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Applying, not ignoring: how feedback uptake and neural synchrony drive creativity

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Feedback drives creativity, yet how individuals benefit from it remains unclear. This study explored the cognitive and neural mechanisms through which interpersonal feedback promotes creativity. The fNIRS measured interpersonal neural synchronization (INS) during feedback, focusing on the prefrontal cortex and the right temporoparietal area. Participants completed creativity tasks (acquisition/transfer) across four groups: interpersonal feedback, one-way feedback, irrelevant communication, and no feedback. Feedback uptake (ignore, copy, and apply) was coded by linking dialogue content to posttest performance, reflecting cognitive processes. Results showed that only interpersonal feedback improved creativity acquisition and transfer. Applying feedback positively correlated with creativity enhancement, while ignoring it was negatively correlated. Notably, interpersonal feedback induced increased INS at the superior frontal gyrus and inferior parietal cortex, which correlated with creativity enhancement and was further amplified when feedback was applied. The study reveals how interpersonal feedback promotes creativity through underlying cognitive and neural mechanisms, offering insights into fostering creativity.

Humans are both the possessors and beneficiaries of creativity, which has significantly contributed to humanity's immeasurable achievements[1]. Given its crucial role in social and personal development, the need to foster individual creativity has been repeatedly emphasized[2]. A wealth of evidence highlights feedback as a critical factor in influencing individuals' willingness to innovate and stimulating creativity[3]. However, previous studies have primarily explored the effects of different types of feedback on creativity, such as feedback valence[4,5] and feedback style[6], overlooking the feedback receiver's position in the feedback process, which limits our deeper understanding of how feedback operates. Furthermore, simplifying the interactive coordination process of feedback has led to insufficient understanding of the interpersonal neural pathways involved[7]. Therefore, investigating how individuals benefit from feedback and the interpersonal neural mechanisms in an interactive feedback context is crucial for understanding the relationship between feedback and creativity, as well as effective enhancement of creativity.

Creativity is defined as the ability to generate original and useful (or potentially useful) products. Divergent thinking, a key cognitive component of creativity, is widely regarded as a reliable indicator for assessing an individual's creative potential[8]. The inherent complexity of the creative process often leads individuals to feel uncertain or directionless[9], while feedback functions as a critical "breakthrough" for facilitating creativity. Feedback refers to information provided by the feedback provider regarding an individual's performance or understanding[10], and serves to guide future behavior. The effectiveness of feedback in enhancing creativity has been supported by numerous studies[11,12]. A meta-analysis of online peer feedback, in particular, revealed that feedback promotes individuals' development of critical thinking and significantly enhances creativity and problem-solving abilities[13]. Positive feedback dialogs fostered students' creative skills[14], encouraging individuals to reflect, evaluate, and enhance their creative designs[15]. And leaders fostered employee creativity through constructive feedback[9]. Therefore, establishing a connection between the feedback provider–receiver dyads (P–R) allows the receivers to generate novel ideas based on the providers' experiences and insights.

Extensive evidence indicates that feedback can enhance individual creativity, yet the cognitive mechanisms underlying its effects remain poorly understood. One significant reason for this gap is that research on the two concepts has largely followed a basic stimulus-response model, where the feedback process is often simplified to a unidirectional and summative exchange. In this model, feedback receivers are assumed to passively receive

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and integrate all feedback[7]. However, in natural contexts, feedback receivers selectively accept and process information[16]. Previous studies have reported that learners accept and process only a fraction of their peer feedback[17]. Individuals may reject or ignore feedback (e.g. perceiving it as "irrelevant") in order to preserve the core features of their own ideas[18]. It is crucial to emphasize that how feedback receivers process information plays a decisive role in their ability enhancement[19,20]. As Li et al. found, the quantity of feedback individuals actively accept and integrate—rather than the total amount of feedback—predicts the quality of their final product[21]. In conclusion, these findings highlight that the types of feedback and how receivers process them may be crucial cognitive mechanisms underlying the impact of feedback on creativity.

Existing studies have employed the "feedback uptake" concept to describe how individuals process feedback information[22]. Researchers also suggested that insufficient absorption of feedback may hinder performance improvement[23]. For example, learners' feedback uptake levels were assessed using three categories: "ignore," "copy," and "apply". "Apply" refers to recognizing feedback as valuable new information and meaningfully incorporating it into one's existing knowledge structures[24]. "Copy" denotes the surface-level reproduction of feedback content without genuine understanding. In contrast, "ignore" involves overtly dismissing or disregarding the feedback. Applying positive feedback by individuals was positively correlated with artifact quality improvement, whereas ignoring negative feedback was negatively correlated with such improvement[22]. Additionally, feedback uptake mediated the relationship between interactive peer evaluation and the improvement of design skills[20]. However, these studies primarily focused on online feedback environments, which, while offering greater flexibility, can also result in fragmented interactions and delays, thereby prolonging the feedback loop. In contrast, face-to-face interpersonal feedback (IF) enables participants to receive immediate solutions to problems, enhancing both the depth and efficiency of their learning. In conclusion, feedback may influence individual creativity through varying levels of feedback uptake. Face-to-face IF provides a valuable perspective for examining how feedback receivers' creativity evolves and the relationship between feedback uptake and creative performance.

When individuals engage in feedback processing and creative tasks, the prefrontal cortex (PFC) and the right temporoparietal area are activated to process feedback and support creativity[25,26]. Research indicates that the PFC, especially the dorsolateral prefrontal cortex (DLPFC), plays a crucial role in working memory and executive functions associated with creativity, potentially helping to resolve the conflict between conventional and original thinking during creative processes[27]. As a core of the default mode network, the temporoparietal area evaluates creative ideas and guides the generation of novel thoughts[28]. Additionally, brain activity involving regions such as the anterior cingulate cortex, DLPFC, and the fronto-parietal areas is engaged in both simple and elaborated feedback processes, such as validating correct answers or correcting errors[29,30]. More importantly, the PFC and the temporoparietal area are activated during mentalizing processes, which are essential for interpreting others' intentions, understanding their mental states, and predicting their responses[31]. Traditional cognitive neuroscience research typically focuses on brain activity associated with individual behavior, yet fails to capture the bidirectional nature of the P–R from an interpersonal neuroscience perspective.

Interpersonal neuroscience allows for the simultaneous recording of brain activity from two or more individuals, providing a potential means to reveal the neural basis of real interpersonal interactions[32]. Existing research further suggests that feedback enhances individual task performance and triggers a significant increase in interpersonal neural synchronization (INS), which may serve as a key indicator for understanding interpersonal communication[33]. A relevant study found that instructors' detailed feedback improved learners' transfer performance, with significant INS observed in the frontal and parietal regions of both instructors and learners[30]. Additionally, when detailed feedback was presented in chunked information, it facilitated long-term transfer in learners with low prior knowledge. A significant increase in INS between the instructor and learner was observed in the frontal and parietal regions, with frontal INS predicting long-term transfer performance and chunking error correction[34]. In line with these findings, Lu et al. used Functional near-infrared spectroscopy (fNIRS) hyperscanning technology to reveal the facilitating effects of positive feedback, compared to both negative and no feedback (NF), on group creativity. They found a significant increase in INS in participants' PFC and right DLPFC[35]. These findings further support the crucial role of INS in brain regions associated with feedback and creativity. Therefore, capturing the similarities in these regions between the P–R may offer a promising approach for objectively quantifying the impact of IF on creativity.

Although the relationship between feedback and creativity has been extensively reported, how individuals benefit from feedback and its neural basis remains unclear. Moreover, in educational contexts, feedback can vary from face-to-face dialogue to unidirectional evaluation comments from instructors, irrelevant social talk, or even NF at all. To address these questions and examine how different types of feedback influence creativity, we compared IF with three control conditions: one-way feedback (OF), irrelevant communication (IC), and NF. To theoretically support the design of these conditions, we drew on the influential Interactive–Constructive–Active–Passive (ICAP) framework[36]. This framework categorizes learning activities into four types: interactive, constructive, active, and passive. According to this framework, the IF condition involves both interactive and constructive engagement and reflects bidirectional instructor-student interactions that may facilitate deeper understanding and processing. The OF condition, while constructive in nature, lacks interactivity and simulates the unidirectional delivery of feedback from instructor to student, potentially leading to more passive processing. The IC condition involves interaction but lacks task-related constructiveness, representing educationally irrelevant conversations. Finally, the NF condition serves as a baseline, simulating a passive learning environment without any feedback. In addition, these control conditions help eliminate potential confounding effects, including: (1) feedback functioning solely as informational input without interpersonal interaction; (2) general social communication unrelated to the task; and (3) time-related influences.

Individuals' creative performance was assessed using the alternative uses task (AUT), a widely used measure of divergent thinking that captures the ability to generate multiple and varied ideas[37,38]. Divergent thinking is considered a core component of creativity[39]. One item was administered at the pretest. The posttest included three items: one was identical to the pretest item to assess direct learning outcomes (acquisition), and two were different items to evaluate the ability to generalize and extend learned knowledge to novel contexts (transfer)[40]. In addition, feedback uptake (i.e., ignore, copy, and apply) was utilized to investigate how individuals process feedback information[22], shedding light on the relationship between feedback processing and creativity enhancement. During the feedback process, fNIRS hyperscanning was employed to capture the brain activity of the P–R dyads. Building on previous studies[35], we focused primarily on the PFC and right temporoparietal area. Furthermore, we explored whether specific feedback uptake behaviors were distinctly associated with INS during the feedback process.

