Behavioral/Cognitive

Cognitive Reappraisal and Expressive Suppression Evoke Distinct Neural Connections during Interpersonal Emotion Regulation

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Interpersonal emotion regulation is the dynamic process where the regulator aims to change the target's emotional state, which is presumed to engage three neural systems: cognitive control (i.e., dorsal and ventral lateral PFC, etc.), empathy/social cognition (i.e., dorsal premotor regions, temporal-parietal junction, etc.), and affective response (i.e., insula, amygdala, etc.). This study aimed to identify the underlying neural correlate (especially the interpersonal one), of interpersonal emotion regulation based on two typical strategies (cognitive appraisal, expressive suppression). Thirty-four female dyads (friends) were randomly assigned into two strategy groups, with one assigned as the target and the other as the regulator to downregulate the target's negative emotions using two strategies. A functional near-infrared spectroscopy system was used to simultaneously measure participants' neural activity. Results showed that these two strategies could successfully downregulate the targets' negative emotions. Both strategies evoked intrapersonal and interpersonal neural couplings between the cognitive control, social cognition, and mirror neuron systems (e.g., PFC, temporal-parietal junction, premotor cortex, etc.), whereas cognitive reappraisal (vs expressive suppression) evoked a broader pattern. Further, cognitive reappraisal involved increased interpersonal brain synchronization between the prefrontal and temporal areas at the sharing stage, whereas expressive suppression evoked increased interpersonal brain synchronization associated with the PFC at the regulation stage. These findings indicate that intrapersonal and interpersonal neural couplings associated with regions within the abovementioned systems, possibly involving mental processes, such as cognitive control, mentalizing, and observing, underlie interpersonal emotion regulation based on cognitive reappraisal or expressive suppression.

Key words: **cognitive reappraisal; expressive suppression; hyperscanning; interpersonal brain synchronization; interpersonal emotion regulation**

Significance Statement

As significant as intrapersonal emotion regulation, interpersonal emotion regulation subserves parent–child, couple, and leader–follower relationships. Despite enormous growth in research on intrapersonal emotion regulation, the field lacks insight into the neural correlates underpinning interpersonal emotion regulation. This study aimed to probe the underlying neural correlates of interpersonal emotion regulation using a multibrain neuroimaging (i.e., hyperscanning) based on functional near-infrared spectroscopy. Results showed that both cognitive reappraisal and expressive suppression strategies successfully downregulated the target's negative emotions. More importantly, they evoked intrapersonal and interpersonal neural couplings associated with regions within the cognitive control, social cognition, and mirror neuron systems, possibly involving mental processes, such as cognitive control, mentalizing, and observing. These findings deepen our understanding of the neural correlates underpinning interpersonal emotion regulation.

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Introduction

When you try to cheer your friend up, to praise your child for good grades, or to calm down your angry colleague, you are involved in interpersonal emotion regulation (IER). IER is considered as the conscious attempt to affect others' emotions (Niven et al., 2009; Niven, 2017), which leads to either positive (Niven et al., 2012) or negative (Lopez-Perez et al., 2017) interpersonal outcomes.

Although emotion regulation research has traditionally focused on intrapersonal processes (Campos et al., 2011), there is now considerable interest in IER processes. IER is an important topic to investigate for many reasons. First, a growing number of studies have shown that IER is associated with several important outcomes, such as psychological well-being and interpersonal relationship satisfaction (Butler and Randall, 2013; Sahi et al., 2021; Springstein et al., 2023). During the COVID-19 pandemic, people often seek out social support from others (e.g., family, friends, or even strangers via helplines) with the goal of regulating their negative emotions or alleviating stress (Tepeli Temiz and Elsharnouby, 2022). Second, IER is important for individuals who have difficulties regulating their own emotions because of different psychopathologies (Akkuş and Peker, 2022; Gunn and Donahue, 2022). Third, some researchers proposed that IER could be more effective than intrapersonal emotion regulation since the regulators might have more objective views of an emotional event than the distressed targets and not be distracted by their emotions during the process of IER (Zaki and Williams, 2013; Horn and Maercker, 2016; Levy-Gigi and Shamay-Tsoory, 2017).

In the field of intrapersonal emotion regulation, research mainly focused on two typical strategies: cognitive reappraisal (CR) and expressive suppression (ES) (Goldin et al., 2008; McRae and Gross, 2020; Gutentag et al., 2022). CR involves reinterpreting the meaning of the target event that induces certain emotions, whereas ES involves inhibiting emotion-related responses/motion (e.g., facial expressions) to the emotion-eliciting event (Bebko et al., 2011). For instance, when individuals encounter an upsetting event, CR guides individuals to optimistically treat the event (this can decrease negative affect and physiological responses to negative events), but ES requires individuals to suppress emotional expressions of upset. ES may exert little or no impact on subjective feeling and even boosts negative physiological responses (Gross and Levenson, 1997) or attenuates positive affect (Fernandes and Tone, 2021). CR can decrease negative emotions and lead to more positive feelings, emotional expressions, and well-being (Gross and John, 2003; Boemo et al., 2022). Research also suggested that the CR is generally effective and adaptive relative to ES (Haga et al., 2009; McRae and Gross, 2020). Specifically, the CR strategy more consistently predicted the increase in positive affect and reduction in negative affect relative to the suppression strategy (Boemo et al., 2022). Ineffective utilization or underutilization of CR was associated with social anxiety and depression (Dryman and Heimberg, 2018; Kivity et al., 2021), whereas ES was negatively associated with positive affect (Fernandes and Tone, 2021). However, it remains unknown whether CR is more effective than ES during IER. The interpersonal CR strategy involves assisting the target in reinterpreting the meaning or context of a stimulus or modifying his/her perspective on certain issues. Accordingly, we hypothesized that CR might be more effective than ES during IER. Although interpersonal physiological synchrony was associated with dyadic emotional interaction (Coutinho et al., 2021), it is an open question whether the underlying neural substrates of these two strategies differ during IER. Most neuroscience research on IER adopted the human–computer interaction paradigm and only revealed the intrapersonal neural substrates associated with the regulators or the targets during IER (Grecucci et al., 2013; Hallam et al., 2014; Morawetz et al., 2021). These studies used the traditional single-brain neuroimaging technique and thus could hardly capture the intrapersonal and interpersonal neural underpinnings underlying IER process.

With the emergence of hyperscanning technique, researchers have proposed that interpersonal brain synchronization (IBS) or interpersonal neural coupling may play an important role in facilitating social interactions (Nguyen et al., 2019; Müller et al., 2021; Long et al., 2022; Lu et al., 2023). Specifically, previous hyperscanning research has also observed that IBS was increased at the dorsolateral PFC (DLPFC) during speed-dating (Yuan et al., 2022), communicating with positive social gestures (Balconi et al., 2021), and group creative idea generation (Lu et al., 2020). Also, an increase in IBS at the temporal-parietal junction (TPJ) was reported during cooperative problem solving (Lu et al., 2020; Nguyen et al., 2021). More importantly, existing studies have applied functional near-infrared spectroscopy (fNIRS)-based hyperscanning to explore IBS under various social interactions related to IER (Reindl et al., 2018; Nguyen et al., 2021; Kelsen et al., 2022). These hyperscanning studies have reported that the inferior frontal gyrus (IFG) not only involves in both speech production and semantic comprehension (Silbert et al., 2014), but also serves as a core region of the alignment-execution system or mentalizing system relating to understanding the underlying goals and motives of others' behavior (Shamay-Tsoory et al., 2019; Gamliel et al., 2021; Li et al., 2022). A review study has also suggested that the IFG is responsible for emotional empathy, which contributes to IER through automatic empathic reactions (e.g., imitation or emotion contagion) (Franklin-Gillette and Shamay-Tsoory, 2021). These automatic empathic reactions can help reduce the targets' distress (Brown et al., 2021; Jurkiewicz et al., 2023). In addition, the superior temporal gyrus (STG) also serves as a key brain region for speech perception (Bhaya-Grossman and Chang, 2022), the mirror neuron system (Shamay-Tsoory et al., 2019), and emotion empathy (Tholen et al., 2020; Yaniv et al., 2021). This multiple-brain research may indicate that the IER process involves brain regions, such as DLPFC, IFG, and STG. Given that the interpersonal CR strategy involves assisting the target in modifying his/her perspective on the current issues, we suggest that this strategy would enhance IBS at regions involving in mentalizing system (e.g., perspective-taking) and alignment system (e.g., emotion contagion or emotion empathy), such as IFG, TPJ, etc.

In addition, several models have been proposed to clarify the core psychological processes/stages of IER. For example, Dixon-Gordon et al. (2015) came up with the encoding-decoding model of IER, and explained how regulation-seeking behavior and regulation-delivering behavior were performed by the target and the regulator during this dynamic, dyadic process. Recently, Reeck et al. (2016) put forward the interaction model of IER and suggested that three neural systems might be recruited during IER, including the social cognition/empathy system (SC; e.g., dorsal premotor regions and TPJ), cognitive control system (CC; e.g., dorsal and ventral lateral PFC), and emotion generation system (e.g., amygdala and ventral striatum). This model subdivides the process of IER according to the mental process of the IER partners (Fig. 1). Notably, three key processes could be extracted from these IER models: (1) emotion sharing, (2) emotion regulation, and (3) feedback. First, IER begins with the target sharing negative emotions with the regulator. The process of emotion sharing during IER mainly recruits brain regions of the mirror

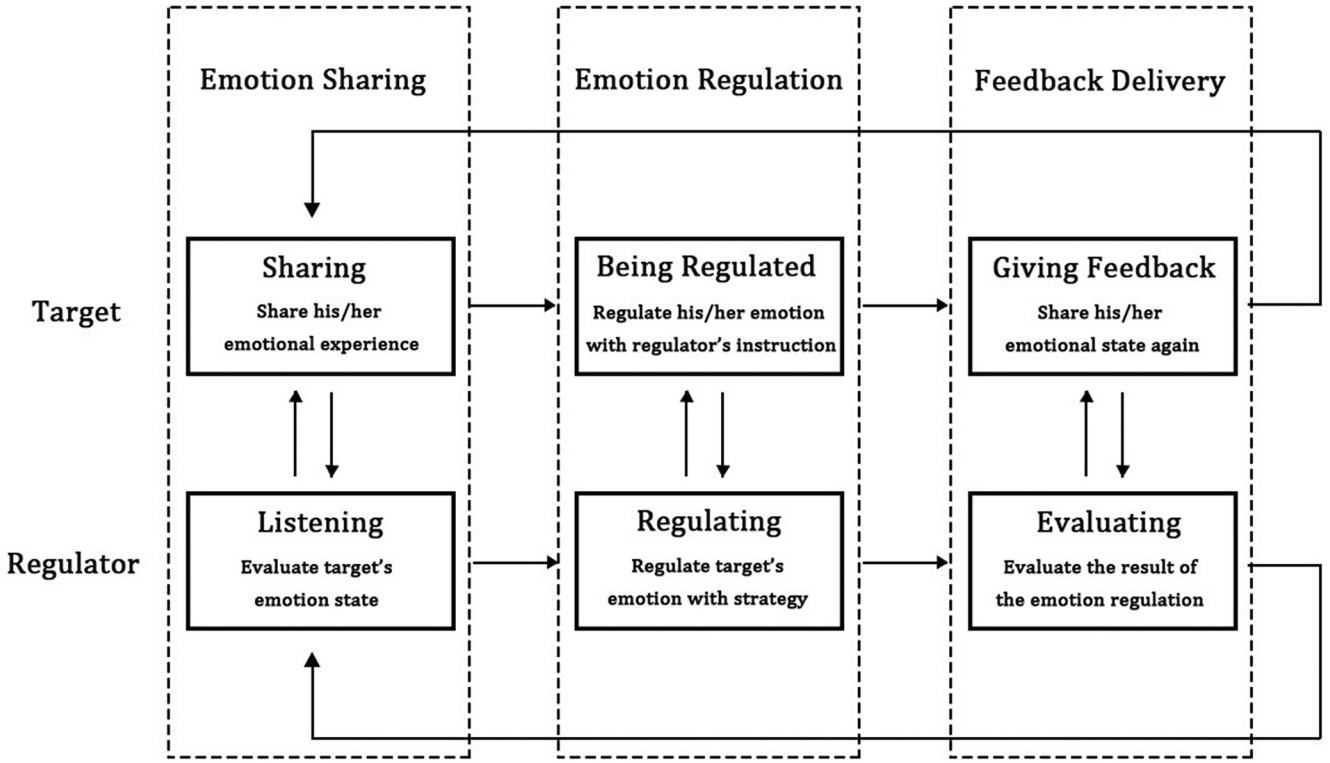

Figure 1. The processes of IER. The processes are divided into three stages, namely, emotion sharing, emotion regulation, and feedback delivery.

