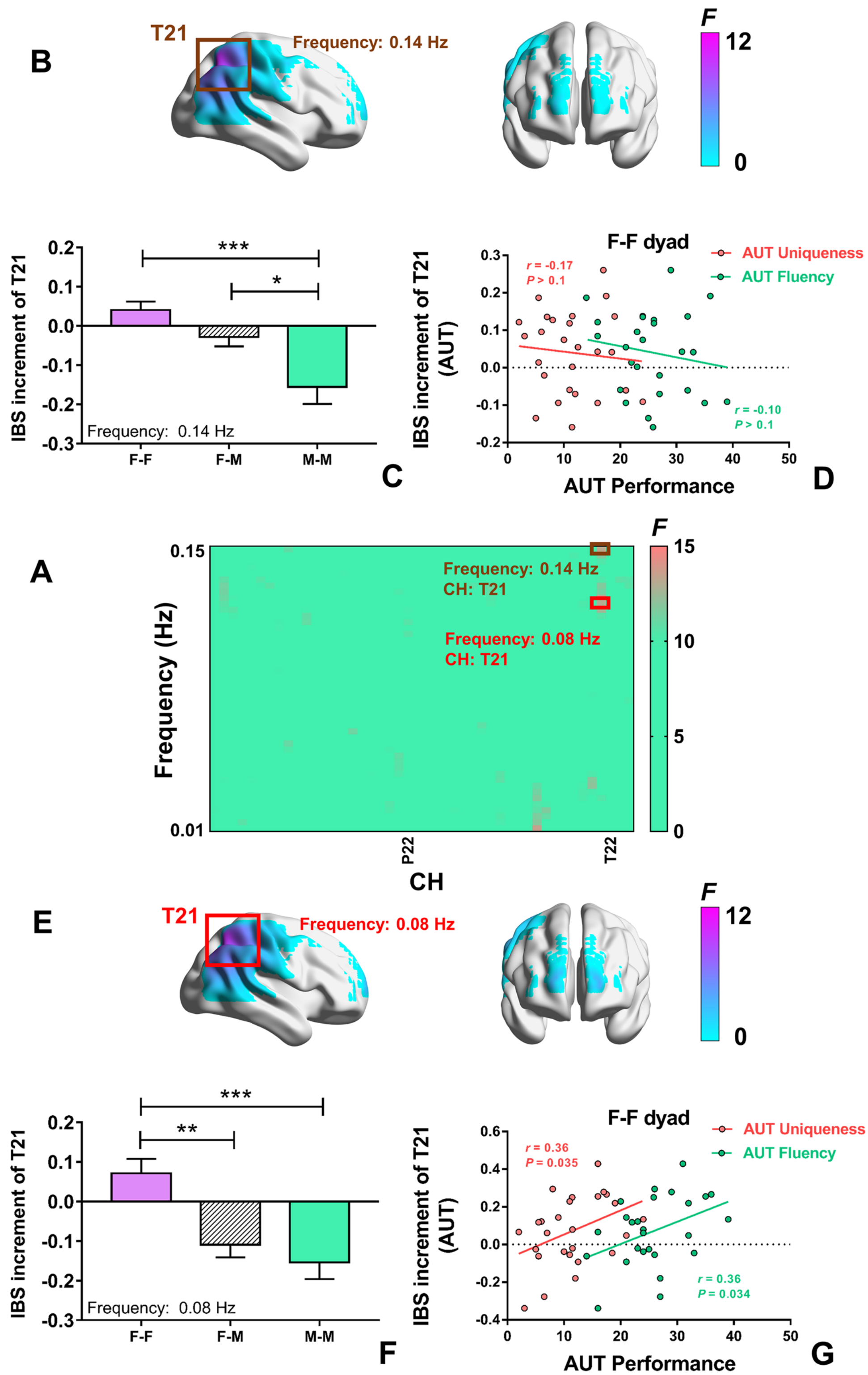

Fig. 3 Interpersonal brain synchronization (IBS) increment during the AUT. **a** The heatmap of the F values for the one-way ANOVAs using GENDER as the between-subject factor was conducted on the IBS increment of all CHs along the full frequency range (0.01–0.15 Hz). The colour bar denotes the F values. The red/brown rectangles indicate the GENDER effect on the IBS increment of T21 at the frequency of 0.08 Hz/0.14 Hz survived the FDR correction. The vertical axis denotes individual frequencies and the horizontal axis denotes CHs. One-way ANOVAs to identify the significant main effects of GENDER (FDR corrected) on the IBS increment of all CHs at the frequency of 0.14 Hz (**b**) and 0.08 Hz (**e**). The amplitude of IBS increment of T21 at the frequency of 0.14 Hz (**c**) and 0.08 Hz (**f**). The correlations between AUT fluency/uniqueness and IBS increment at CH21 at the frequency of 0.14 Hz (**d**) and 0.08 Hz (**g**) in the F–F dyad. Error bars indicate standard errors of the mean. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

patch; T24 = CH24 in the r-TPJ probe patch). The results showed significant main effects for GENDER on the IBS increment of T21 at the frequency of 0.08 Hz [F (2, 63) = 10.96, $P_{corrected}$ = 0.044, η_p^2 = 0.26] and 0.14 Hz [F (2, 63) = 11.25, $P_{corrected}$ = 0.048, η_p^2 = 0.26] (see Fig. 3a). Specifically, regarding T21 at the frequency of 0.08 Hz, post hoc tests showed that the IBS increment was significantly higher in the F–F dyad (M = 0.07, SD = 0.18) than in the F–M dyad (M = − 0.11, SD = 0.15; P = 0.002, Cohen's d = 1.09, Bonferroni corrected) and M–M dyad (M = − 0.15, SD = 0.18; P < 0.001, Cohen's d = 1.22, Bonferroni corrected) (see Fig. 3e, f). No other significant difference was observed. Regarding T21 at the frequency of 0.14 Hz, post hoc tests showed that the IBS increment was significantly lower in the M–M dyad (M = − 0.16, SD = 0.18) than in the F–M dyad (M = − 0.03, SD = 0.11; P = 0.012, Cohen's d = 0.87, Bonferroni corrected) and F–F dyad (M = 0.04, SD = 0.11; P < 0.001, Cohen's d = 1.34, Bonferroni corrected) (see Fig. 3b, c). No other significant difference was observed.