Our hypotheses were as follows: (1) IF could deepen individuals' understanding of the learning content and facilitate their learning transfer[41]. Consequently, we inferred that IF, compared to other types of feedback, would improve individuals' creativity acquisition and transfer. (2) The extent to which individuals benefited from feedback depended on how they processed and responded to it[22]. Therefore, we reasonably hypothesized that the degree of individuals' feedback uptake would effectively track creative performance. (3) Effective understanding of feedback information is reflected in the enhancement of INS, which can serve as a key predictor of creativity performance[42]. Thus, we hypothesized that P–R dyads would exhibit increased INS during IF; the INS would ultimately predict creativity enhancement and effectively identify key feedback uptake.

Results

A series of one-way analyses of variance (ANOVAs) revealed no significant group differences in pretest creativity (fluency, flexibility, and uniqueness; $Fs(3, 96) \leq 2.150$, $ps \geq 0.099$, $\eta_P^2 s \leq 0.063$). These results indicated that the four groups were comparable in their pretest creativity levels. Additional details can be found in the Supplementary Table 3. No significant differences were found among receivers in the three groups (IF, OF, and IC) in subjective evaluation dimensions ($Fs(2,72) \leq 1.762$, $ps \geq 0.179$, $\eta_P^2 s \leq 0.047$), particularly regarding clarity and comprehensibility ($Fs(2, 72) \leq 0.977$, $ps \geq 0.381$, $\eta_P^2 s \leq 0.026$). These results suggest that participants were generally comparable in their ability to communicate effectively within the task context. Additional details can be found in the Supplementary Table 4. Additionally, we conducted a series of 2 (Role: provider, receiver) × 4 (Group: IF, OF, IC, and NF) two-way ANOVAs on the scores of TIPI (Ten-Item Personality Inventory), IRI (Interpersonal Reactivity Index), and NfC (Need for Consistency scale). The analyses revealed no significant main or interaction effects ($Fs \leq 2.330$, $ps \geq 0.129$, and $\eta_P^2 s \leq 0.012$). These results suggest that feedback providers and receivers were homogeneous in terms of personality traits, empathy, and need for cognition. Further details are provided in the Supplementary Table 4.

Creativity acquisition performance

To examine changes in receivers' creative performance following feedback, a series of 2 (Time: pretest, posttest) × 4 (Group: IF, OF, IC, and NF) repeated-measures ANOVAs was conducted on AUT scores (fluency, flexibility, and uniqueness), with Group as the between-subjects factor and Time as the within-subjects factor. Bonferroni corrections were applied to control for multiple comparisons. Initial boxplot analyses revealed no extreme outliers (beyond *M* ± 3 *SD*).

No significant main effect of Group was found on creativity scores (fluency, flexibility, and uniqueness; $Fs(3, 96) \leq 2.507$, $ps \geq 0.064$, $\eta_P^2 s \leq 0.073$). However, the main effect of Time was significant ($Fs(1, 96) \geq 5.332$, $ps \leq 0.023$, η_P^2 s ≥ 0.053). Post-hoc tests revealed that creativity scores in the posttest (*M* ± *SD*; fluency: 8.89 ± 2.87; flexibility: 4.07 ± 1.28; uniqueness: 4.71 ± 2.21) were significantly higher than in the pretest (fluency: 7.74 ± 2.06, $p < 0.001$; flexibility: 3.80 ± 1.22, $p = 0.023$; uniqueness: 4.09 ± 2.01, $p < 0.001$).

Results indicated a significant interaction effect on creativity scores (fluency, flexibility, and uniqueness; $Fs(3, 96) \geq 4.142$, $ps \leq 0.008$, $\eta_P^2 s \geq 0.115$). Subsequent simple effects analyses revealed that posttest creativity scores in the IF group (fluency: 9.97 ± 3.64; flexibility: 4.64 ± 1.83; uniqueness: 5.08 ± 2.21) were higher than those in the pretest (fluency: 7.21 ± 2.08; flexibility: 3.80 ± 1.70; uniqueness: 3.59 ± 1.84; $ps < 0.001$). The posttest fluency score in the OF group (9.31 ± 2.47) was higher than that in the pretest (8.42 ± 2.12, $p = 0.038$). Furthermore, the posttest flexibility score in the IF group (4.64 ± 1.82) was higher than that in the IC group (3.51 ± 0.77, $p = 0.011$). The posttest uniqueness score in the NF group (3.56 ± 2.61) was lower than that in the OF group (5.19 ± 1.66, $p = 0.045$).

Creative transfer performance

The main effect of Group on fluency score was not significant ($F(3, 96) = 1.516$; $p = 0.251$, $\eta_P^2 = 0.045$). However, a significant main effect of Group was observed for flexibility and uniqueness ($Fs(3, 96) \geq 3.831$, $ps \leq 0.012$, $\eta_P^2 s \geq 0.107$). Participants in the IF group (4.45 ± 1.86) outperformed those in the IC group (3.59 ± 0.67, $p = 0.031$) and the OF group (3.58 ± 0.71, $p = 0.022$) on flexibility. Additionally, the uniqueness score in the NF group (3.33 ± 2.01) was significantly lower than that in the IF group (4.63 ± 2.47, $p = 0.043$), IC group (4.65 ± 1.61, $p = 0.040$), and OF group (4.63 ± 0.71, $p = 0.039$). Furthermore, a significant main effect of Time on creativity scores (fluency, flexibility, and uniqueness; $Fs(3, 96) \geq 4.878$, $p \leq 0.030$, $\eta_P^2 \geq 0.048$) was found, indicating that the creativity scores in the posttest (fluency: 8.53 ± 2.47; flexibility: 4.08 ± 1.29; uniqueness: 4.53 ± 2.11) were higher than those in the pretest (fluency: 7.74 ± 2.06; flexibility: 3.80 ± 1.22; uniqueness: 4.09 ± 2.01).

Results demonstrated a significant interaction effect on creativity scores (fluency, flexibility, and uniqueness; $Fs(3, 96) \geq 8.269$, $ps < 0.001$, $\eta_P^2 \geq 0.205$). To break up the significant interaction, simple effects analyses were performed. Posttest scores in the IF group (fluency: 9.68 ± 3.12; flexibility: 5.09 ± 1.85; uniqueness: 5.67 ± 2.61) were higher than the pretest scores (fluency: 7.21 ± 2.08; flexibility: 3.80 ± 1.70; uniqueness: 3.59 ± 1.84; $ps < 0.001$). Additionally, the posttest scores in the IF group were also significantly higher than those in the NF group (fluency: 7.49 ± 1.42, $p = 0.010$; flexibility: 4.18 ± 0.95, $p = 0.031$; uniqueness: 3.05 ± 1.35, $p < 0.001$), the IC group (flexibility: 3.47 ± 0.59, $p < 0.001$), and the OF group (flexibility: 3.56 ± 0.63, $p < 0.001$). The posttest uniqueness score in the NF group (3.05 ± 1.35) was significantly lower than that in the IC group (4.76 ± 1.70, $p = 0.014$) and OF group (4.62 ± 1.75, $p = 0.026$). Overall, on the behavioral level, the OF was primarily effective in enhancing fluency acquisition, while IF more effectively facilitated the acquisition and transfer of fluency, flexibility, and uniqueness. See Fig. 1.

Furthermore, the receiver's posttest self-assessments of creative performance (4.41 ± 0.83) were higher than their pretest self-assessments (3.95 ± 0.84, $p < 0.001$). For the IF group, posttest assessments of creativity by others (4.92 ± 1.12) were higher than pretest assessments (4.32 ± 0.80, $p = 0.002$). The participants in the IF group showed significantly higher posttest assessments of creativity by others (4.92 ± 1.12) than the IC group (3.92 ± 0.78, $p = 0.003$) and the OF group (4.04 ± 1.04, $p = 0.011$). Please see Supplementary Table 5.

Results of feedback uptake coding

A text coding approach was employed to categorize different types of feedback uptake, including ignore, copy, and apply. The amounts and percentages of feedback uptake for the IF and OF groups are presented in Supplementary Table 6. In the IF group, 46.26% of the feedback was ignored, 32.84% was copied, and 20.90% was applied. In contrast, the OF group exhibited 47.32% ignored, 41.07% copied, and only 11.61% applied. Independent samples *t*-tests were conducted to compare the amount and percentages of ignoring, copying, and applying feedback between the two groups. The amount of apply (1.12 ± 1.24) and the total amount of feedback (5.36 ± 1.08) in the IF group were significantly higher than those in the OF group (amount of apply: 0.50 ± 0.76; total amount of feedback: 4.31 ± 0.88; $t(49) \geq 2.167$, $p \leq 0.035$, Cohen's $d \geq 0.603$). No other significant differences were observed ($ps > 0.05$).