neuron system or mentalizing network, such as IFG, superior temporal sulcus, mPFC, and TPJ (Franklin-Gillette and Shamay-Tsoory, 2021; Schmidt et al., 2021). Second, after evaluating the interpersonal regulation needs of the target, the regulator uses a suitable IER strategy to regulate the target's negative emotions. The executive control network is involved in the process of emotion regulation during IER. This network involves regions, such as the IFG, inferior parietal lobule, DLPFC, superior temporal sulcus, and premotor cortex (Shamay-Tsoory et al., 2019). Third, the target would give positive or negative feedbacks depending on the emotional state that he or she is undergoing. If the IER succeeds, the reward system, which includes the ventral striatum, orbitofrontal cortex, and ventromedial PFC, would be activated. On the contrary, if the IER fails, the brain regions related to negative emotions would be activated (e.g., amygdala) (Grecucci et al., 2013; Hallam et al., 2014; Reeck et al., 2016).

This study also attempted to explore how two strategies affect these three IER processes and unveil the underlying neural substrates. Previous studies have suggested that emotional empathy plays an important role in the emotion sharing process, and cognitive empathy mainly operates in the emotion regulating process (Franklin-Gillette and Shamay-Tsoory, 2021). Emotional empathy involves affective sharing: feeling the physical or emotional distress of someone else. Therefore, the mirror neuron system, which involves observing others and understanding other's emotions, might play an important role in the emotion sharing stage during IER (Rizzolatti and Craighero, 2004; Franklin-Gillette and Shamay-Tsoory, 2021). On the other hand, cognitive empathy involves understanding or inferring the thoughts and motivations of others, active perspective-taking (spontaneously take the psychological perspective of others), and theory of mind (having metarepresentations of minds of others). Therefore, the mentalizing network system might be a key brain network to the emotion regulation stage during IER. In addition, research on intrapersonal emotion regulation reported that the CR strategy required more mental processes related to changing one's perspective or reinterpretation than the ES strategy. All these could help the target to recognize positive aspects of the current issue and downregulate the target's negative emotions more successfully. Therefore, we speculated that compared with the interpersonal ES strategy, the interpersonal CR strategy would involve higher neural sensitivity to neural circuits of emotion empathy or cognitive empathy and thus led to more intrapersonal functional connectivity (Fc) or IBS related to mirror neuron system, mentalizing system or cognitive control system.

Here, this study aimed to examine how two typical IER strategies (cognitive appraisal [CR]; expressive suppression [ES]) affect IER, and uncover the underlying intrapersonal and interpersonal neural substrates. To do so, we developed a new dual-brain fNIRS paradigm for simultaneously scanning the brains of the target (the one whose negative emotion was induced using a negative emotional task) and the regulator (the one who used strategies to regulate the target's negative emotions) during IER. This new paradigm artificially divided the IER process into three stages so that the neural substrates underlying the effect of strategies on IER processes could be explored. We hypothesized that, compared with the ES strategy, (1) the CR strategy would be more effective in downregulating other's negative emotions; (2) the CR strategy would also enhance Fc related to the mirror neuron system, mentalizing system, or cognitive control system, such as STG, AG, and DLPFC, etc.; and (3) the CR strategy would enhance IBS at regions involving in mentalizing system and alignment system, such as IFG, and TPJ, etc. Finally, we attempted to explore how two strategies affect the neural connections that underlie different IER stages without specific hypothesis.

Materials and Methods

Participants and design

Thirty-five pairs of same-sex (female) dyads (friends) participated in this study ($N = 70$, mean age $= 19.60 \pm 1.48$). *A priori* power analysis using G*power 3.1 (Faul et al., 2007) was performed to estimate the sample size necessary for the interaction effect of STRATEGY × STAGE at 0.80 power. The effect size was set to effect size $f = 0.25$. Accordingly, the required sample size is 28 dyads. We also examine the sample sufficiency using a *post hoc* g*power computation. Results showed that most of the power values exceeded 0.79 (e.g., interaction effect of STRATEGY × STAGE, main effect of STRATEGY, *t* tests, etc.), which indicate the sample size is satisfactory in this study. All participants are native Chinese college students, right-handed, and heterosexual. Participants had normal or corrected-normal vision and reported no recent traumatic life event or history of neurologic, psychiatric, or mood disorders. Each participant was paid ¥ 60 for participation. The experiment consisted of a 2 (strategies: CR vs. ES) × 3 (stages: emotion sharing vs. emotion regulation vs. feedback) factorial design, with IER strategies as the between-subject factor and IER stages as the within-subject factor. All dyads were randomly assigned to the CR or ES group. One dyad was excluded from all analyses because of missing data. Consequently, the CR and ES group comprised of 18 (mean age: 20.09 ± 1.21) and 16 dyads (mean age: 19.11 ± 1.75), respectively. Age was matched between the two groups ($t_{(66)} = 0.99$, $p = 0.31$).

Informed consent was obtained from all the participants before the start of the experiment. The study protocol was approved by the University Committee on Human Research Protection of East China Normal University.

Experimental materials

Relationship Closeness Inventory. Relationship closeness was measured using the Relationship Closeness Inventory (Berscheid et al., 1989). Two dimensions were extracted from this scale: acquaintance length and relationship closeness. The acquaintance length was assessed by a single item, "How many months they had known each other?" The relationship closeness was assessed based on four items: (1) "How well does X know you?"; (2) "How well do you know X?"; (3) "In general, how close are you and X?"; (4) "In terms of information of a personal nature, how much do you confide in X?". "X" indicated their dyadic partner. These questions were rated on 5 point Likert scales. The internal consistency for these four questions was acceptable (Cronbach's $\alpha = 0.87$) in this sample.

Pre-experiment practice on strategies. The pre-experiment practice on strategies included (1) comprehending the definitions of IER strategies and (2) going through relative real-life examples. Three IER examples were presented to the regulators in each group. Three examples for the CR strategy were as follows: (1) "Your roommate accidentally spoils the last bottle of milk on the floor of your dormitory. The fact that she has no milk to drink as well as she must deal with the mess that makes she really upset. In this case, you would say 'Why don't we take this opportunity to clean our dormitory together and make it just like a new place?' Your roommate can't agree with you more. She clams herself down and starts cleaning up with you." (2) "Your classmate next door watched a scary movie alone in the dorm late at night and is too scared to go to the washroom alone. She texted you, asking you to go to the washroom with her. In this case, you would say 'It's just a movie, there are no ghosts in the real world. Even if ghosts do exist, they only punish those who do evil. There is nothing to be afraid of.' She listened to you and became less nervous." (3) "A friend of you reported her experimental procedure to her tutor in a team meeting. The tutor seriously pointed out a couple of simple mistakes toward the procedure, asking her to redesign her experiment and report it again next week. Your friend got back to the dorm so depressed that she wept bitterly. In this case, you would say 'Your tutor was trying to avoid unpredictable mistakes during the formal experiment. What he did is for your own good.' Your friend gets refreshed, and starts to redesign the procedure immediately." Three examples for the ES strategy were as follows: (1) "Your classmates are about to give a speech to 2000 people. It was the first time for her to speak in front of so many people. Backstage, getting ready, she was so nervous that her hands couldn't stop shaking. In this case, you said to her, 'Hide your negative emotions during your speech or you'll screw it up.' She tried to calm down and stop shaking her hands any more." (2) "Before a math competition, your classmate got a call from her mother telling her that her dog had gone to the heaven. Your classmate was so sad that she couldn't help crying after hearing the words. In this case, you would say 'You'd better calm down and hide your emotions regarding the upcoming competition.' She held back her tears and started to get prepared for the competition." (3) "Your friend met a subway breakdown, then she was scolded by her supervisor for late. Walking out of the office, she felt wronged, angry and resentful toward her supervisor. In this case, you would say 'You'd better not offend your boss. Let's be patient and calm down.' Your friend tried to calm down, sit back and get to work."

Emotional video clips. Six ~2 min video clips, which presented scenarios of natural disasters, assaulting events or human wars, were obtained from video sharing websites and used to induce negative emotions of the target.

To ensure that the video clips could successfully induce the target's negative emotions, 30 additional female participants (mean = 19.90, SD = 1.47) were recruited to rate their emotional valence (1 = very negative; 7 = very positive) and arousal (1 = very calm; 7 = extremely excited) for each clip on 7 point Likert-type scales. Based on these ratings, three of the six video clips induced moderate levels of negative emotions (i.e., sadness, fear, and anger) and were selected for the formal experiment. Meanwhile, these three video clips did not differ in ratings on emotional valence and arousal ($F_{(2,58)\ valence} = 1.20$, $p > 0.05 = 0.31$; $F_{(2,58)\ arousal} = 1.08$, $p > 0.05 = 0.42$). The sequence of the three videos clips was counterbalanced across dyads.

Emotion Rating Scale. Participants rated their emotional states using the 14 item Emotion Rating Scale (Gross, 1998). This scale contains six items of positive emotions (amusement, contentment, happiness, interest, relief, and relax) and eight items of negative emotions (anger, contempt, embarrassment, fear, pain, disgust, sadness, and tension). These items were scored on a 9 point Likert sale, ranging from 1 (not at all) to 9 (extremely). Participants were also asked to rate their general emotional arousal on a single item using a 9 point Likert scale ranging from 1 (very calm) to 9 (very excited). We created a positive emotion score by averaging the scores of six positive emotions and a negative emotion score by averaging the scores of eight negative emotions. Moreover, participants rated the IER effectiveness by scoring on a single item: "How effective do you think this regulation was?" using a 9 point Likert scale ranging from 1 (not at all) to 9 (extremely) immediately after each IER task.

Experimental procedures

In each dyad, one participant was randomly assigned as the regulator and the other as the target. Five days before the experiment, the regulators were asked to learn and practice the CR or ES strategy based on a practicing material which contained the instructions on the CR or ER strategy and five relative examples. The targets were not told or explained what these two strategies referred to before the formal experiment. The targets were told that the regulators would use CR or ES strategy to downregulate their negative emotions after undergoing a negative emotion induction session. Upon arrival, the participants in each dyad were asked to sit in chairs and complete the Relationship Closeness Inventory. During the experiment, the participants sat with a 90° angle (Fig. 2*a*). There was a laptop in front of the target, and a desk computer in front of the regulator. The latter was connected to the fNIRS system. Participants could not see the screen of each other. In each IER task session, a beep sound sent by the desktop computer prompted the regulator and the target to focus on the instructions on their respective screen, and prepare for entering to the coming task session. Except specific prompts, participants could switch between attending to the screen and partner freely.