To determine whether the significant main effect of GENDER on the IBS increment was specific to group creative process, we, respectively, conducted a mixed-design ANOVA with the TASK (AUT, OCT) as the within-subject factor and GENDER as the between-subject factor on the significant IBS increment of T21 at the frequencies of 0.08 Hz and 0.14 Hz. Regarding the frequency of 0.08 Hz, the results showed that the interaction effect of GENDER × TASK was not significant, F (2, 63) = 2.45, P = 0.10, η_p^2 = 0.07. Further simple effect analysis showed that the IBS increment was significantly higher in the F–F dyad (M = 0.06, SD = 0.16) than in the F–M dyad (M = − 0.10, SD = 0.15; P = 0.009, Cohen's d = 1.03, Bonferroni corrected) and M–M dyad (M = − 0.08, SD = 0.24; P = 0.049, Cohen's d = 0.69, Bonferroni corrected) during the OCT. No other significant group difference was observed during the OCT (Ps > 0.05). Intriguingly, we found that the IBS increment in the M–M dyad was significantly higher during the OCT (M = − 0.08, SD = 0.24) than the AUT (M = − 0.15, SD = 0.18; P = 0.017, Cohen's d = 0.33, Bonferroni corrected). However, no significant group difference between the two tasks was observed for the F–F or F–M dyad (Ps > 0.05). Regarding the frequency of 0.14 Hz, the results showed that the interaction effect of GENDER × TASK was not significant, F (2, 63) = 2.12, P = 0.13, η_p^2 = 0.06. Further simple effect analysis showed that the IBS increment was significantly lower in the M–M dyad (M = − 0.11, SD = 0.15) than in the F–F dyad (M = 0.02, SD = 0.13; P = 0.006, Cohen's d = 0.93, Bonferroni corrected) during the OCT. No other significant group difference was observed (Ps > 0.05). Meanwhile, no significant group difference between the two tasks was observed for each dyad (Ps > 0.05). All of these findings might indicate that the GENDER effect was not specific to group creative process.