Correlations between creativity performance and feedback uptake

A series of Pearson correlation analyses was performed to examine the relationship between changes in creativity (both acquisition and transfer) and feedback uptake (total amount and percentage of "ignore", "copy", and "apply"). In the IF group, the amount of feedback ignored ($r = -0.641$; $p_{corr} = 0.003$) and the percentage of feedback ignored ($r = -0.627$; $p_{corr} = 0.003$) were significantly negatively correlated with fluency acquisition, respectively. Additionally, a significant negative correlation was found between the percentage of feedback ignored and uniqueness acquisition ($r = -0.515$; $p_{corr} = 0.020$). The total amount and percentage of feedback applied were significantly positively correlated with fluency acquisition (amount of apply: $r = 0.473$; $p_{corr} = 0.026$; percentage of apply: $r = 0.527$; $p_{corr} = 0.014$) and uniqueness acquisition (amount of apply: $r = 0.504$; $p_{corr} = 0.020$; percentage of apply: $r = 0.532$; $p_{corr} = 0.020$), respectively. The results of the OF reveal that the amount of feedback ignored ($r = -0.735$; $p_{corr} < 0.001$) and the percentage of feedback ignored ($r = -0.645$; $p_{corr} = 0.001$) were negatively correlated with fluency acquisition, respectively. Additionally, the amount of feedback applied ($r = 0.540$; $p_{corr} = 0.008$) and the percentage of feedback applied ($r = 0.489$; $p_{corr} = 0.017$) were positively correlated with fluency acquisition, respectively. Further details are represented in Supplementary Table 7. No significant correlations were found between creativity transfer and feedback uptake. Overall, creativity acquisition was significantly negatively correlated with both the amount and

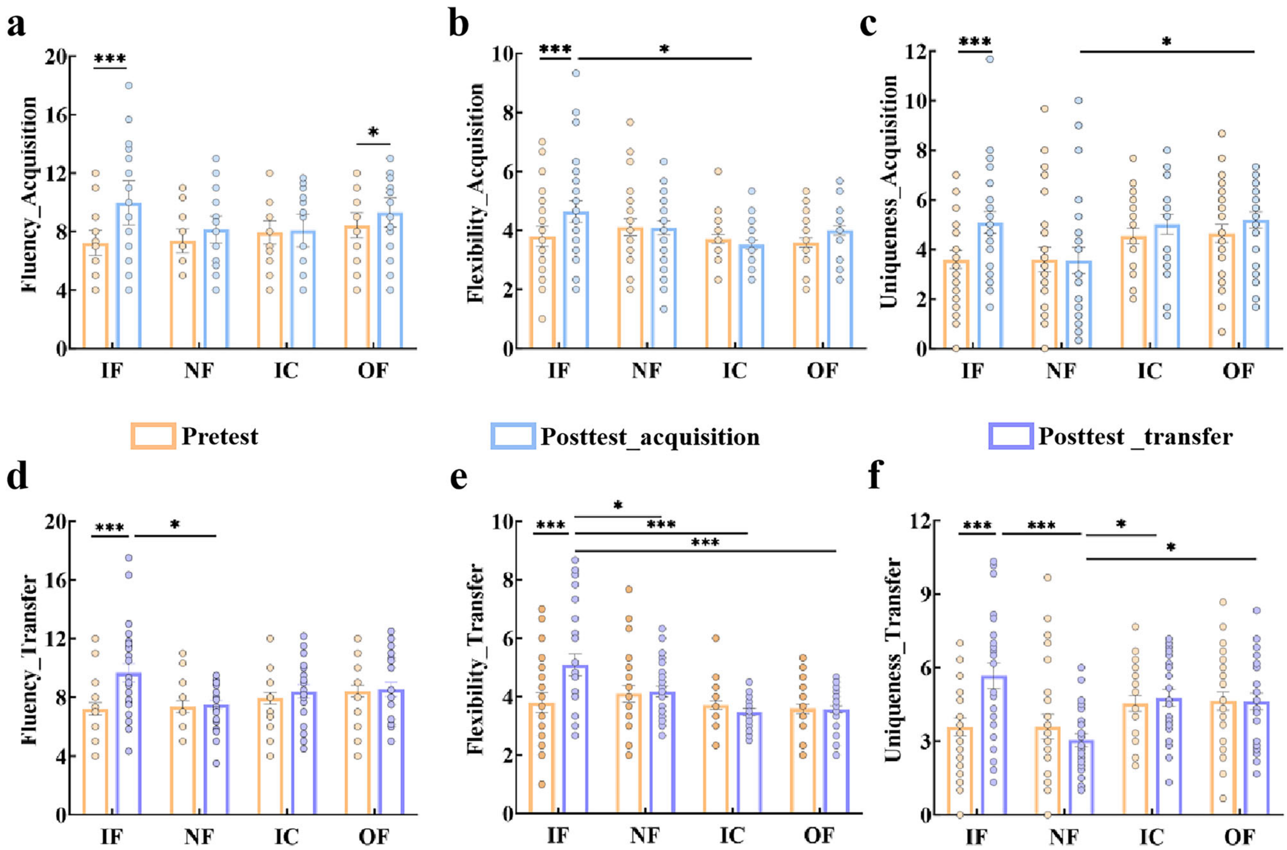

Fig. 1 | Results of creativity acquisition and transfer. Fluency score of acquisition **a**; Flexibility score of acquisition **b**; Uniqueness score of acquisition **c**; Fluency score of transfer **d**; Flexibility score of transfer **e**; and Uniqueness score of transfer **f**. IF interpersonal feedback, OF one-way feedback, IC irrelevant communication, NF no feedback. Error bars represent standard errors of the mean. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

percentage of ignored feedback, while it was significantly positively correlated with the amount and percentage of applied feedback.

Exploration of interaction sequences

We further examined which feedback behavior sequences were statistically significant in influencing participants' adoption of feedback. Frequency counts (shown in Supplementary Table 8 and Table 9) and adjusted residual results were automatically calculated using GSEQ 5.1 (a free software for analyzing interaction sequences). For the adjusted residual results, a z-score greater than 1.96 indicates that the sequence of a row and column has reached a significance level ($p < 0.05$). See Fig. 2. The behavioral sequence analyses for both IF and OF groups revealed that when participants received feedback containing comments or scaffolding, individuals preferred to apply the feedback. In contrast, when participants received positive or negative feedback or assessed feedback, they were more likely to ignore it. Taken together, the combined results of the correlation and behavioral sequence analyses indicated that when feedback included "why" (comment) or "how"(scaffolding), participants were more likely to apply feedback. More frequent application of feedback was associated with better performance in creativity acquisition. Conversely, participants tended to ignore affective or assessing feedback, and the more feedback was ignored, the less improvement was observed.

INS results

Frequencies of interest (FOI) refer to the specific frequency range most likely to reflect task-relevant neural activity. We conducted a series of one-way ANOVAs on the INS of channel combinations (denoted as "CH" with an identifying number) in FOI1(CH6–CH14 and CH12–CH14) and FOI2 (CH4–CH14 and CH17–CH17), with group as the independent variable. The results revealed significant variation in INS at CH6–CH14 (FOI 1) among the four groups ($F(3, 95) = 8.840$, $p_{corr} = 0.047$; $\eta_P^2 = 0.218$). Specifically, the INS of the IF group (0.07 ± 0.08) was significantly higher than that of the NF group (-0.06 ± 0.10, $p < 0.001$), the IC group (-0.01 ± 0.09, $p = 0.023$), and the OF group (-0.03 ± 0.11, $p = 0.002$). Notably, one data point in the INS at CH6–CH14 was identified as an outlier (beyond $M \pm 3$ SD). After removing the outlier, the results remained consistent with the original findings (see Supplementary Result 1). Similarly, the INS at CH12–CH14 showed a significant group difference ($F(3, 96) = 7.599$, $p_{corr} = 0.048$, $\eta_P^2 = 0.192$). The INS of the IF group (0.04 ± 0.09) was significantly higher than that of the NF group (-0.10 ± 0.14, $p < 0.001$). CH6, CH12, and CH14 roughly cover the left superior frontal gyrus (lSFG), right superior frontal gyrus (rSFG), and right inferior parietal cortex (rIPC), respectively.

The results revealed that INS at CH4–CH14 (FOI 2) varied significantly among the four groups ($F(3, 96) = 8.139$, $p_{corr} = 0.009$, $\eta_P^2 = 0.203$). Specifically, the INS of the IF group (0.07 ± 0.14) was significantly higher than that of the NF group (-0.09 ± 0.12, $p < 0.001$) and the IC group (-0.03 ± 0.13, $p = 0.039$). Additionally, the INS of the OF group (0.05 ± 0.14) was significantly higher than that of the NF group (-0.09 ± 0.12, $p = 0.002$). The INS of CH17–CH17 also demonstrated a significant group difference ($F(3, 96) = 9.078$, $p_{corr} = 0.009$, $\eta_P^2 = 0.221$). Specifically, the INS of the IF group (0.04 ± 0.16, $p < 0.001$) and the IC group (0.05 ± 0.13, $p < 0.001$) were significantly higher than that of the NF group (-0.13 ± 0.15). CH4 and CH17 roughly cover the lSFG and right supramarginal gyrus, respectively, see Fig. 3.