The experiment procedure consisted of three resting sessions and three IER sessions. In each resting session, participants were asked to remain still and wait for the following task session (Fig. 2*b*). Each IER session consisted of a negative emotion induction process and three

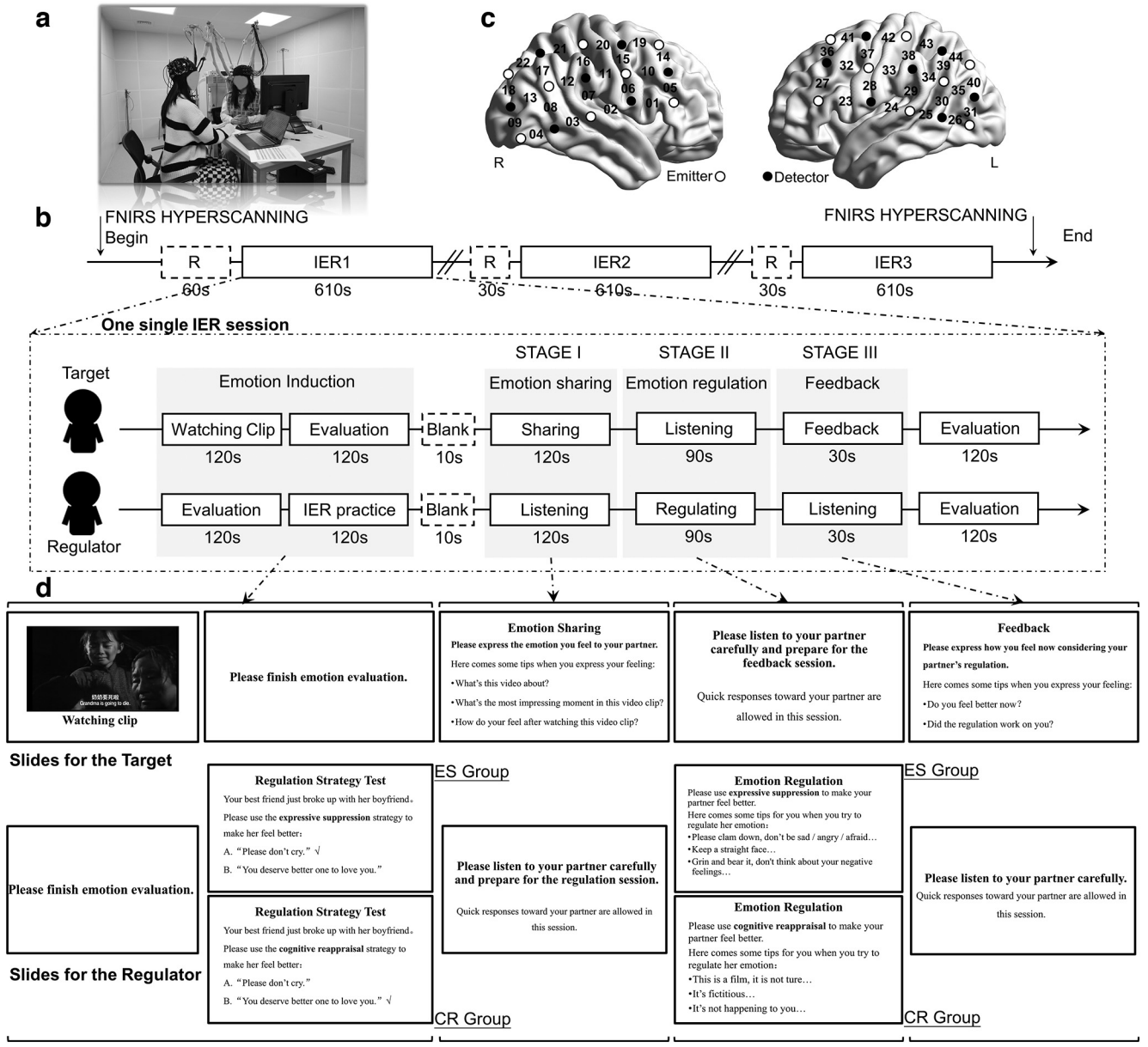

Figure 2. The experimental design. ***a***, Experimental setting. ***b***, Study design. ***c***, Optode probe set on the bilateral prefrontal, temporal, and parietal regions. ***d***, Examples for slides on the screens of the target and the regulator.

substages of IER: emotion sharing (Stage I), emotion regulation (Stage II), and feedback (Stage III). During the emotion induction process, the target watched a 120 s video clip and then rated her emotional states using the Emotion Rating Scale. Meanwhile, the regulator was also asked to rate her emotional states and completed a test for the IER strategy. This test was designed to ensure that the regulator had successfully acquired the IER strategy and understood the IER task (Fig. 2*d*). After negative emotion induction, targets of the whole sample exhibited quite low positive emotion scores (1.64 ± 0.78) and moderate negative emotion scores (5.00 ± 1.00). This suggested that these video clips successfully induced targets' negative emotions.

Next, during the emotion sharing stage, the target shared her negative feelings with the regulator referring to the three questions on the screen in front of her. These questions were as follows: "What's this video about?" "What's the most impressing moment in this video clip?" and "How do you feel after viewing this video?" The regulator needed to listen to the target carefully and give some simple interactive responses, such as nodding head, say "yes," or making facial expression (Fig. 2*d*).

During the emotion regulation stage, the regulator used the CR strategy or ES strategy to downregulate the target's negative emotions. Some tips were presented on the screen in front of the regulator to ensure that the regulator used the correct IER strategies (e.g., tips like "It's just a film," "It's fictitious," and "It's not happening to you" were included in the CR group; tips like "please control your emotions by not expressing them," "please keep your face calm," and "grin and bear it, don't think about your negative feelings" were included in the ES group). The regulator was told that the tips on the screen were no more than suggestions. She is supposed to use her own words to implement the relative strategy (Fig. 2*d*). The targets were asked to carefully listen to the regulator and focus on the IER process. To ensure that the targets carefully followed the regulator's regulation instructions, the whole process was under the supervision of the laboratory assistant.

Eventually, during the feedback stage, the target gave her feedback to the regulator referring to two questions on the screen: (1) "How do you feel now?" (2) "How effective do you find the regulation at altering your emotions?" Meanwhile, the regulator should listen to the target carefully. Simple responses were also allowed while listening. The target was asked

to freely share her current feeling referring to these two cues rather than rate on a 5 or 9 point Likert scale.

Immediately after each IER session, participants in each dyad were asked to rate their emotional states and emotional arousal again, and scored the IER effectiveness.

fNIRS data acquisition

An ETG-7100 optical topography system (Hitachi Medical) was used to collect imaging data of the regulator and the target simultaneously. The absorption of two near-infrared light wavelengths (695 and 830 nm) was measured with a sampling rate of 10 Hz. The modified Beer-Lambert law was used to convert the raw optical intensities to the relative oxyhemoglobin (HbO) and deoxy-hemoglobin concentrations. The present study focused on the HbO signal as proven to be sensitive to cerebral blood flow compared with the deoxy-hemoglobin (Hoshi, 2007) and commonly analyzed in fNIRS studies (Jiang et al., 2015; Lu et al., 2020; Pan et al., 2020).

Two 3×5 optode probe sets (eight emitters and seven detectors forming 22 measurement points with 3 cm optode separation for each probe set) were used to cover each participant's bilateral frontal, temporal, and parietal regions (Fig. 2*c*). The middle optodes of the lowest probe rows on the patches was placed at T3 and T4 based on the international 10–20 system (Okamoto et al., 2004). To ensure the consistency of the positions within and across participants dyads, all probe sets had been examined and adjusted before the experiment started. The virtual registration method was used to determine the correspondence between the NIRS channels (CHs) and the measurement points on the brain (Tsuzuki et al., 2007). The MNI coordinates of the CHs of a typical participant are presented in Table 1).

Behavioral analysis

In order to examine whether the IER regulation was successful, a series of one-sample *t* tests (using 0 as the test value) were performed on the emotional change, and arousal change (i.e., change in the scores of positive/negative emotions and emotional arousal; see Emotion Rating Scale). Before the abovementioned *t* tests, the final scores of positive/negative emotions and emotional arousal before or after IER, were obtained by averaging relative scores from three IER task sessions, respectively. Next, the emotional change was calculated by subtracting the scores of positive/negative emotions before IER from those after IER. The arousal change was obtained in the same way.

Furthermore, a series of independent-sample *t* tests using STRATEGY (CR vs. ES) as independent variable were conducted on the IER effectiveness, emotional change (including positive and negative emotions), and arousal change for the targets and regulators, respectively.

fNIRS data analysis

Preprocessing. Preprocessing of the fNIRS data was performed in MATLAB (The MathWorks). The principal component analysis was used to remove the global components in the fNIRS data (Zhang et al., 2016). Moreover, the correlation-based signal improvement method was used to remove head motion artifacts (Cui et al., 2010).

Neural coupling analysis. We assessed Fc/IBS based on the cross-correlations between HbO time-series across CHs within/between participants (Liu et al., 2021). Cross-correlation is particularly suited to assess how two signals move together over time (Fig. 3).

We calculated 44×44 Fc matrices of three IER stages (sharing, regulation, and feedback) in each IER task session for the targets or regulators. Similarly, 44×44 IBS matrices of three IER stages were also calculated for each IER task session. The final 44×44 Fc/IBS matrix of each IER stage was obtained by averaging those from three IER task sessions (e.g., the 44×44 Fc matrix of the emotion sharing stage was calculated by averaging 44×44 Fc matrices of the emotion sharing stages from three IER task sessions). This resulted in a total of 946 intrapersonal connections (i.e., Fc) for each target/regulator and 1936 interpersonal connections (i.e., IBS) for each dyad (Fig. 3). The averaged 44×44 Fc/IBS matrices of three resting sessions was obtained in the same way. After baseline correction (Fc/IBS matrix$_{[\text{task session}]}$-Fc/IBS matrix$_{[\text{resting session}]}$), Fc and IBS values were transformed using Fisher's *r*-to-*z* transformation that could help increase normality of data distribution (Simony et al., 2016). The session-averaged and baseline-corrected Fc and IBS matrices of the CR and ES groups were also presented (Extended Data Figs. 5-1, 5-2, 6-1).

Two-way mixed-design ANOVAs with STRATEGY as the between-subject factor and STAGE as the within-subject factor were conducted on Fc and IBS. The resulting *p* values were corrected by false discovery rate (FDR) method. Further Bonferroni-corrected *post hoc* test or simple effect analysis would be performed when necessary.

Eventually, bivariate Pearson's correlations were calculated to reveal brain–behavior relationship for significant Fc and IBS. The resulting *p* values were also FDR-corrected.