To further examine the trajectory of IBS increments over time in different dyads, a two-way mixed-design ANOVA using GENDER as the between-subject factor and EPOCH as the within-subject factor was conducted on IBS increments of T21 at the frequency of 0.08 Hz and 0.14 Hz during the AUT and OCT, respectively. However, no significant main effect of EPOCH or interaction effect of GENDER × EPOCH was observed (Ps > 0.05).

Correlations between IBS increments and behaviours

We respectively performed bivariate Pearson correlations on IBS increment of T21 at the frequency of 0.08 Hz and behavioral performance [i.e. AUT fluency, AUT uniqueness, AUT feasibility, collective flexibility and sqrt (IOC)] during the AUT for each dyad. It should be noted that the correlation results were not corrected. Regarding the F–F dyad, the IBS increment was positively correlated with AUT uniqueness (r = 0.40, P = 0.041) and AUT fluency (r = 0.40, P = 0.040) (see Fig. 3g). Regarding the M–M dyad, the IBS increment was marginally negatively corrected with collective flexibility (r = − 0.46, P = 0.054). No other significant correlation was observed. Similar correlations were performed on the IBS increment of T21 at the frequency of 0.14 Hz. However, no significant correlation was observed (Ps > 0.05) (see Fig. 3d; see details in Table S2).

Similarly, we, respectively, performed bivariate Pearson correlations on IBS increment of T21 at the frequencies of 0.08 Hz and 0.14 Hz, and OCT fluency for each dyad. No significant correlation was observed (Ps > 0.05) (see details in Table S2).

Discussion

The present study explored the effects of gender composition on the group creative process and unveiled the underlying interpersonal neural correlates, using the fNIRS-based hyperscanning technique. According to gender, participants were assigned into F–F, F–M, and M–M dyads to solve one AUT and one OCT. First, the results showed no significant difference in group creative performance across these three dyads. For the group creative process, the F–F dyad showed the highest IOC among the three dyads. Moreover, the F–M and F–F dyads showed higher collective flexibility than the M–M dyad. In the fNIRS results, the F–F dyad showed higher IBS increments in the right posterior parietal cortex (T21) than the other dyads during both AUT and OCT. The IBS increment in the right posterior parietal cortex was also positively correlated with creative performance (i.e. AUT fluency and AUT uniqueness).

More specifically, regarding the creative outcomes, no significant difference was observed among different dyads. However, with respect to the creative process, we found that the level of cooperative interaction was the highest in the F–F dyad: the highest IOC, the earliest occurrence of the first idea convergence, the longest duration of idea convergence (see Fig. S1). Meanwhile, higher collective flexibility was observed in the F–F dyad than in the M–M dyad. These findings suggest that when females work together on creativity tasks, they tend to solve problems by interacting with each other more frequently (pay attention to ideas, take their partners' perspectives, and depend on each other). These results thus partly support social–cultural theory (Eagly and Wood 1999) and self-construal theory (Cross and Madson 1997; Eckel and Grossman 1998; Zakriski et al. 2005), both of which suggest that females are more communal, interdependent, sharing, and affiliative than males. Accordingly, during the AUT, participants in the F–F dyad may not only seek potential ideas in each single category together (higher IOC), but also explore potential ideas from broad categories (higher collective flexibility). One explanation may be a temporal mode shift (i.e. seek potential ideas from broad categories in the earlier phase and seek potential ideas by deeply exploring one single category in the later phase). This may be partially supported by the finding that IOC increased over time, while collective flexibility decreased over time in the F–F dyad. Another possibility can be that there was a division of roles in the F–F dyad. To examine this, we compared the individual idea convergence behaviour (the frequency of combining the partner' idea) between group members for each dyad. We calculated the difference value of idea convergence behaviour between the two participants for each dyad. Next, a one-way ANOVA using GENDER as the between-subject fact was performed on the absolute value of the difference value. The results showed no significant main effect of GENDER on the absolute value of the difference value, F (2, 63) = 0.80, $P = 0.46$, $\eta_p^2 = 0.03$. This finding did not support the 'role division' hypothesis. Furthermore, although the results showed no significantly enhanced IOC for the F–M dyad compared to the M–M dyad, collective flexibility was higher in the F–M dyad than in the M–M dyad. One explanation may be that gender-heterogeneous groups are capable of taking advantage of their broader range of perspectives and mental abilities to generate new ideas for solving complex problems (Frink et al. 2003; Hirschfeld et al. 2005). Accordingly, when one group consists of one female and one male, the group may tend to develop creative ideas by seeking potential responses from quite broad categories.