Validation of INS differences

A permutation test further confirmed that the observed differences in INS were specific to the interactions within real dyads. Compared with the distribution generated by the permutation procedure, the F-

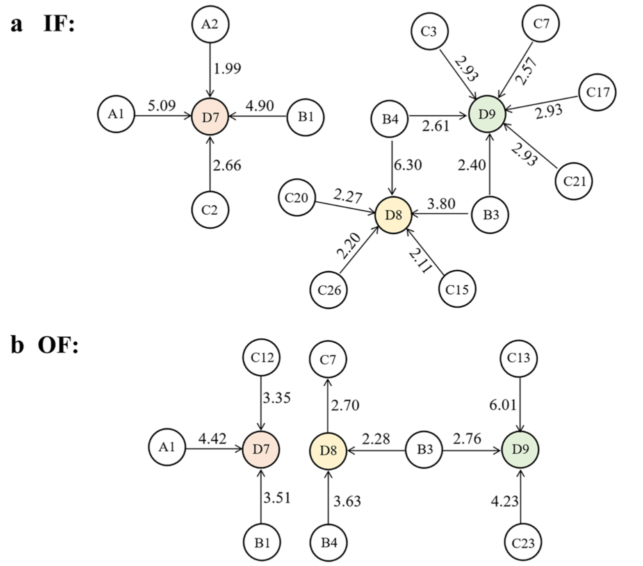

Fig. 2 | Behavioral sequence analysis results. Behavioral sequence diagram for IF **a** and OF **b**. The arrows indicate the sequence of behaviors, with numbers on the arrows representing the *z*-scores. A *z*-score > 1.96 means a statistically significant behavioral sequence. For example, when A1 (positive feedback) was followed by D7 (Ignore), the sequence was significant. D7: Ignore; D8: Copy; D9: Apply; A1: Positive feedback; A2: Negative feedback; B1: Clarification; B3: Comments; B4: Scaffolding; C2: Positive feedback + Negative feedback; C3: Positive feedback + Clarification + Scaffolding; C7: Clarification + Scaffolding; C12: Positive feedback + Assessing; C13: Negative feedback + Scaffolding; C15: Assessing + Scaffolding; C17: Positive feedback + Comments; C20: Positive feedback + Scaffolding; C21: Positive feedback + Comments + Scaffolding; C23: Comments + Negative feedback + Comments; C26: Clarification + Positive feedback.

values of the actual dyads were in the 5% areas of the distribution (Fig. 3g). Collectively, the findings indicated that IF effectively elicited INS, and this INS-based effect was specific to real feedback-based P–R dyads.

Granger causality analysis (GCA) results

One-sample *t*-tests revealed GCA values significantly greater than zero in both directions (provider → receiver and receiver → provider) across all four groups (IF, OF, IC, and NF) for both channel combinations (CH6–CH14 and CH12–CH14), with $ts \geq 3.115$, $p_{corr} \leq 0.005$, Cohen's $d \geq 0.623$. For the CH6–CH14, a 4 (Group: IF, OF, IC, NF) × 2 (Direction: provider → receiver, receiver → provider) mixed-design ANOVA revealed a significant main effect of group ($F(3, 96) = 4.951$, $p = 0.003$, $\eta_P^2 = 0.134$). Post-hoc comparisons indicated that the IF group (0.0044 ± 0.0045) exhibited significantly higher GCA values than the NF group (0.0014 ± 0.0015; $p = 0.002$). A significant interaction was also observed ($F(3, 96) = 3.065$, $p = 0.032$, $\eta_P^2 = 0.087$). Post-hoc tests showed that, in the OF group, GCA values were significantly higher in the provider → receiver direction (0.0044 ± 0.0032) than in the receiver → provider direction (0.0026 ± 0.0028; $p = 0.013$). Further comparisons for the provider → receiver direction indicated that GCA values were significantly higher in the IF (0.0038 ± 0.0034), OF (0.0044 ± 0.0032), and IC groups (0.0038 ± 0.0037) compared to the NF group (0.0013 ± 0.0013; $ps \leq 0.034$). For the receiver → provider direction, only the IF group (0.0049 ± 0.0055) showed significantly higher GCA values than the NF group (0.0015 ± 0.0019; $p = 0.006$). In contrast, for CH12–CH14, no significant differences were observed in the subsequent analyses ($ts \leq 2.343$, $ps \geq 0.078$, $\eta_P^2 \leq 0.068$). No other significant differences were observed ($ps > 0.05$). These results indicate that IF uniquely enhances bidirectional neural information flow between provider and receiver, while OF primarily strengthens the influence from provider to receiver.

Association of the INS with creativity performance

A series of Pearson correlation analyses was conducted to explore relationships between INS values (FOI 1: CH6–CH14, CH12–CH14; FOI 2: CH4–CH14, CH17–CH17) and the creative performance metrics (changes in fluency, flexibility, and uniqueness; acquisition and transfer). The results were corrected using the false discovery rate (FDR)[43] ($p < 0.05$). The analysis revealed positive correlations between changes in uniqueness (acquisition: $r = 0.257$; $p_{corr} = 0.020$; transfer: $r = 0.293$; $p_{corr} = 0.009$) and flexibility (transfer: $r = 0.352$; $p_{corr} = 0.002$) with the INS at CH6–CH14 (see Fig. 4). Notably, the INS at CH6–CH14 contained one data point identified as an outlier (beyond $M \pm 3\ SD$). However, when the outlier was removed, the results remained consistent with the original findings (refer to Supplementary Result 2). The permutation test further confirmed that the observed INS patterns were specific to interactions with real dyads and not attributable to chance. These findings suggest that INS at CH6–CH14 was uniquely associated with creativity acquisition and transfer. In contrast, no significant correlations were found between the INS at CH12–CH14 (ROI 1), ROI 2, and creative performance ($p_{corr} > 0.05$). Consequently, the remainder of the analysis focused exclusively on the INS at CH6–CH14.

Combination of INS and feedback uptake

INS values were extracted based on feedback uptake (ignore, copy, and apply) for individuals in the IF and OF groups, and a 2 (IF, OF) × 3 (ignore, copy, and apply) ANOVA. The results revealed a significant group difference ($F(1, 112) = 10.915$, $p = 0.001$, $\eta_P^2 = 0.089$). The IF group exhibited significantly greater INS (0.37 ± 0.01) than the OF group (0.33 ± 0.01). The main effect of feedback uptake was also significant ($F(2, 112) = 17.100$, $p < 0.001$, $\eta_P^2 = 0.234$). Specifically, the "apply" (0.39 ± 0.01) elicited stronger INS than "copy" (0.35 ± 0.01, $p = 0.010$) and "ignore" (0.30 ± 0.01, $p < 0.001$). The "copy" elicited stronger INS than "ignore" ($p = 0.004$). The interaction effect was significant ($F(2, 112) = 4.856$, $p = 0.009$, $\eta_P^2 = 0.080$). Further simple effect analysis (Bonferroni-corrected) showed that "apply" (0.42 ± 0.06) and "ignore" (0.33 ± 0.07) in the IF group elicited stronger INS than "apply" (0.36 ± 0.06, $p = 0.008$) and "ignore" (0.27 ± 0.04, $p = 0.001$) in the OF group. In the IF group, the "apply" (0.42 ± 0.06) elicited stronger INS than both "copy" (0.34 ± 0.07, $p < 0.001$) and "ignore" (0.33 ± 0.07, $p < 0.001$). In the OF group, the "apply" (0.36 ± 0.06) elicited stronger INS than "ignore" (0.27 ± 0.04, $p = 0.001$), and the "copy" (0.35 ± 0.06) elicited stronger INS than "ignore" (0.27 ± 0.04, $p < 0.001$; see Fig. 5). Collectively, our findings suggest that INS was more pronounced when feedback was applied, rather than other feedback uptake behaviors.

Discussion

The present study utilized fNIRS hyperscanning to examine the impact of IF (with control conditions: OF, IC, and NF) on creativity, feedback uptake (i.e., ignore, copy, apply), and related inter-brain mechanistic features. In summary, we found that individuals engaged in IF exhibited significant improvements in creativity acquisition and transfer. Participants' creativity enhancement was positively correlated with actively applying feedback and negatively correlated with ignoring feedback. Specifically, IF elicited stronger INS in the SFG and IPC, and this INS was positively associated with improvements in both creativity acquisition and transfer. Notably, INS during feedback segments that were later applied was significantly higher than that in segments that were later ignored. However, the control condition did not yield satisfactory results and lacked significant INS. These findings suggest that feedback uptake effectively tracks creativity enhancement and may serve as the cognitive basis underlying the role of IF in fostering creativity. The INS effectively identifies feedback uptake and predicts creativity enhancement, potentially reflecting the key neural mechanisms through which IF fosters creativity. This study advances our understanding of the relationship between IF and creativity enhancement, emphasizing the crucial roles of feedback uptake and INS. The subsequent section addresses the implications of these findings.