Validation analysis on neural couplings. The results of Fc and IBS were validated based on permutation tests (Lu et al., 2023). Regarding Fc, the phase randomization was applied to individual preprocessed

Table 1. The MNI coordinates of channels[a]

	MNI coordinates (mm)			Brodmann areas	
CHs	*x*	*y*	*z*	Location	Percentage
CH01	63	17	17	IFG, Broca's area	97.39
CH02	71	−14	9	Primary and auditory association cortex	41.59
CH03	72	−41	1	STG	50.95
CH04	60	−67	−6	Fusiform gyrus	56.79
CH05	56	33	25	DLPFC	84.45
CH06	68	−1	24	Premotor and supplementary motor cortex	68.89
CH07	71	−29	22	Supramarginal gyrus part of Wernicke's area	52.15
CH08	65	−59	13	STG	42.96
CH09	51	−82	−1	V3	78.20
CH10	58	13	38	DLPFC	71.70
CH11	68	−17	37	Primary somatosensory cortex	56.21
CH12	67	−46	33	Supramarginal gyrus part of Wernicke's area	100.00
CH13	55	−74	20	Angular gyrus, part of Wernicke's area	65.44
CH14	45	26	50	Includes frontal eye fields	91.81
CH15	58	−6	50	Premotor and supplementary motor cortex	75.77
CH16	66	−31	48	Supramarginal gyrus part of Wernicke's area	57.09
CH17	58	−64	37	Angular gyrus, part of Wernicke's area	62.59
CH18	37	−89	27	V3	100.00
CH19	44	10	59	Premotor and supplementary motor cortex	79.92
CH20	56	−20	58	Primary somatosensory cortex	92.86
CH21	56	−49	55	Supramarginal gyrus part of Wernicke's area	100.00
CH22	42	−79	41	V3	76.09
CH23	−63	9	17	IFG, Broca's area	55.81
CH24	−68	−19	14	Primary and auditory association cortex	58.26
CH25	−70	−45	5	STG	58.54
CH26	−61	−67	1	Fusiform gyrus	49.65
CH27	−54	26	27	DLPFC	74.65
CH28	−66	−8	29	Premotor and supplementary motor cortex	56.77
CH29	−68	−36	27	Supramarginal gyrus part of Wernicke's area	82.77
CH30	−65	−59	16	STG	51.70
CH31	−53	−79	6	V3	82.35
CH32	−58	7	39	DLPFC	41.79
CH33	−66	−22	38	Primary somatosensory cortex	60.59
CH34	−65	−48	35	Supramarginal gyrus part of Wernicke's area	100.00
CH35	−57	−70	27	Angular gyrus, part of Wernicke's area	95.24
CH36	−43	21	54	Frontal eye fields	88.70
CH37	−57	−11	50	Premotor and supplementary motor cortex	60.23
CH38	−63	−37	48	Supramarginal gyrus part of Wernicke's area	85.51
CH39	−57	−63	41	Supramarginal gyrus part of Wernicke's area	57.25
CH40	−45	−84	28	V3	54.84
CH41	−40	9	62	Premotor and supplementary motor cortex	90.04
CH42	−54	−21	59	Primary somatosensory cortex	94.80
CH43	−55	−49	54	Supramarginal gyrus part of Wernicke's area	100.00
CH44	−51	−68	47	Angular gyrus, part of Wernicke's area	45.61

[a]The coordinates of all channels estimated using the 3D locator. Percentage indicates that the scope of each channel belongs to the corresponding cortical areas.

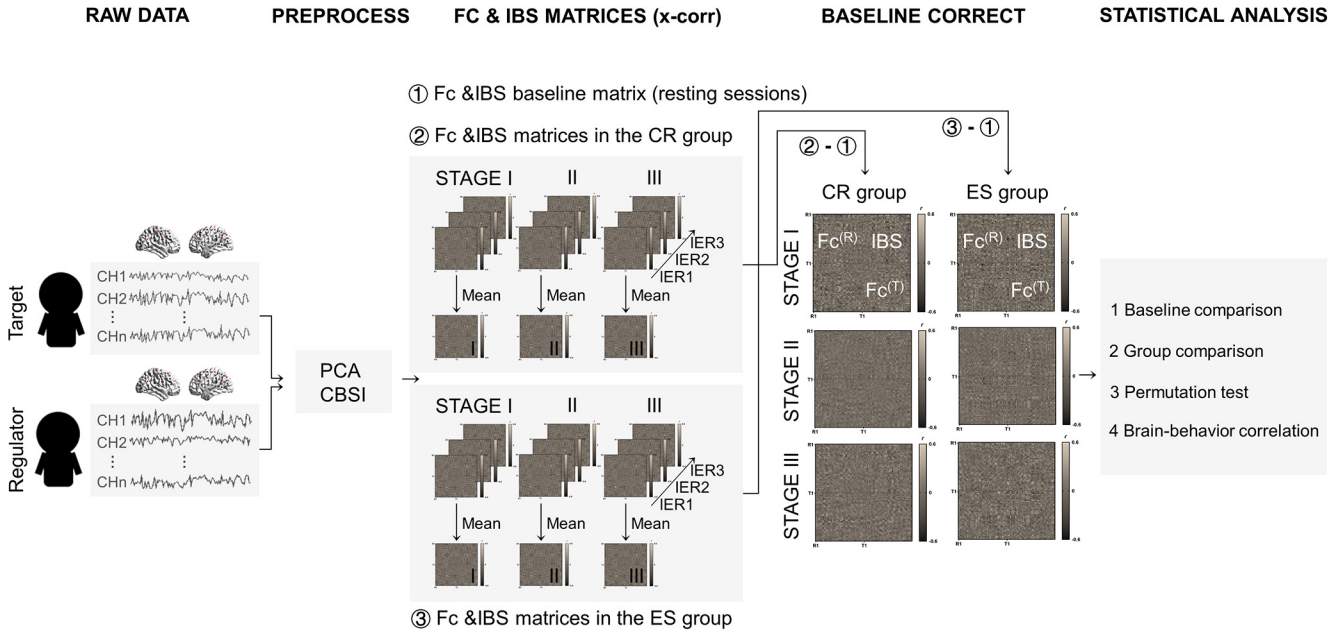

Figure 3. Analysis pipeline of the fNIRS data. Raw data from each participant were first preprocessed using the principal component analysis (PCA) and the correlation-based signal improvement method (CBSI). Next, each IER block was segmented into three stages. Based on this, we computed the Fc and IBS matrices for three stages, and then obtained the block-aggregated Fc and IBS matrices by averaging those in three blocks. Eventually, these Fc and IBS matrices were baseline-corrected by subtracting Fc/IBS values of the resting sessions, and submitted to the following statistical tests.

HbO signals to generate surrogate data (Simony et al., 2016). Similar Fc analysis was conducted on the surrogate data for the target/regulator in each dyad. This permutation process repeated 1000 times. This could examine whether significant Fc resulted from long-range temporal autocorrelation in the BOLD signal. Regarding IBS, the preprocessed HbO signals of all participants were reshuffled randomly, which led to 34 repaired dyads (nominal dyads) (Reindl et al., 2018). Similar IBS analysis was then conducted on the data of nominal dyads. This permutation process also repeated 1000 times. This could help examine whether significant IBS was specific to IER process.

Data and code availability

The data and code used to support the findings of this study are available from the corresponding author upon request. The data can only be for research use. If the associated research is to be published, the statement, "The data and code were acquired from the Shanghai Key Laboratory of Mental Health and Psychological Crisis Intervention, School of Psychology and Cognitive Science, East China Normal University" is required in the manuscript.

Results

Behavioral results

Interpersonal relationship closeness check

The interpersonal relationship closeness was confirmed using scores on the Relationship Closeness Inventory. Independent-sample t tests showed that the CR group and ES group did not differ in how long they had known each other ($t_{(66)} = -0.118$, $p = 0.691$), how well her friend had known her ($t_{(66)} = 0.886$, $p = 0.907$), how well she had known her friend ($t_{(66)} = 0.466$, $p = 0.948$), how closed they had been ($t_{(66)} = 1.287$, $p = 0.708$), and how much she had confided in her friend ($t_{(66)} = 1.752$, $p = 0.090$). Accordingly, these two groups did not differ in interpersonal relationship closeness.

IER effectiveness check

One-sample t tests on the emotional change and arousal change of the targets showed a significant decrease in negative emotions (-1.94 ± 0.85; $t_{(33)} = -13.302$, $p < 0.001$, Cohen's $d = 3.21$) and emotional arousal (-1.53 ± 1.59; $t_{(33)} = -5.60$, $p < 0.001$, Cohen's $d = 1.36$), but a significant increase in positive emotions (0.89 ± 0.85; $t_{(33)} = 6.11$, $p < 0.001$, Cohen's $d = 1.48$). These results indicated a success in IER.

Similar one-sample t tests showed that the regulators' positive emotions significantly were decreased (-0.57 ± 0.82; $t_{(33)} = -4.04$, $p < 0.001$, Cohen's $d = 0.98$); negative emotion (0.29 ± 0.55; $t_{(33)} = 3.08$, $p < 0.001$, Cohen's $d = 0.75$) and emotional arousal was increased (1.04 ± 1.26; $t_{(33)} = 4.82$, $p < 0.001$, Cohen's $d = 1.17$).

Group comparison of the behavioral indices

Independent-sample t tests compared the targets' IER effectiveness, emotional change, and arousal change between the CR group and the ES group. Results showed significantly higher IER effectiveness in the CR group (6.54 ± 0.79) than in the ES group (4.88 ± 1.81) ($t_{(20.05)} = 3.40$, $p = 0.003$, Cohen's $d = 1.19$). No other difference was observed (p values > 0.05). Similar independent-sample t tests on those of regulators showed that the regulators' increase in emotional arousal was stronger in the CR group (1.44 ± 1.14) compared with the ES group (0.58 ± 1.26) ($t_{(32)} = 2.09$, $p = 0.044$, Cohen's $d = 0.72$). No other difference was observed (p values > 0.05).

We also conducted further analyses on whether changes in specific emotions differed between conditions. Independent-sample t tests compared the targets' changes in specific emotions between the CR and ES group. No significant difference was observed (p values > 0.05). Similar independent-sample t tests on those of regulators showed that increase in amusement was stronger in the CR group (0.26 ± 1.36) than in the ES group (-0.90 ± 0.86) ($t_{(32)} = 2.92$, $p = 0.006$, Cohen's $d = 1.02$); decrease in fear was stronger in the CR group (-0.22 ± 0.38) than in the ES group (0.17 ± 0.50) ($t_{(32)} = -2.57$, $p = 0.015$, Cohen's $d = 0.88$). No other significant difference was observed (p values > 0.05).

Pairwise correlations between the behaviors of the targets and regulators

Pearson correlations revealed that the targets' IER effectiveness was positively correlated with the regulators' IER effectiveness

($r = 0.54$, $p = 0.02$) and positive emotional change ($r = 0.51$, $p = 0.03$) in the CR group (Table 2). In the ES group, the targets' positive emotional change was positively correlated with the regulators' arousal change ($r = 0.71$, $p = 0.002$), but the targets' negative emotion decreased along with the increase in the regulators' IER effectiveness ($r = -0.52$, $p = 0.04$; Table 3).

Table 2. The pairwise correlations between behavioral indices in the CR group[a]

	T1	T2	T3	T4	R1	R2	R3	R4
T1 IER effectiveness	1	1.69	0.06	0.20	0.54*	−0.22	0.51*	−0.13
T2 Δ emotional arousal		1	−0.28	0.38	0.21	−0.21	0.01	−0.23
T3 Δ positive emotion			1	−0.74***	0.33	0.25	0.17	−0.04
T4 Δ negative emotion			<0.001	1	−0.16	−0.23	−0.11	−0.06
R1 IER effectiveness	0.02				1	−0.06	0.69**	−0.39
R2 Δ emotional arousal						1	−0.15	0.35
R3 Δ positive emotion	0.03				0.001		1	−0.69**
R4 Δ negative emotion							0.001	1

[a]R, Regulator; T, target; Δ, value change.
*$p < 0.05$. **$p < 0.01$. ***$p < 0.001$. p values of the significant correlations were presented in the lower triangle.