Intriguingly, the M–M dyad showed lower IOC and collective flexibility, later occurrence of the first idea convergence, and shorter duration of idea convergence compared to the F–F dyad. Therefore, the frequency of interpersonal interaction between males in the dyad was quite low and late, and the idea categories from which they sought creative responses were also few. Accordingly, we suppose that two males working together on a creative task may tend to ignore the ideas reported by their partner and persist in searching alone for potential responses from a few idea categories. Since males are supposed to be more independent, assertive, ambitious, and dominant than females (Eagly 2009), males may be reluctant to take their partner's perspectives even when they have exhausted their own ideas. Nevertheless, no significant difference in creative outcomes was observed among the three dyads. We surmise that males are likely able to develop creative or novel ideas independently when working on a group creativity task. Consequently, such an independent interaction pattern might help the M–M dyad perform equally to the F–F and F–M dyad on the creative task.

Furthermore, we also examined the trajectories of task performance and communication behaviours in different dyads over time. In all dyads, we found that AUT fluency and collective flexibility decreased over time, whereas AUT feasibility increased over time. These findings suggest that the serial order effect theory, which indicates that the quantity of ideas decrease and the quality of ideas increase over time during individual creativity tasks, can also apply to group creativity (Christensen et al. 1957). However, there were no significant differences in AUT uniqueness among three epochs in any dyad. Hence, it seems that the idea uniqueness in groups does not conform to the serial order effect. Intriguingly, only in the F–F dyad, we found that AUT fluency was significantly higher in EPOCH2 than in EPOCH3. We suggest that the frequent and effective interaction between females might provide more cognitive stimulation or resources to develop new ideas, which may not occur when working alone. Hence, they had more resources to develop new ideas and thus their AUT fluency decreased more slowly than the other dyads.

In the fNIRS results, the F–F dyad showed higher IBS increments in the right posterior parietal regions (T21) at the frequency of 0.08 Hz during the AUT than the other dyads. Previous studies highlight the close association between creative performance and the right parietal regions (Fink et al. 2010; Benedek et al. 2014, 2016; Wu et al. 2015). Additionally, the observed IBS increment was roughly located at the r-TPJ regions. The r-TPJ is associated with social cognitive processes, such as perspective taking, mind reading and theory of mind (Saxe and Powell 2006; Santiesteban et al. 2015; Schurz et al. 2017; Filmer et al. 2019). The enhanced IBS increment might be associated with the perspective-taking process during the group creative activity. It may reflect that, in the F–F dyad, females tend to comprehend and use their partners' ideas to generate novel ideas. This can also be partly seen in the finding that the IOC was the highest for the F–F dyad. Meanwhile, no significantly enhanced IBS increment was observed for the other two dyads and their IOC was quite lower than the F–F dyad. This might indirectly support the suggestion that the enhanced IBS increment in the F–F dyad was associated with the perspective-taking process during the group creative activity. In addition, the right parietal cortex is also associated with the modulation of pain on interpersonal social interaction (Wang et al. 2019) and mental representation of hand movements (Sirigu et al. 1996). Accordingly, the higher IBS increment in the right posterior parietal regions might be associated with an enhanced mental representation of the partner's mental state during the creative task. Also, the IBS increment in the right posterior parietal regions was positively correlated with creative performance (i.e. AUT fluency, AUT uniqueness). Therefore, the IBS increment in the right posterior regions may be the interpersonal neural correlate that underlies the collaboratively creative process in the F–F dyads. However, it should be noted that a similar difference in IBS increment was also observed in the right posterior parietal brain regions during the OCT. This indicates that although the enhanced IBS increment in the right posterior regions may be associated with the effect of gender composition on group creativity, it is not specific to the group creative process.