The present study emphasizes that IF plays a crucial role in enhancing creativity (fluency, flexibility, and uniqueness), whereas the control

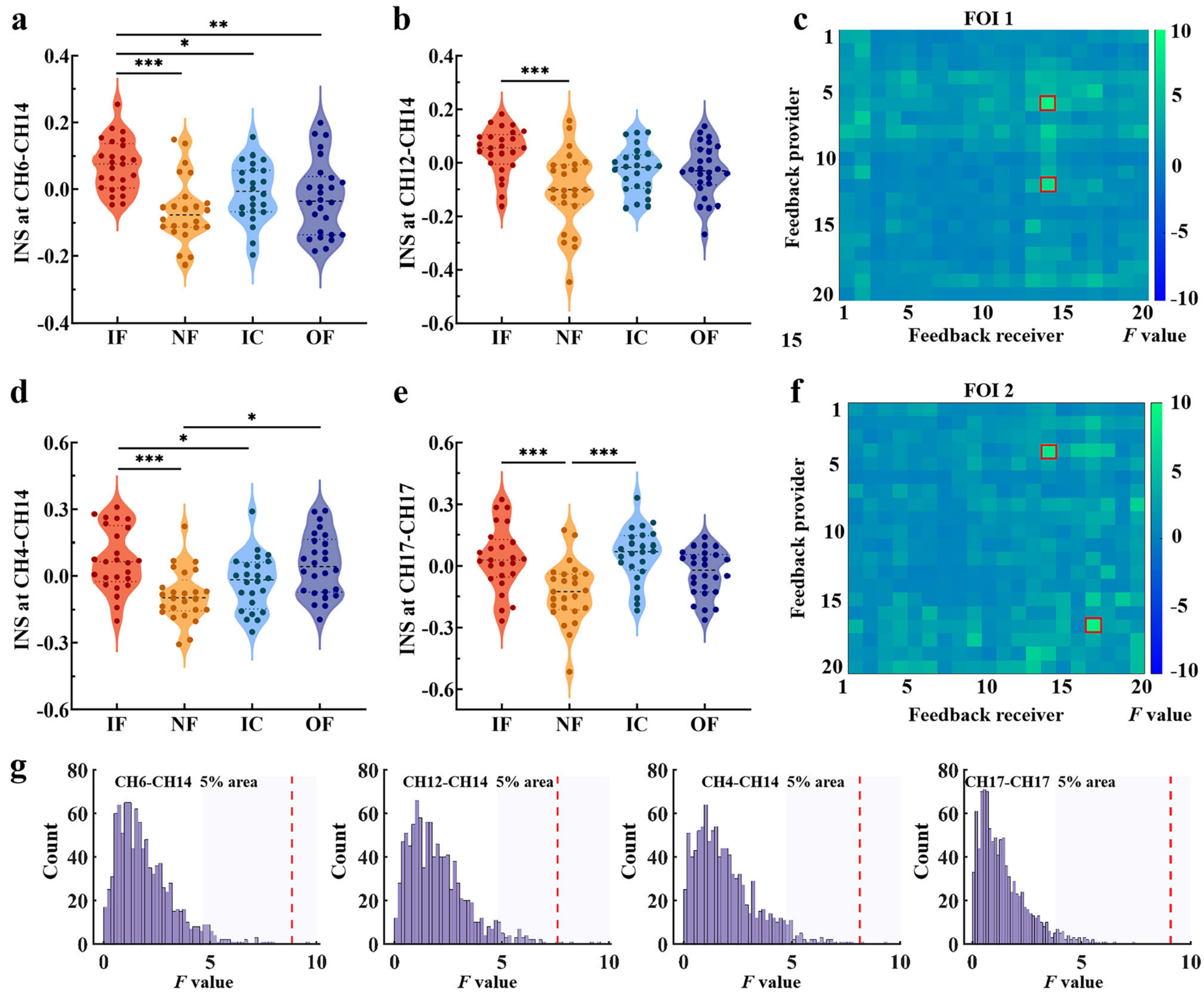

Fig. 3 | The INS differences for FOI1 and FOI2. FOI1: CH6–CH14 **a** and CH12–CH14 **b**; FOI 2: CH4–CH14 **d** and CH17–CH17 **e**. The INS matrix for FOI 1 **c**)and FOI 2 **f** with significant CH combinations highlighted in red boxes. The validation results for FOI1 and FOI2 **g**.

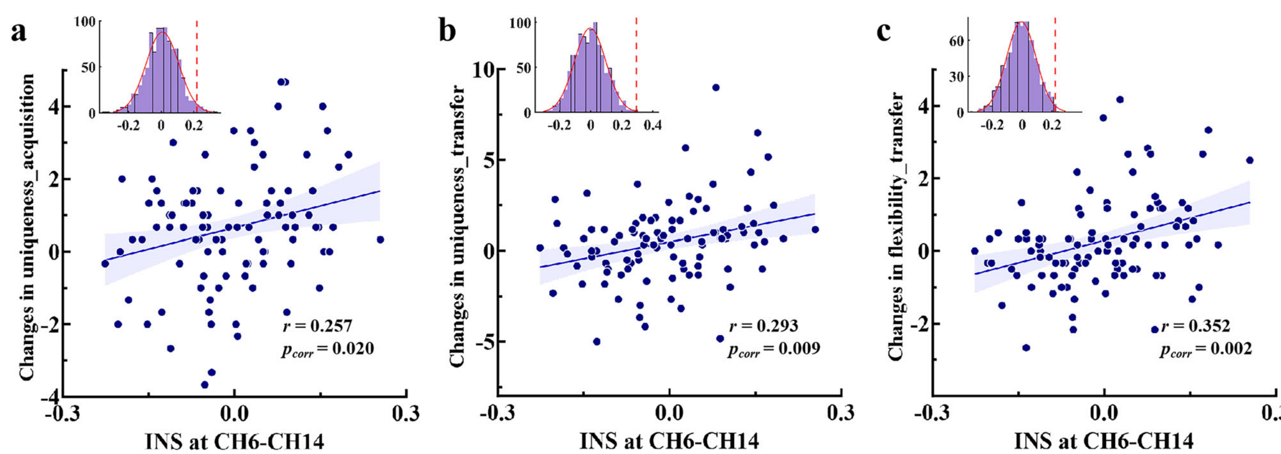

Fig. 4 | Correlation between INS and creativity changes. Correlation between INS at CH6–CH14 and changes in uniqueness acquisition **a** and transfer **b**, and changes in flexibility transfer **c**.

conditions exhibit limited effects. This finding corroborates the claim that IF fosters creativity[44] and aligns with prior research. For example, online peer feedback improved students' creativity through artifact creation[22], while turn-taking encouragement feedback boosted fluency, originality, and convergence in remote online group tasks compared to random timing feedback and NF[44]. These effects align with evidence that external inputs (e.g., feedback or guidance) may stimulate cognitive processing[45], thereby enhancing creativity in interactive contexts[35,42]. In this study, the

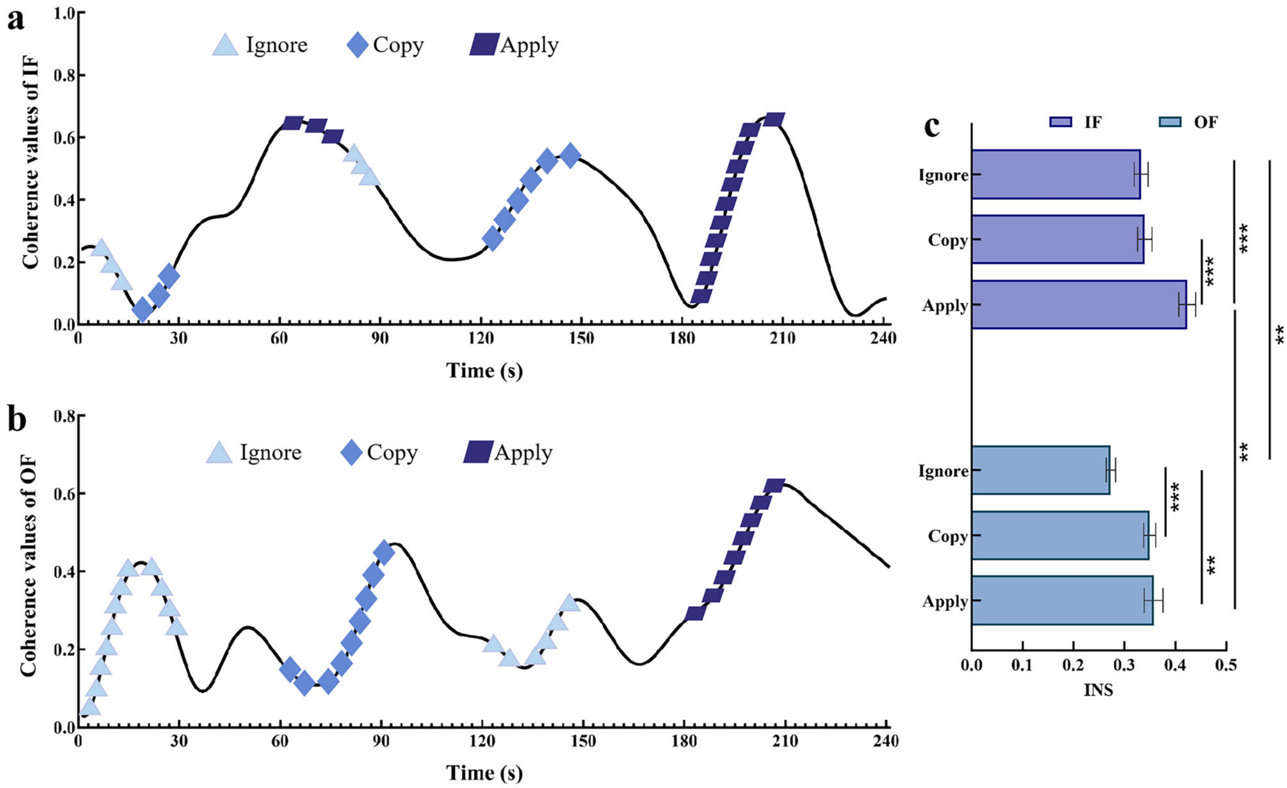

Fig. 5 | INS time course and feedback uptake. The INS time course of a randomly selected dyad during IF **a** and OF **b**. Feedback uptake comparison between IF and OF **c**. IF interpersonal feedback, OF one-way feedback.