Table 3. The pairwise correlations between behavioral indices in the ES group[a]

	T1	T2	T3	T4	R1	R2	R3	R4
T1 IER effectiveness	1	0.08	0.68**	−0.07	0.12	0.43	0.48	−0.07
T2 Δ emotional arousal		1	0.07	0.72**	−0.36	0.43	−0.05	0.04
T3 Δ positive emotion	0.004		1	−0.31	0.28	0.71**	0.24	−0.21
T4 Δ negative emotion		0.002		1	−0.52*	0.29	−0.06	0.39
R1 IER effectiveness				0.04	1	−0.05	0.40	−0.19
R2 Δ emotional arousal			0.002			1	0.06	−0.04
R3 Δ positive emotion							1	−0.28
R4 Δ negative emotion								1

[a]R, Regulator; T, target; Δ, value change.
*$p < 0.05$. **$p < 0.01$. p values of the significant correlations were presented in the lower triangle.

Brain imaging results

Fc of the targets

Two-way mixed-design ANOVAs using STRATEGY as the between-subject factor and STAGE as the within-subject factor were conducted on the Fc of the targets across CHs. Results showed significant main effects of STRATEGY on multiple connections ($ps_{fdr} < 0.05$), such as Fc of T8-T23 (rSTG-lIFG), T30-T32 (lSTG-lDLPFC), and T3-T25 (rSTG-lSTG), etc. (Fig. 4*a*). T (n) denotes CH(n) of the target (e.g., T1 denotes CH1 of the target). *Post hoc* tests showed that most of these connections were higher in the CR group than in the ES group (Table 4).

Results also revealed several significant interaction effects of STRATEGY × STAGE on the following Fc: T5-T8 ($F_{(2,64)} = 9.70$, $p_{fdr} = 0.040$, $\eta^2 = 0.23$), T22-T28 ($F_{(2,64)} = 10.37$, $p_{fdr} = 0.040$, $\eta^2 = 0.25$), T33-T34 ($F_{(2,64)} = 15.08$, $p_{fdr} = 0.004$, $\eta^2 = 0.32$), and T42-T43 ($F_{(2,64)} = 9.80$, $p_{fdr} = 0.046$, $\eta^2 = 0.24$; Fig. 5*a*; for descriptive details, see Table 5).

Regarding the Fc of T5-T8 (rDLPFC and rSTG), simple effect analysis showed that two groups only differed at the emotion sharing stage (CR > ES; $p = 0.002$, Cohen's $d = 1.16$). No difference was observed at other stages. A similar pattern was observed for the Fc of T33-T34 (right primary somatosensory cortex and rSMG; CR > ES; $p < 0.001$, Cohen's $d = 1.35$; Fig. 5*c*). The following PSC denotes the primary somatosensory cortex. Further analysis showed that the Fc of T5-T8 at the sharing stage was higher than that at the feedback stage in the CR group ($p = 0.013$, Cohen's $d = 0.68$), whereas a reverse pattern was observed in the ES group (sharing < feedback; $p = 0.019$, Cohen's $d = 0.63$). The Fc of T33-T34 at the sharing stage was higher than that at the feedback stage in the CR group ($p = 0.005$, Cohen's $d = 0.68$). However, the Fc of T33-T34 at the sharing stage was lower than that at the regulation stage ($p = 0.011$, Cohen's $d = 0.69$) and feedback stage in the ES group ($p = 0.006$, Cohen's $d = 0.85$).

Regarding the Fc of T22-T28 (rV3 and left premotor and supplementary motor cortex [lMotor]), simple effect analysis showed that two groups only differed at the emotion sharing stage (CR < ES; $p < 0.001$, Cohen's $d = 1.59$). No difference was observed at other stages. A similar pattern was also observed for the Fc of T42-T43 (right primary somatosensory cortex and rSMG; CR < ES; $p = 0.008$, Cohen's $d = 0.98$). Further analysis showed that the Fc of T22-T28 at the sharing stage was lower than that at the regulation stage ($p = 0.002$, Cohen's $d = 0.89$) and the feedback stage in the CR group ($p = 0.003$, Cohen's $d = 0.84$). The Fc of T42-T43 at the sharing stage was higher than that at the feedback stage in the ES group ($p = 0.015$, Cohen's $d = 0.80$).

Fc of the regulators

Two-way mixed-design ANOVAs using STRATEGY as the between-subject factor and STAGE as the within-subject factor were conducted on the Fc of the regulators across CHs. Results showed significant main effects of STRATEGY on the Fc of R1-R28 (rIFG and lMotor), and Fc of R1-R36 (rIFG and right frontal eye field; Fig. 4*b*). R(n) denotes CH(n) of the regulator (e.g., R1 denotes CH1 of the regulator). *Post hoc* tests showed that the Fc of R1-R28 was significantly higher in the CR group than in the ES group, whereas the Fc of R1-R36 was significantly lower in the CR group than in the ES group (Table 4).

Results also showed a significant interaction effect of STRATEGY × STAGE on the Fc of R29-R37 (lSMG and lMotor; $F_{(1.64,\ 52.55)} = 12.82$, $p_{fdr} = 0.020$, $\eta^2 = 0.29$; Fig. 5*b*). Simple effect analysis showed that the Fc of R29-R37 of two groups only differed at the emotion sharing stage (CR < ES; $p = 0.002$, Cohen's $d = 1.17$; Fig. 5*d*). Further analysis showed that the Fc of R29-R37 at the sharing stage was higher than that at the regulation stage ($p = 0.002$, Cohen's $d = 0.87$) and feedback stage in the ES group ($p = 0.013$, Cohen's $d = 1.01$).

Meanwhile, results also showed a marginal interaction effect of STRATEGY × STAGE on the Fc of R4-R44 (right fusiform gyrus and lAG; $F_{(1.62,\ 51.62)} = 10.61$, $p_{fdr} = 0.049$, $\eta^2 = 0.25$). Further analysis showed that the Fc of R4-R44 of two groups only differed at the feedback stage (CR > ES; $p = 0.002$, Cohen's $d = 1.12$). No difference was observed at other stages. Further analysis showed that the Fc of R4-R44 at the feedback stage was higher than that at the regulation stage in the CR group ($p = 0.01$, Cohen's $d = 0.74$), whereas a reverse pattern was observed in the ES group ($p = 0.02$, Cohen's $d = 0.67$).

IBS during IER

Two-way mixed-design ANOVAs using STRATEGY as the between-subject factor and STAGE as the within-subject factor were conducted on the IBS across CHs. Results showed a significant main effect of STRATEGY on the IBS of R22-T21 (rV3 and rSMG) and R23-T3 (lIFG and rSTG; Fig. 4*c*). *Post hoc* tests showed that the IBS of R22-T21 was significantly lower in the CR group than in the ES group, whereas a reverse pattern was observed for the IBS of R23-T3 (Table 4).

Results also showed a significant interaction effect of STRATEGY × STAGE on the IBS of R4-T27 (right fusiform gyrus and lDLPFC; $F_{(1.47,\ 47.02)} = 15.38$, $p_{fdr} = 0.007$, $\eta^2 = 0.33$),

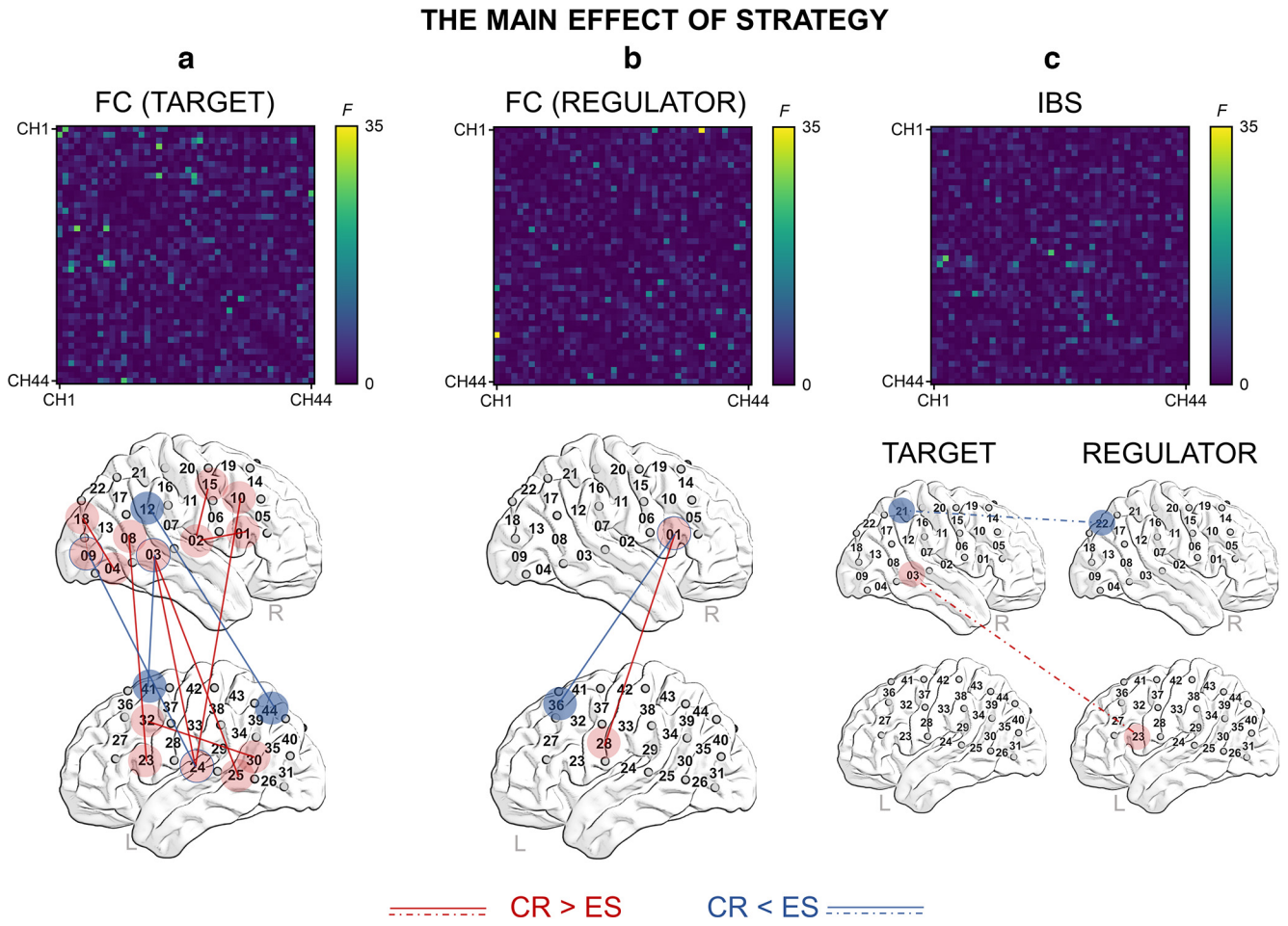

Figure 4. Fc and IBS with significant main effects of STRATEGY. The FDR-corrected *F*-value map (top) and significant neural connections (bottom) resulting from two-way mixed-design ANOVAs on the Fc of the targets (***a***), regulators (***b***), and IBS (***c***). See relative permutation tests in Extended Data Figure 4-1.