We also observed higher IBS increment in the right posterior parietal regions (T21) at the frequency of 0.14 Hz in the F–F dyad than the M–M dyad. Although the IBS increment was higher in the F–F dyad than the F–M dyad, the difference was not significant (the P value is 0.08 without Bonfferoni correction). Note that the frequency of 0.14 Hz is adjacent to the frequency of 0.08 Hz (separated by 8 frequencies) and the GENDER effects on the IBS increment of T21 at these frequencies were significant before FDR correction (Ps < 0.05, see Fig. 3a). Therefore, we suggested that the GENDER effect at the frequency of 0.14 Hz might have similar meanings as that at the frequency of 0.08 Hz.

Previous hyperscanning studies have also explored the interpersonal neural correlates that underlie the effects of gender on the interpersonal cooperative interaction. Enhanced IBS in the frontopolar cortex, orbitofrontal cortex, and left dorsolateral prefrontal cortex was observed for the female–male dyad during cooperative interaction in the study conducted by Cheng and her colleagues (Cheng et al. 2015). Based on the similar tasks, Baker et al. (2016) found enhanced IBS in the right temporal cortex for the female–female dyad and enhanced IBS in the right inferior prefrontal cortex for the male–male dyad. The cooperation task used in these studies was simple button-press tasks, whereas the creativity task used in the present study is relatively more complicated. In this case, our findings may highlight multiple important and previously undetected impacts of gender on high-level human cooperation and may extend the understanding of the neural correlates that underlie the human cooperation to a higher or more complex level. Moreover, our findings might also provide some indirect empirical evidence, from the view of group creativity, to suggest that while females and males do not differ in terms of intellectual abilities, they may differ in cognitive strategies, functional task sets, or cognitive styles that each are predisposed to adopt physiologically (Abraham et al. 2014).

The present study contained several limitations. First, and primarily, participants in each dyad were strangers to each other. However, in the real collaborative innovation or creation context, team members are usually familiar with each other. Hence, further investigation is required on whether the effect of gender composition on group creative processes can be modulated by familiarity between team members. Second, only cerebral activities in the PFC and right temporal and parietal regions were recorded, with other brain regions unexplored. To more fully explore neural correlates that underlie gender composition effects on group creative processes, future studies should include more brain areas. Third, due to the limitation of the fNIRS device, only neural activity in the outer cortex was recorded. Deeper brain areas should also be explored in future studies. Moreover, the effect was observed in the context of a turn-taking and reporting setting. However, the effect of gender composition on group creative idea generation might be more profoundly revealed when a more natural, unconstrained, and voluntary communication is introduced. Therefore, to reveal the effect more profoundly, a more natural and unconstrained communication setting should be considered in future studies. Finally, since males are more interested in fishing in the real life, one may expect that males may be more familiar with the 'Fishing rod' and have better OCT performance. Although no significant group difference in OCT fluency was observed, which might indirectly indicate our findings were not contaminated by such gender difference, something else may be different (ex. thinking process) than idea fluency. Therefore, the object for AUT or OCT should be gender independent in future studies, especially for studies about gender difference.

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Data availability statement Data is only available upon reasonable request.

Compliance with ethical standards

Conflict of interest The authors have nothing to disclose.

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