distinguishing feature of IF, compared to the control conditions, is that the recipient receives real-time feedback and actively articulates understanding, clarifies misunderstandings, and even offers rebuttals. This dynamic exchange promotes constructive dialogue, facilitates deeper reflection, and enhances the ability to critically apply feedback[19,46], thereby fostering high-quality creative solutions. More importantly, IF promotes creativity acquisition and facilitates its transfer to new contexts. This transfer effect is likely due to enhanced cognitive engagement, particularly in innovative skills and cognitive strategies[47]. When the transfer task aligns with the acquisition task in difficulty, mastered strategies may automatically apply themselves to new contexts, thereby improving creativity transfer.

Current research explores three levels of feedback uptake (ignore, copy, and apply) and the corresponding behavioral sequences, advancing our understanding of how IF enhances creativity. This suggests that feedback uptake may serve as a key cognitive mechanism underlying creativity enhancement. Notably, participants were more likely to apply feedback categorized as "comments" and "scaffolding"; applying feedback was significantly associated with creativity enhancement. In contrast, participants were more inclined to ignore "emotional" and "assessing" feedback, and ignoring feedback was negatively associated with creativity enhancement. This result replicates prior evidence[22] and further emphasizes that explaining why (comments feedback) or how to proceed (scaffolding feedback) is more likely to be applied. One possible interpretation is that comments and scaffolding offer detailed elaborations, which engage learners in deeper cognitive processing[48], thereby enhancing creative performance[9,49]. For instance, explaining why a particular answer lacks novelty can prompt individuals to shift from surface-level processing to metacognitive awareness[50]. This explanatory approach not only offers valuable insights for subsequent tasks but also enhances individuals' comprehension, thereby facilitating their effective application of feedback.

In contrast, positive feedback typically does not encourage increased effort, as it signals that individuals are "good enough"[51]. While negative feedback may be more instructive, it can trigger self-threat, leading individuals to either direct less attention to the task or even abandon it entirely to protect their self-esteem[50]. As a result, emotional feedback is more likely to be ignored[4,5,16]. Nevertheless, both positive and negative feedback hold value in enhancing creativity, although this is not the focus of the current study. We advocate including "why" or "how-to" feedback alongside emotional feedback to help individuals apply feedback more effectively. Additionally, we did not observe a direct correlation between feedback uptake and creativity transfer performance. One possible explanation is related to the feedback script setup. Since the feedback content is more relevant to the creativity acquisition task than to the transfer task, the feedback uptake consequently serves as a stronger predictor of acquisition performance than of transfer performance. Certainly, future research is essential to investigate feedback uptake and its potential effects on creativity outcomes.

We observed that, compared to the control condition, IF triggered the alignment of neural processes in the SFG and IPC between participants. The SFG, as part of the PFC, is involved in working memory, attention[52], and task preparation processes[53], all functions associated with creativity. In interpersonal interactions, the parietal cortex plays a critical role in processing feedback information, adjusting overall performance, and correcting errors[26,29]. Research on interpersonal collaboration also indicates that the increased INS-SFC may reflect its active role in the theory of mind, imitation, and predicting others' behavior[54]. Additionally, the IPC, located in the temporoparietal area and serving as a key component of the mirror neuron system[55], plays a crucial role in the theory of mind[56]. The activation of these regions provides neural support for a deeper understanding of feedback, facilitating behavior adjustment and enhancing creative performance. Consistent with previous research, INS may be influenced by the level of interaction and communication among participants[57]. IF providing detailed elaborations, enhances the depth of communication between participants, it may be a key factor contributing to increased INS. Moreover, IF not only enhances the overall strength of INS but also facilitates bidirectional information flow between interacting partners. The significant Granger-causal influences in both directions further indicate that, during IF, the receiver is not a passive recipient of information but an active participant in the exchange, proactively anticipating the provider's expressions and communicative intentions. This bidirectional coupling reflects more interactive and co-regulated neural dynamics, underscoring the critical role of IF in fostering creativity.

Our study further revealed that SFG-INS and IPC-INS during IF were positively associated with improvements in creativity acquisition. Similar findings have been reported in previous studies[58,59]. For instance, enhanced SFG-INS between instructors and learners during scaffolding interactions was positively associated with improvements in creative thinking metrics[42], while INS in the parietal region during detailed feedback processes was significantly associated with learning transfer[30]. Consistent with these views, INS in these areas may be associated with high mutual attention, efficient information transfer, and predictability between the two parties[33]. For example, enhancing task performance by increasing attention to and understanding others' feedback may require substantial neural resources in the frontal and parietal regions. These findings suggest that the SFG-INS and IPC-INS may serve as the interpersonal neural mechanism underlying the role of IF in fostering creativity and effectively predicting improvements in creativity acquisition.

As a complement, different levels of feedback uptake are manifested in the intensity of INS, which may be a crucial factor in effectively tracking and identifying it. In both the IF and OF groups, the INS effect was amplified when participants applied feedback, compared to when they ignored it. A relevant study by Pan et al. found that, compared to the "debate" process (cognitive imbalance), the INS effect is enhanced when a "consensus" (cognitive balance) is reached[60]. Similarly, ignoring feedback in this study may reflect a cognitive imbalance, where feedback information conflicts with an individual's pre-existing cognition. For example, negative feedback may threaten self-esteem, leading individuals to disregard it[61]. In other words, sustained low INS may indicate a lack of understanding of feedback from others. In contrast, when individuals apply feedback, they may narrow the gap in understanding others' perspectives, lessening the complexity of comprehending the feedback provider's thoughts[62]. This process facilitates the acceptance of ideas, as evidenced by an increased INS. Remarkably, during applying or ignoring feedback, INS in the IF group was significantly higher than that in the OF group under the same conditions. This finding aligns with other results from the study showing that IF, compared to the control conditions, resulted in stronger neural synchronization between participants. This may indicate that IF facilitates more effective information exchange and mutual understanding, with INS serving as evidence of cognitive alignment. Based on these findings, INS can serve as a reliable and objective indicator for adjusting and optimizing participants' feedback uptake.

Our findings have important implications for educational practice. First, the results highlight the potential of interactive feedback environments, such as dialogic exchanges between teachers and students or structured peer collaboration, to promote cognitive alignment and facilitate divergent thinking. Second, rather than merely serving as a vehicle for information delivery, effective feedback should actively guide learners in integrating and applying new input. Importantly, these insights also extend to organizational contexts. In performance review settings, for instance, interactive feedback structures that promote mutual understanding and encourage employees to apply feedback could enhance creative problem-solving and task engagement. In summary, the results highlight feedback uptake and INS as potential mechanisms that promote creativity. These findings provide a foundation for designing learning and feedback practices that more effectively support innovation in both educational and workplace settings.

The limitations of this study should be acknowledged. First, the majority of participants were female. Previous research has highlighted potential gender differences in creativity[63]. Therefore, future studies should examine the effects of IF on creativity in a more gender-diverse sample to enhance the generalizability of the findings. Second, participants' acquisition and transfer performance were assessed within the same experimental session, which involved a relatively short time interval. Future research should explore whether the benefits of feedback on creativity persist over longer periods. Third, the study relied on the AUT as a measure of creativity, which primarily reflects divergent thinking and does not capture the full range of creativity. Future studies could incorporate more comprehensive assessments, such as tasks combining divergent and convergent thinking, to better capture the multifaceted nature of creativity and its underlying mechanisms. Finally, the 1-min resting period between the feedback and posttest sessions, intended to allow brain activity to return to baseline, may have unintentionally introduced an incubation effect[64]. Future studies should consider systematically manipulating or controlling the duration of this interval to better isolate and clarify its role in creativity enhancement.

In conclusion, this study demonstrates that IF effectively facilitates both the acquisition and transfer of creativity. Additionally, applying feedback positively correlated with participants' creativity acquisition performance, while ignoring feedback negatively correlated with it. These findings suggest that feedback uptake may be a key cognitive process underlying how IF enhances creativity. More importantly, INS in the left SFG and right IPC may serve as neural indicators of how feedback enhances creativity, distinguishing between applying and ignoring feedback, and tracking creativity enhancement. These results provide direct empirical support and insights into how IF influences creativity, and contribute to the understanding of the neural underpinnings of enhancing creativity.