Table 4. Main effects of STRATEGY on Fc and IBS[a]

CH	Location	CR (mean ± SD)	ES (mean ± SD)	$F_{(1,32)}$	p_{fdr}	η_p^2	*Post hoc*
T1-T2	rIFG-rPAC[b]	−0.02 ± 0.23	−0.40 ± 0.46	26.1	0.007	0.45	CR > ES
T2-T15	rSMC-rMotor[c]	0.12 ± 0.32	−0.23 ± 0.39	15.67	0.037	0.33	CR > ES
T3-T24	rSTG-lPAC[c]	0.09 ± 0.39	−0.32 ± 0.42	14.97	0.043	0.32	CR > ES
T3-T25	rSTG-lSTG[c]	0.02 ± 0.35	−0.38 ± 0.33	21.96	0.008	0.41	CR > ES
T4-T18	rFG-rV3[e]	0.20 ± 0.38	−0.37 ± 0.37	27.61	0.009	0.46	CR > ES
T8-T23	rSTG-lIFG[b]	0.26 ± 0.35	−0.18 ± 0.41	16.05	0.036	0.33	CR > ES
T9-T18	rV3-rV3[e]	0.13 ± 0.33	−0.37 ± 0.40	25.35	0.006	0.44	CR > ES
T10-T24	rDLPFC-lPAC[b]	0.08 ± 0.39	−0.30 ± 0.32	15.6	0.040	0.33	CR > ES
T30-T32	lSTG-lDLPFC[b]	0.20 ± 0.30	−0.23 ± 0.43	19.88	0.013	0.38	CR > ES
T3-T41	rSTG-lMotor[c]	−0.01 ± 0.24	0.25 ± 0.33	14.96	0.040	0.32	CR < ES
T9-T24	rV3-lPAC[e]	−0.21 ± 0.43	0.34 ± 0.41	22.73	0.007	0.42	CR < ES
T12-T44	rSMG-lAG[c]	−0.26 ± 0.38	0.25 ± 0.38	24.96	0.005	0.44	CR < ES
R1-R28	rIFG-lMotor[b]	0.01 ± 0.27	−0.29 ± 0.31	18.53	0.047	0.37	CR > ES
R1-R36	rIFG-lFEF[d]	−0.11 ± 0.30	0.35 ± 0.36	34.82	0.001	0.52	CR < ES
R23-T3	lIFG-rSTG[c]	0.02 ± 0.40	−0.43 ± 0.40	26.47	0.025	0.45	CR > ES
R22-T21	rV3-rSMG[e]	−0.25 ± 0.33	0.17 ± 0.29	24.96	0.020	0.44	CR < ES

[a]T, Target; R, regulator; T1, CH1 of the target; R1, CH1 of the regulator; PAC, primary and auditory association cortex; SMC, sensorimotor cortex; Motor, premotor and supplementary motor cortex; SMG, supramarginal gyrus; AG, angular gyrus; FG, fusiform gyrus; FEF, frontal eye field.
[b]Fc between the cognitive control system (CC) and social cognition system (SC).
[c]Fc/IBS within the SC.
[d]Fc within the CC.
[e]Fc/IBS beyond the SC and CC.

R7-T32 (rSMG and lDLPFC; $F_{(2,64)} = 11.19$, $p_{fdr} = 0.032$, $\eta^2 = 0.26$), R17-T36 (rAG and left frontal eye field; $F_{(2,64)} = 12.86$, $p_{fdr} = 0.020$, $\eta^2 = 0.29$), R31-T21 (lV3 and rSMG; $F_{(1.62,51.94)} = 12.44$, $p_{fdr} = 0.018$, $\eta^2 = 0.28$), and R42-T29 (lPSC and lSMG; $F_{(1.69,\ 54)} = 11.53$, $p_{fdr} = 0.026$, $\eta^2 = 0.27$; for descriptive details, see Table 5).

Simple effect analysis showed that the IBS of R4-T27 (right fusiform gyrus and lDLPFC) differed between groups at the emotion regulation stage (CR < ES; $p = 0.048$, Cohen's $d = 0.73$) and feedback stage (CR < ES; $p < 0.001$, Cohen's $d = 1.60$). Further analysis showed that the IBS of R4-T27 at the feedback stage was lower than that at the regulation stage ($p = 0.001$, Cohen's $d = 0.77$) in the CR group. In the ES group, the IBS of R4-T27 at the sharing stage was lower than that at the regulation stage ($p = 0.019$, Cohen's $d = 0.74$) and feedback stage ($p < 0.001$, Cohen's $d = 1.00$) in the ES group.

The IBS of R7-T32 (rSMG and lDLPFC) only differed between groups at the emotion sharing stage (CR > ES; $p = 0.013$, Cohen's $d = 0.90$). No difference was observed at other stages. Further analysis showed that the IBS of R7-T32 at the sharing stage was higher than that at the regulation stage ($p = 0.004$, Cohen's $d = 0.76$) and feedback stage in the CR group ($p < 0.001$, Cohen's $d = 0.93$).

The IBS of R17-T36 (rAG and left frontal eye field) differed between groups at the emotion regulation stage (CR < ES; $p = 0.04$, Cohen's $d = 0.75$). Further analysis showed that the IBS at the feedback stage was lower than that at the sharing stage ($p = 0.002$, Cohen's $d = 0.83$) and regulation stage in the ES group ($p < 0.001$, Cohen's $d = 0.91$).

The IBS of R31-T21 (lV3 and rSMG) did not differ between groups in any stage. Further analysis showed that the IBS at the

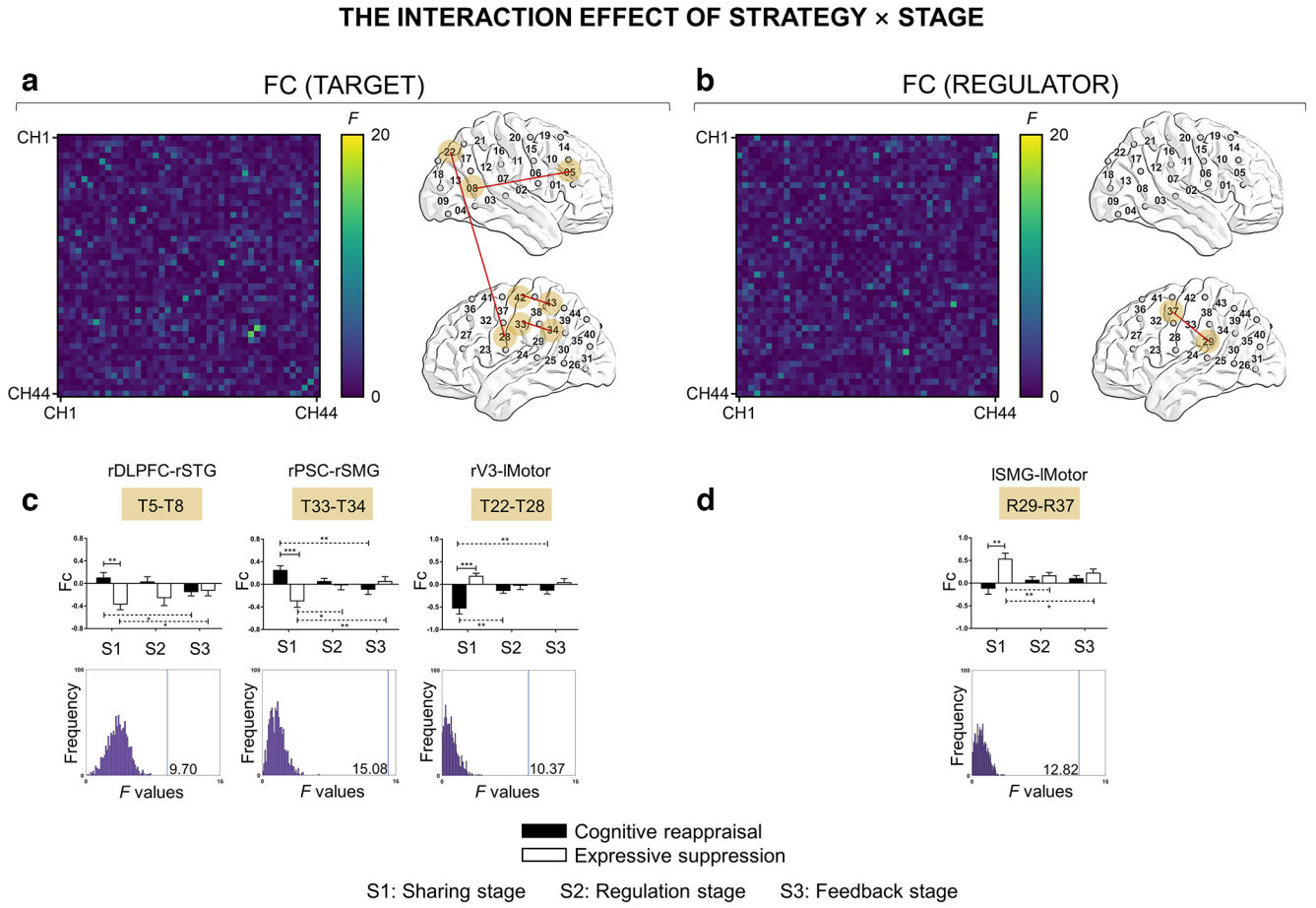

Figure 5. Fc with significant and marginal interaction effects of STRATEGY × STAGE. The FDR-corrected *F*-value map (left) and significant Fc (right) resulting from two-way mixed-design ANOVAs on the Fc of the targets (***a***) and regulators (***b***). The histogram of the significant Fc and the corresponding distribution of *F* values from the permutation tests of the targets (***c***) and regulators (***d***). See Fc matrices of the targets and regulators in Extended Data Figures 5-1 and 5-2. Blue lines indicate the original *F* values. $^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

Table 5. Descriptive details for Fc and IBS[a]

	CR (mean ± SD)			ES (mean ± SD)		
Location	Sharing	Regulation	Feedback	Sharing	Regulation	Feedback
rDLPFC-rSTG$^{(T5\text{-}T8)}$	0.10 ± 0.41	0.03 ± 0.38	−0.15 ± 0.32	−0.37 ± 0.40	−0.25 ± 0.56	−0.12 ± 0.39
rV3-lMotor$^{(T22\text{-}T28)}$	−0.52 ± 0.56	−0.13 ± 0.26	−0.13 ± 0.35	0.18 ± 0.27	−0.02 ± 0.37	0.04 ± 0.36
rPSC-rSMG$^{(T33\text{-}T34)}$	0.25 ± 0.34	0.05 ± 0.23	−0.09 ± 0.39	−0.29 ± 0.45	−0.01 ± 0.35	0.05 ± 0.34
rPSC-rSMG$^{(T42\text{-}T43)}$	−0.11 ± 0.28	0.02 ± 0.10	0.07 ± 0.25	0.16 ± 0.27	0.05 ± 0.27	−0.10 ± 0.37
lSMG-lMotor$^{(R29\text{-}R37)}$	−0.11 ± 0.56	0.07 ± 0.32	0.10 ± 0.29	0.53 ± 0.53	0.16 ± 0.29	0.22 ± 0.36
rFG-lAG$^{(R4\text{-}R44)}$	0.09 ± 0.41	0.01 ± 0.36	0.28 ± 0.37	−0.10 ± 0.33	0.05 ± 0.26	−0.22 ± 0.51
rFG-lDLPFC$^{(R4\text{-}T27)}$	0.00 ± 0.36	−0.04 ± 0.24	−0.27 ± 0.35	−0.2 ± 0.60	0.14 ± 0.25	0.29 ± 0.35
rSMG-lDLPFC$^{(R7\text{-}T32)}$	0.30 ± 0.40	0.03 ± 0.30	−0.07 ± 0.40	−0.05 ± 0.38	0.12 ± 0.48	0.12 ± 0.45
rAG-lFEF$^{(R17\text{-}T36)}$	−0.20 ± 0.52	−0.12 ± 0.33	−0.01 ± 0.22	0.14 ± 0.44	0.14 ± 0.36	−0.22 ± 0.43
lV3-rSMG$^{(R31\text{-}T21)}$	0.16 ± 0.60	−0.01 ± 0.41	−0.09 ± 0.31	−0.15 ± 0.47	0.14 ± 0.46	0.14 ± 0.41
lPSC-lSMG$^{(R42\text{-}T29)}$	−0.03 ± 0.56	0.08 ± 0.38	−0.21 ± 0.53	−0.02 ± 0.49	0.01 ± 0.29	0.35 ± 0.42

[a]T, Target; R, regulator; T5, CH5 of the target; R4, CH4 of the regulator; Motor, premotor and supplementary motor cortex; SMG, supramarginal gyrus; AG, angular gyrus; FG, fusiform gyrus; FEF, frontal eye field; PAC, primary and auditory association cortex; PSC, primary somatosensory cortex.

sharing stage was higher than that at the feedback stage ($p = 0.043$, Cohen's $d = 0.52$) in the CR group. In the ES group, the IBS at the sharing stage was lower than that at the regulation stage ($p = 0.003$, Cohen's $d = 0.66$) and feedback stage ($p = 0.024$, Cohen's $d = 0.62$).