Methods

Participants

The experiment employed a 2 (Time: pretest, posttest) × 4 (Group: IF, OF, IC, NF) mixed factorial design, with Group as a between-subjects factor. The required sample size was calculated using G*Power 3.1.9[65], which indicated that 76 dyads were needed to achieve a significance level of 5%, a statistical power of 95%, and an effect size of $f = 0.25$. To ensure an adequate sample size after potential exclusions, 104 dyads (208 participants, 52 males; age range: 18–26 years; $M = 20.54$, $SD = 1.78$) were recruited. Participants were randomly assigned to one of four groups (IF, OF, IC, and NF) based on same-gender pairing (female–female or male–male dyads), with 26 dyads in each group. Due to technical issues, four dyads (IF: 1, NF: 1, IC: 2) were excluded, leaving 100 dyads (24 male–male dyads) for analysis. The final sample consisted of participants aged 18–26 years ($M = 20.54$, $SD = 1.80$), with group distributions as follows: IF ($n = 25$ dyads, 7 male–male dyads), OF ($n = 26$ dyads, 6 male–male dyads), IC ($n = 24$ dyads, 5 male–male dyads), and NF ($n = 25$ dyads, 6 male–male dyads). There were no significant differences in age composition among the four groups ($F(3, 196) = 2.039$, $p = 0.110$, $\eta_p^2 = 0.030$). All dyad partners were previously unacquainted. Participants were right-handed, had normal hearing, and normal or corrected vision, with no neurological or psychiatric disorders. Refer to the Supplementary Table 1 for additional demographic details. The experiment was approved by the Ethics Committee of Shanghai Normal University and carried out following the Declaration of Helsinki. All participants signed written informed consent and received ¥35 compensation for their time.

Creativity materials

The creativity measures were derived from the AUT and included scores for fluency, flexibility, and uniqueness. The AUT, an established measure of divergent thinking, has been widely utilized in behavioral and neuroscientific studies of creativity[1,37]. During the AUT, participants were instructed to generate as many original and creative uses for common objects as possible within 3 min. Acquisition performance was assessed using one AUT item ("shoes") consistent with the pretest, while transfer performance was evaluated using two different AUT items ("umbrella" and "books"). The three AUT items demonstrated similar difficulty levels (7-point Likert scale ranging from 1 "*very easy*" to 7 "*very difficult*"; F(2,

297) = 0.636, $p = 0.530$, $\eta_P^2 = 0.004$), ensuring comparability of the assessments.

Three measures of participants' creative performance were derived from the AUT: fluency, flexibility, and uniqueness. Fluency was scored as the total number of valid responses generated by each participant, with one point per idea. Flexibility was determined by the number of response categories generated, with one point assigned per category. For the uniqueness score, all participants' responses were collected, and synonyms were removed. Responses reported by fewer than 1% of participants were scored as "2", those reported by 2–5% were scored as "1", and all other responses were scored as "0". Transfer was manifested as the average score across two different AUT items ("umbrella" and "books"). Three trained raters independently scored the responses, and the final scores were averaged across the raters. The internal consistency coefficients (ICCs) for AUT measures (fluency, flexibility, and uniqueness) ranged from 0.825 to 0.994, indicating satisfactory reliability. Further details on the ICCs are provided in Supplementary Table 2.

Experimental procedures

The feedback provider arrived 10 min early to familiarize themselves with the AUT and feedback script, which was available to the IF and OF groups as a reference for the content and requirements of the feedback (refer to Supplementary feedback script). Upon the receiver's arrival, P–R dyads were seated facing each other. For P–R dyads, personality traits were assessed using the TIPI [66] (Cronbach's $\alpha > 0.713$), need for cognition was evaluated by the NfC [67] (Cronbach's $\alpha > 0.747$), and the empathy level was measured using the IRI[68] (Cronbach's $\alpha > 0.765$). The experiment consisted of three sessions: pretest, feedback, and posttest, with a 60-s rest between each session. The entire study lasted approximately 30 min. Before the experiment began, all participants received standardized procedural instructions to ensure they fully understood the experimental protocol. The procedure was timed and programmed using E-Prime 3.0 (Psychology Software Tools, Inc., Sharpsburg, PA, USA), which ensured consistency across sessions and participants. Please see Fig. 6 (a).

In the pretest session, all participants were asked to relax and remain quiet for the first 60 s to minimize artifacts caused by head and body movements. After completing the pretest AUT, the feedback providers evaluated the receiver's creative performance, while the receivers conducted self-assessments. Neither participant could view the other's responses.

During the feedback session, the provider delivered verbal feedback based on the receiver's creative performance in the pretest. Verbal feedback was chosen because it is the most accessible and controllable form of IF, and it minimizes the risk of misinterpretation[50,69]. The feedback session consisted of four turns. For the IF group, feedback was provided for 30 s per turn (with a cue indicating the end), followed by a 30 s response from the receiver. The content of the receiver's response was not restricted. In the OF group, feedback was also provided for 30 s per turn, but the receiver rested without responding during the subsequent 30 s. In the IC group, P–R alternately reported typical features of a "laptop" for 30 s per turn. This process did not require creativity but instead involved a memory retrieval task designed to stimulate relevant information directly[25]. In the NF group, P–R dyads remained still for 4 min.

During the posttest session, receivers completed three counterbalanced AUT items: one consistent with the pretest (acquisition performance) and two different AUT items (transfer performance). Afterwards, the provider evaluated the receiver's performance, and the receiver conducted a self-assessment. Furthermore, participants' subjective evaluations were collected to further describe the feedback/communication process, including engagement, clarity, effectiveness, appropriateness, comprehensibility, and trustworthiness, along with ratings of task difficulty. The details of the subjective evaluation are provided in the Supplementary questionnaires.

Audio data acquisition and coding

With participants' consent, a digital video camera (Nikon Z5, MTS format) and two voice recorders (iFLYTEK B1Y20J, MP3 format) were used to record dyadic interaction behaviors. The steps for the coding scheme are outlined below.

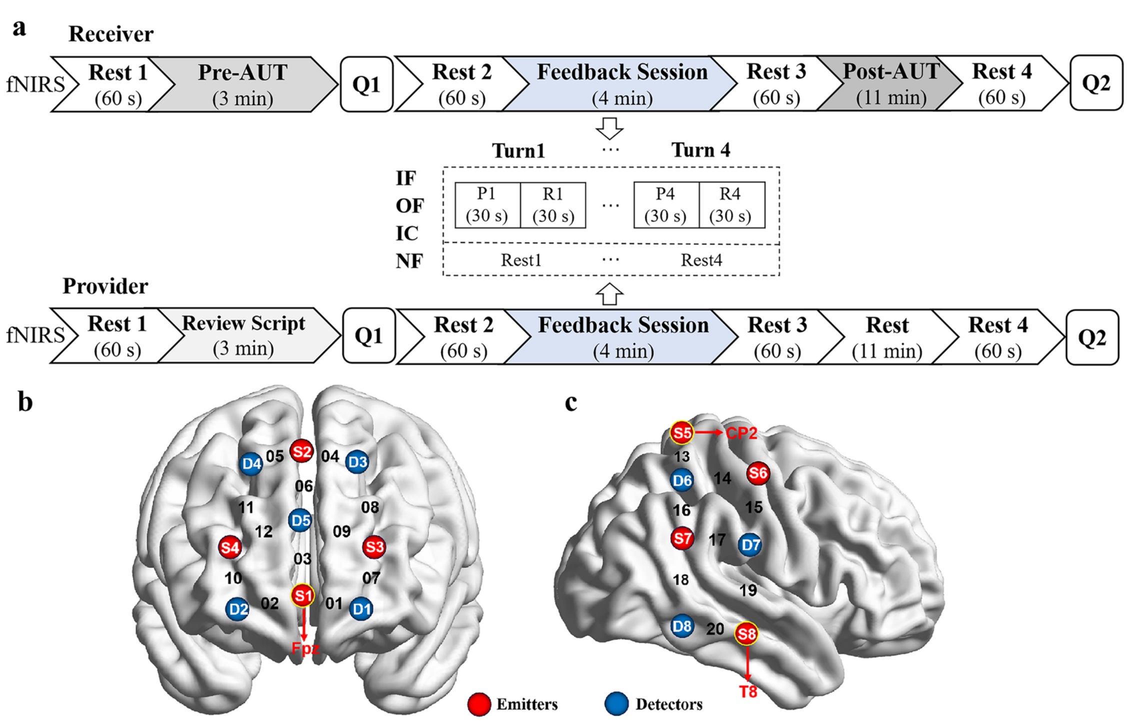

Fig. 6 | Experiment flow and fNIRS probe placement. Experiment flow chart **a**. Q1 (Questionnaire 1): self-assessment and others' assessment of creative performance; Q2 (Questionnaire 2): subjective evaluation of the feedback session. IF interpersonal feedback, OF one-way feedback, IC irrelevant communication, NF no feedback. P1: provider; R1: receiver; optode probe placement on the PFC **b** and right temporoparietal area **c**. Red and blue circles indicated emitters and detectors, respectively. Measurement channels were labeled by numbers.

Step 1: Coding scheme for feedback content

Before coding, the quality of the audio data was thoroughly checked to exclude data with insufficient interaction (i.e., less than 2 min of total communication time). Based on this criterion, no data were excluded. Two trained raters, blind to the study's purpose, classified the feedback delivered by the provider and coded the social interactions. In cases of disagreement between the two raters, a third rater was consulted to reach a consensus. Based on relevant literature[22], the identified feedback utterances were classified into two main categories (affection and cognition) and six subcategories: positive affection (e.g., "*Your answer is very original!*"), negative affection (e.g., "*Your answer is very common!*"), clarification (e.g., "*Does this answer (squirrel's home) consider the shoe as a container?*"), assessing (e.g., "*You only mentioned the shoe as a 'container' category of answers.*"), comments (e.g., "*Since this answer (flower pots) was pretty common, I thought some more original answers needed to be worked out.*"), and scaffolding (e.g., "*You could try to generate more novel answers by decomposing and reorganizing it.*"). Please refer to Supplementary Table 10 for definitions of these categories in feedback coding.

Step 2: Coding of feedback uptake

Based on the correspondence between the feedback receiver's posttest creative performance ("shoes") and the interactive dialog content, feedback uptake was coded to reflect how the receiver responded to and integrated the feedback. Specifically, two trained raters classified participants' responses into three categories: ignore, copy, and apply[70]. The code "ignore" indicated that receivers did not incorporate the received feedback into their posttest creative performance. The code "copy" signified that the receivers merely repeated, mentioned, or inserted the feedback. The code "apply" suggested that the receiver internalized the feedback and demonstrated learning from it. Total amounts and proportion scores (range: 0–1) were calculated for each level. The original coding yielded an acceptable intraclass correlation coefficient (ICC = 0.746), and any inconsistencies between raters were resolved through discussion to reach a consensus.

Step 3: Relationship between feedback uptake and creative performance

To examine the relationship between participants' changes in fluency, flexibility, and uniqueness (acquisition and transfer) and their feedback uptake (total amount and percentages of ignore, copy, and apply), Pearson correlation analyses were conducted. The FDR ($p < 0.05$) method was applied to adjust for multiple comparisons.

Step 4: Exploration of interaction sequences

Based on the results from steps 1 and 2, we coded the feedback content and feedback uptake (see Table 1). Sequential analyses were conducted to examine the probability of one behavior following another during the feedback process and determine whether these transitions reached statistical significance. The coding sequences of all participants were imported into GSEQ 5.1 to summarize the frequency of each behavior type (refer to Supplementary Table 8 and Table 9) and to calculate the adjusted residuals for behavior transitions. These residuals were used to determine whether specific behavior sequences were significant (z-score > 1.96).

Table. 1 | Example of the code definitions

N	Definition	N	Definition
A1	Positive feedback	C2	Positive feedback + negative feedback
A2	Negative feedback	…	…
B1	Clarification	C18	Scaffolding + clarification
…	…	D7	Ignore
B4	Scaffolding	D8	Copy
C1	Positive feedback + clarification	D9	Apply

fNIRS data acquisition

Functional near-infrared spectroscopy (fNIRS) data were continuously recorded using the NIRSport2 Optical Topography System (NIRx Medical Technology, LLC, Germany). The system utilized two wavelengths (760 and 850 nm) with a sampling rate of 10.17 Hz. Probes were placed over the PFC and the right temporoparietal area, regions implicated in creative idea generation[37,71], social information processing, and interactive learning[60]. For each participant, 8 emitters and 8 detectors were attached to an EEG cap following the 10–20 configuration, forming 20 measurement CHs (see Fig. 6b, c for the reference and channel locations). Specifically, the PFC was monitored using 4 emitters and 5 detectors, constituting 12 CHs, with the center point of the bottom row of optode probes located at Fpz. The right temporoparietal area was monitored using 4 emitters and 3 detectors, constituting 8 CHs, with probe placement based on CP2 and T8. The acquired coordinate data were normalized and registered to Montreal Neurological Institute (MNI) coordinates using virtual registration[72]. The anatomical locations of the probes are detailed in Supplementary Table 11.

Preprocessing

Following established preprocessing protocols[42], raw optical intensity signals were first converted into optical density. Principal component analysis (PCA) was applied to eliminate global components associated with scalp blood flow and fluctuations in blood pressure. A band-pass filter (0.01 Hz–1.00 Hz) was subsequently applied to mitigate slow drifts and high-frequency noise. To mitigate artifacts from head motion, correlation-based signal improvement (CBSI) was employed[73]. The modified Beer-Lambert law was then applied to quantify the fNIRS data, yielding measurements of oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR), and total hemoglobin concentrations[74]. Of these, HbO concentration, the most sensitive indicator of cerebral blood flow, was used as the primary index[75].

INS

A wavelet transform coherence (WTC) was employed to assess the cross-correlation of two HbO time series in each dyad as a function of frequency and time[76]. This analysis yielded a two-dimensional time-frequency coherence matrix. WTC enables the detection of localized phase-locked patterns that may be overlooked by conventional analyses such as Pearson's correlation. All possible CH combinations (20 CHs × 20 CHs, 400 CHs) were examined. Coherence values were time averaged across the feedback and rest sessions and subsequently converted into Fisher-z values, following established procedures[77]. The analysis primarily focused on the frequency band of 0.01–0.7 Hz to minimize the influence of physiological noise, such as cardiac activity (0.8–2.5 Hz) and respiratory activity (~0.15–0.3 Hz)[42]. Within the 0.01–0.7 frequency band, specific FOIs and CHs related to the task were identified. To achieve this, a series of t-tests was performed to assess whether INS during the feedback session differed from the baseline session (averaged from Rest 2 and Rest 3). The t-test results were thresholded at a significance level of $p < 0.0005$. No further corrections were applied, as this analysis primarily aimed to identify FOIs[71]. Subsequently, INS values were averaged within the identified FOIs for each CH combination, and a one-way ANOVA was conducted with Group as the independent variable. The FDR ($p < 0.05$) method was used to adjust for multiple comparisons. This procedure identified two significant FOIs: FOI 1 (0.081–0.096 Hz, 10.4–12.4 s) and FOI 2 (0.045–0.051 Hz, 19.6–22.1 s). Post-hoc analyses of INS values for all CH combinations within FOI 1 and FOI 2 were performed with Bonferroni corrections.

Validation analyses

A within-condition permutation test was used to ensure the specificity of the WTC findings. Specifically, for each group, participants were randomly shuffled and assigned to new dyads with no real interaction, and the INS was recalculated[42]. This procedure was repeated 1000 times. Significance levels ($p < 0.05$) were determined by comparing the *F*-value from the original dyads with those from the new shuffled dyads.

Directional analysis

To examine the directional characteristics of INS, we performed GCA to quantify the information flow between the provider and the receiver. The analysis focused on channel combinations showing significant INS effects. GCA is a statistical method based on the Vector Autoregressive model that estimates the causal influence between two time series[78]. We used the Multivariate Granger Causality Toolbox (MVGC) in MATLAB to compute pairwise GCA values in both directions (i.e., "provider → receiver" and "receiver → provider"). For statistical analysis, one-sample *t*-tests were first conducted to determine whether the GCA values for each direction and group (IF, OF, IC, NF) were significantly greater than zero. Then, the GCA values were entered into a 4 (Group) × 2 (Direction) mixed-design ANOVA to examine group-level effects and directional asymmetries, with resulting *p*-values corrected using the FDR method ($p < 0.05$).

Relationship between INS and creative performance

To examine the functional significance of INS, we investigated whether participants' synchronized brain activity during feedback was associated with creative performance. Pearson correlations were performed to assess the possible relevance of the creative performances (i.e., changes in fluency, flexibility, and uniqueness from pretest to posttest) and overall INS (INS averaged across the entire feedback session). The results were corrected using the FDR method ($p < 0.05$). To ensure the robustness of the findings, a permutation test was performed (1000 times; $p < 0.05$). In this test, INS values were randomly shuffled, and Pearson correlation analyses were repeated using these shuffled values to evaluate their association with creative performance.

Combination of INS and feedback uptake

To investigate the association between specific feedback uptake behaviors and INS in the IF and OF groups, we examined how different levels of feedback uptake (ignore, copy, and apply) influenced INS. To achieve this, we aligned the time course of INS data with the video recordings. The sampling rate of the INS data was reduced to 1 Hz to align the time series with the video data[60]. INS data were identified and extracted corresponding to the previously coded feedback uptake, followed by time-averaging and Fisher-*z* transformation of the INS data[77]. A 2 (IF, OF) × 3 (ignore, copy, and apply) ANOVA was then performed, focusing on significant channels, to examine the differences.

Data availability

Data availability data supporting this study are available from the corresponding author upon reasonable request.

Code availability

The code supporting this study are available on request by contacting the corresponding author.

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Author contributions

J.Y., Y.L., Y.Z., and J.L. designed the research. J.Y., Z.J., and X.L. performed the research. J.Y., Y.Z., and Y.L. analyzed the data. Z.J., X.L., and G.Z. interpreted the data. J.Y. and Y.L. wrote the paper. Y.L., G.Z., and J.L. critically reviewed the manuscript. All authors edited and approved the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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