In addition, the IBS of R42-T29 (lPSC and lSMG) only differed between groups at the emotion feedback stage (CR < ES; $p = 0.002$, Cohen's $d = 1.17$). No difference was observed at other stages. Further analysis showed that the IBS at the feedback stage was higher than that at the sharing stage ($p = 0.016$, Cohen's $d = 0.81$) and the regulation stage in the ES group ($p = 0.001$, Cohen's $d = 0.94$). Meanwhile, the IBS at the regulation stage was higher than that at the feedback stage ($p = 0.004$, Cohen's $d = 0.63$) in the CR group.

Permutation tests on neural couplings

As for Fc of the targets or regulators, the permutation tests showed that the original *F* values of the significant main or

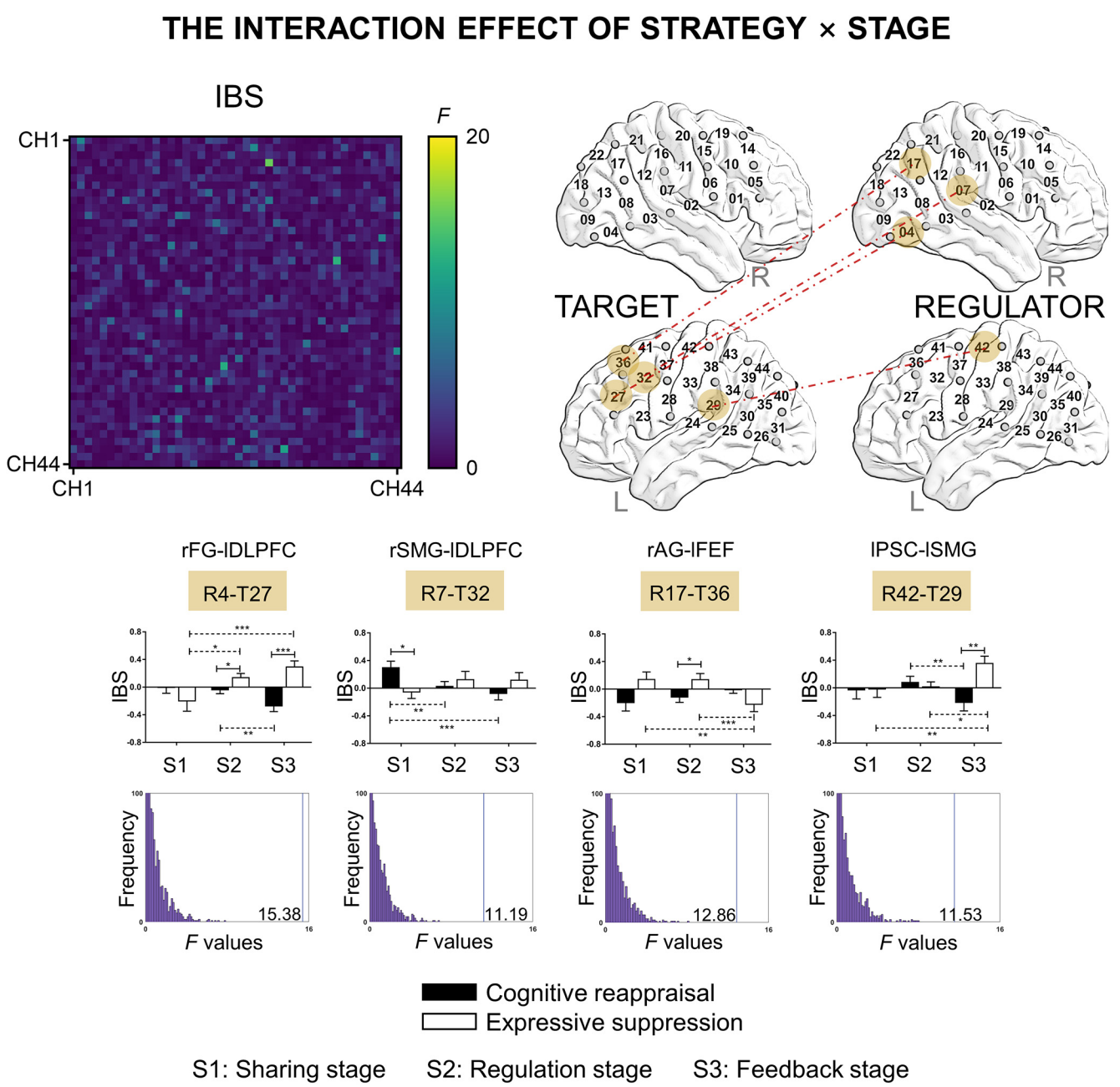

Figure 6. IBS with significant interaction effects of STRATEGY × STAGE. The FDR-corrected *F*-value map and significant IBS resulting from two-way mixed-design ANOVAs (top). The histogram of the significant IBS (middle) and the corresponding distribution of *F* values from the permutation tests of the significant IBS (bottom). See IBS value matrices in Extended Data Figure 6-1. Blue lines indicate the original *F* values. $^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

interaction effects are located at the top 1% areas of the permutation distributions (Fig. 5*c*,*d*; Extended Data Fig. 4-1).

Regarding IBS, the permutation tests showed that the original *F* values of the significant main or interaction effects also located at the top 1% areas of the permutation distributions (Fig. 6; Extended Data Fig. 4-1).

Brain–behavior relationships

Bivariate Pearson correlation analyses were performed on the significant Fc and behavior of the targets/regulators for the CR group and ES group, respectively. In the CR group, the Fc of R1-R36 in the feedback stage was positively correlated with the positive emotional change of the regulators ($r = 0.60$, $p_{corr} = 0.049$). In the ES group, the Fc of T30-T32 in the regulation stage was positively correlated with the negative emotional change of the targets ($r = 0.79$, $p_{corr} = 0.007$; Fig. 7*a*,*b*). No other significant correlation was observed.

Bivariate Pearson correlation analyses were performed on the significant Fc of targets and behavior of the regulators for each strategy, and vice versa. Results showed that, in the CR group, the Fc of T12-T44 in the feedback stage was positively correlated with the positive emotional change ($r = 0.81$, $p_{corr} = 0.006$; Fig. 7*c*). No other significant correlation was observed.

Similar correlation analyses on the significant IBS showed that the IBS of R17-T36 in the regulation stage was positively correlated with the IER effectiveness of the targets ($r = 0.72$, $p_{corr} = 0.023$) in the CR group. The IBS of R42-T29 in the feedback stage was positively correlated with the positive emotional

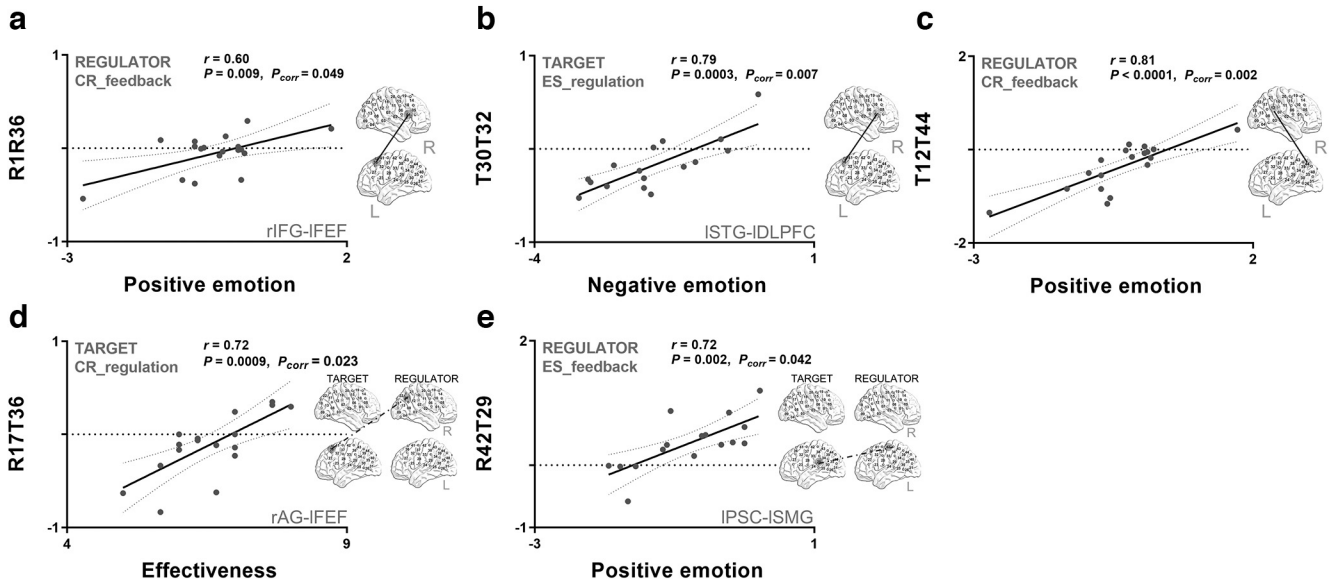

Figure 7. Linear correlations between significant Fc/IBS and behaviors. ***a***, The correlation between the regulator's positive emotional change and Fc of R1-R36 at the CR_feedback stage. ***b***, The correlation between the target's negative emotional change and Fc of T30-T32 at the ES_regulation stage. ***c***, The correlation between the regulator's positive emotional change and Fc of T12-T44 at the CR_feedback stage. ***d***, The correlation between the target's IER effectiveness and IBS of R17-T36 at the CR_regulation stage. ***e***, The correlation between the regulator's positive emotion changes and IBS of R42-T29 at the ES_feedback stage. T, Target; R, regulator; T1, CH1 of the target; R1, CH1 of the regulator.

change of the regulators ($r = 0.72$, $p_{corr} = 0.042$) in the ES group (Fig. 7*d*,*e*). No other significant correlation was observed.

Discussion

This study first explored how two typical IER strategies (CR and ES) affect the dynamic process (emotion sharing, emotion regulation, and feedback) and outcome of IER, and uncover the underlying neural substrates using fNIRS-based hyperscanning. Behavioral results showed that both IER strategies successfully decreased the targets' negative emotions and increased their positive emotions. Also, the targets' self-rated IER effectiveness was significantly higher in the CR group than in the ES group. Regarding the targets, the fNIRS results showed the CR strategy evoked broad higher Fc across regions, including PFC, TPJ, sensory and motor cortex, but lower Fc between the rTPJ and sensory and motor regions than the ES strategy. Regarding the regulators, the CR strategy evoked higher Fc of rIFG-lMotor, but lower Fc of rIFG-lFEF than the ES strategy. As for IBS, the CR strategy evoked higher IBS of $lIFG_{regulator}$-$rSTG_{target}$, but lower IBS of $rV3_{Regulator}$-$rSMG_{Target}$ than the ES strategy. Further analysis on IER stages showed that the CR strategy evoked higher Fc of rDLPFC-rSTG and rPSC-rSMG in the targets, and IBS of $rSMG_{regulator}$-$lDLPFC_{target}$ than the ES strategy at the sharing stage. In contrast, the ES strategy evoked higher Fc of rV3-lMotor in the targets and Fc of lSMG-lMotor in the regulators than the CR strategy at the sharing stage. Moreover, the ES strategy also evoked higher IBS of $rFG_{regulator}$-$lDLPFC_{target}$ and $rAG_{regulator}$-$lFEF_{target}$ than the CR strategy at the regulation stage.

Specifically, both IER strategies successfully and comparably downregulated the emotional valence and arousal of the targets' negative emotion. These findings suggested that both CR and ES were effective in IER, which extended the previous finding that CR is more effective in intrapersonal emotion regulation than the ES (Boemo et al., 2022). Regarding CR, we suggest that it engages reinterpreting the meaning or context of the emotion-eliciting event, and thus helps get rid of negative emotions because of previous view on the event. Regarding ES, it seems that merely suppressing others' emotional expressions can improve their negative emotional state. Another interpretation could be that a sense of social support, along with the interpersonal ES strategy, may contribute to decreasing individual negative emotions. This also parallels recent studies on developing the IER questionnaire (Hofmann et al., 2016; Akkuş and Peker, 2022). They found that ES-related items, such as "When I am annoyed, others can soothe me by telling me not to worry" and "Having people telling me not to worry can calm me down when I am anxious," could successfully decrease one's negative feelings.

Intriguingly, the targets subjectively considered the CR strategy more effective in downregulating their negative emotions than the ES strategy. Such a difference in subjective feeling might result from the fact that CR can help the targets optimistically treat the emotion-eliciting event and contribute to positive feelings, emotional expressions, and well-being compared with ES (Gross and John, 2003). However, the regulators' ratings on IER effectiveness did not differ between two strategies, but the increase in emotional arousal was stronger in the CR group than in the ES group. Further analysis showed the regulators' amusement increased but fear decreased in the CR group compared with the ES group. These findings also indicate that using different strategies to downregulate others' negative emotions also lead to changes in the regulator's emotional state. CR involves directing the target to reinterpret the meaning of the emotion-eliciting event and get rid of negative emotion resulting from previous view of the event. However, the regulators merely instructed the targets to bear negative feelings and keep calm when using the ES strategy. In comparison, the regulator might experience a stronger sense of achievement, which had led to an increase in their amusement in the CR scenario.

The FC analysis on the whole IER course showed that the CR strategy evoked broad Fc across regions, including PFC, TPJ, STG, and sensory and motor cortex in the targets compared with the ES strategy. These results were consistent with previous findings that the CR strategy recruited brain systems related to

cognitive control and linguistic elaboration during intrapersonal emotion regulation (Buhle et al., 2014; Sokołowski et al., 2022). This finding further demonstrated a relationship between the IER process based on CR and social cognition system (e.g., TPJ, STG). This could be explained by the fact that the target needed to comprehend the views of the regulator during CR-based IER process (Naor et al., 2020; Tholen et al., 2020). Moreover, in the case of CR, the target engaged in a series of more complex mental process, such as detecting the viewpoint gap between the target and regulator, imitating mental actions (e.g., change viewpoint) related to regulating negative emotions during the IER process (Franklin-Gillette and Shamay-Tsoory, 2021). In addition, this finding was also in line with the model of IER linking social cognition system with the IER process (Zaki and Williams, 2013; Reeck et al., 2016), and provided neuroscientific evidence that the CR-based IER process engages broad neural connections associated with the cognitive control system and social cognition system in the targets. In contrast, the ES strategy triggered stronger Fc of $rSTG_{Target}$-$lMotor_{Target}$, $rV3_{Target}$-$lPAC_{Target}$, and $rSMG_{Target}$-lAG_{Target} than the CR strategy. Sikka et al. (2022) reviewed the neuroimaging studies on the neural bases of ES and also found that the temporo-occipital areas related to visual processing were recruited during ES. Given that the target paid more attention to response inhibition rather than emotion eliciting stimuli, neural responses in these areas would be expected. Furthermore, previous research showed that the DLPFC, premotor, and supplementary motor cortex were engaged in emotional regulation based on CR or ES (Steward et al., 2021; Sikka et al., 2022). Both reappraisal and suppression strategies activated the DLPFC (Berboth and Morawetz, 2021; Gao et al., 2021). The current findings further emphasized the important roles of these regions in both intrapersonal and IER (Gao et al., 2021; Sikka et al., 2022), and provided neuroimaging evidence for the interaction model of IER (Reeck et al., 2016).

The IBS analysis on the whole IER course showed a significant increase in IBS of $lIFG_{Regulator}$-$rSTG_{Target}$ in the CR group compared with the ES group. Increases in IBS were often observed during various social interaction processes (Pan et al., 2020; Lu et al., 2023), indicating a state of information processing or exchange. During CR-based IER, the regulator needs to engage in multiple mental processes, including emotion recognition, language production, and mentalizing or empathizing; the target is required to comprehend the regulator's perspective and reinterpret the emotion-eliciting issue as the regulator suggested. The IFG is related to language production (Silbert et al., 2014), emotion recognition (Arioli et al., 2021), and mentalizing (Shamay-Tsoory et al., 2019; Weng et al., 2022); and rSTG is involved in speech comprehension (Bhaya-Grossman and Chang, 2022) and communication (Stephens et al., 2010). All of these may explain the increase in IBS of $lIFG_{Regulator}$-$rSTG_{Target}$ in the CR group. However, the ES strategy evoked higher IBS of $rV3_{Regulator}$-$rSMG_{Target}$ than the CR strategy. During ES-based IER, the regulator needs to supervise the target's facial expression or behavioral response to confirm that the target suppressed emotional expressions as suggested; the target needs to monitor her emotional expressions. The possible relationship between the rSMG and ongoing monitoring of one's facial expression (Dörfel et al., 2014), and the role of visual areas in visual information processing, may offer an explanation for the increased IBS of $rV3_{Regulator}$-$rSMG_{Target}$ in the ES group.

The current paradigm artificially divided the IER process into three stages (sharing, regulation, and feedback) and thus allowed uncovering the neural correlates underpinning the effect of two strategies on the IER process. CR is an antecedent-focused strategy, whereas ES is a response-focused strategy (Gross, 1998). CR requires the regulator to recognize what the target is experiencing and feeling at the sharing state, so as to generate appropriate ideas to help the target reinterpret the emotion-eliciting issue. This may engage an increase in IBS of $rSMG_{regulator}$-$lDLPFC_{target}$ at the sharing stage of IER, which could be further supported by previous research: the rSMG is recruited in judging others' internal states and processing others' thoughts (Silani et al., 2013; Steinbeis, 2016; Bukowski et al., 2020). The DLPFC is strongly implicated in advanced cognitive functions, such as executive control (Huang et al., 2022) and verbal working memory (Koshy et al., 2020). We also observed higher Fc of $rDLPFC_{Target}$-$rSTG_{Target}$ and $rPSC_{Target}$-$rSMG_{Target}$, but lower $lSMG_{regulator}$-$lMotor_{regulator}$ in the CR group than in the ES group at the sharing stage. These results may reveal that the influence of CR and ES strategies on the IER process began early in the emotion sharing stage. These two strategies affected the mutual interaction between the regulator and target when the target was sharing emotional feelings. For instance, CR requires the regulator to recognize and empathize with the target's shared negative emotions (antecedent-focused), which may contribute to the target's feeling of being cared about. Meanwhile, the target was observing the reaction of the regulator (e.g., facial expressions), identifying whether the regulator was sincerely caring about her feeling, and eventually determining whether to open heart and continue sharing emotions to the regulator. Interestingly, the PSC, a part of the mirror neuron system, involves processing incoming sensory information, such as recognizing facial expression (Volynets et al., 2020). All these could help explain the increased Fc between the cognitive control system, social cognition system, and mirror neuron system (Fc of $rDLPFC_{Target}$-$rSTG_{Target}$ and $rPSC_{Target}$-$rSMG_{Target}$). In contrast, ES put more emphasis on practicing suppression instructions, and thus does not heavily rely on interpersonal empathy or mentalizing. In this case, the regulator may focus on the internal practice of suppression strategies, which may enhance the Fc of $lSMG_{regulator}$-$lMotor_{regulator}$. It is worth noting that a marginal interaction effect of STRATEGY × STAGE on Fc of R4-R44 (rFG-lAG) was also observed. Considering the sample size of dyads is small in this study, we consider it more proper to treat this marginal effect as insignificant for prudential reasons.

With respect to the regulation stage of the IER process, we observed higher IBS of $rFG_{Regulator}$-$lDLPFC_{Target}$ and $rAG_{Regulator}$-$lFEF_{Target}$ in the ES group than in the CR group. During the ES-based IER process, the regulator needed to recognize the targets' facial or bodily expressions to confirm whether the targets have suppressed their emotional expressions successfully; the target engaged in more cognitive control, such as suppressing their emotional expressions. Given the role of frontal cortex in inhibitory control or response inhibition (Zheng et al., 2008; Cai et al., 2014), and FG in facial recognition (Rangarajan et al., 2014), the increased IBS of $rFG_{Regulator}$-$lDLPFC_{Target}$ and $rAG_{Regulator}$-$lFEF_{Target}$ may underlie the abovementioned social cognitive processes during the ES-based IER process.

This study has both theoretical and practical implications. Theoretically, this study extends the effectiveness of two typical intrapersonal emotion regulation strategies (CR and ES) to the IER process. More importantly, this study uncovers the intrapersonal and interpersonal neural correlates, mainly engaging brain areas within the social cognition system, cognitive control system, and mirror neuron system, that underlie the CR-based and ES-based real-time IER process using the nascent hyperscanning technique. All of this helps deepen our understanding of the

neural substrates underpinning IER. Practically, the current findings indicate that both CR and ES strategies can downregulate others' negative emotions during the IER process. In light of this, CR and ES strategies are effective in not only intrapersonal emotion regulation, but also IER. One can use various emotion regulation strategies to regulate her own or others' (e.g., friends, followers) negative emotional states. In addition, these findings also offer suggestions to emotion regulation in contexts, such as interpersonal conflict, customer service, etc.

Several limitations should be noted in this study. First, the findings should be cautiously generalized because of the external and ecological validity of this study. Participants were randomly asked to use the CR or ES strategy in this study. Whether the effect of strategies on IER process can be moderated by individual differences, such as personal preference for IER strategy, emotion regulation abilities, should be further examined. Second, although a series of *a priori* and *post hoc* g*power computation indicated that the current sample size was sufficient, which was also comparable to previous hyperscanning research (Jiang et al., 2012; Hou et al., 2020), the current findings would better be further examined in a larger sample. Third, only females were recruited in this study. For one thing, previous studies have shown that gender difference can affect the neural basis underlying interpersonal interaction (Baker et al., 2016) and intrapersonal emotion regulation (Stoica et al., 2021). This study originally aimed to unveil the neural basis underlying IER without tapping the gender effect, and thereby only females or males would be recruited. For another, given females are more responsive to negative emotion stimulus (Stoica et al., 2021) and partners' social support (Lüscher et al., 2014), and also more likely to provide better social support than males (Neff and Karney, 2005), female dyads were considered more proper than males for this study. It is worth noting that the current findings may be limited to females, and the potential gender effect on these findings deserves further exploration. Fourth, emotional states were only measured using self-reported scales, more objective indicators (e.g., heart rates, galvanic skin response, etc.) should be used in future research to quantify emotional changes. Ultimately, given that using IER strategies flexibly based on the context or the personality traits of the target are important (Fernandes and Tone, 2021), future research can also examine whether assessing regulation strategies flexibly can contribute to the IER process.

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