Cerebral Cortex, 2023, **33**, 7960–7970

https://doi.org/10.1093/cercor/bhad091
Advance access publication date 21 March 2023
Original Article

Affective or cognitive interpersonal emotion regulation in couples: an fNIRS hyperscanning study

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Sadness regulation is crucial for maintaining the romantic relationships of couples. Interpersonal emotion regulation, including affective engagement (AE) and cognitive engagement (CE), activates social brain networks. However, it is unclear how AE and CE regulate sadness in couples through affective bonds. We recruited 30 heterosexual couple dyads and 30 heterosexual stranger dyads and collected functional near-infrared spectroscopy hyperscanning data while each dyad watched sad or neutral videos and while the regulator regulated the target's sadness. Then, we characterized interbrain synchronization (IBS) and Granger causality (GC). The results indicated that AE and CE were more effective for couples than for strangers and that sadness evaluation of female targets was lower than that of male targets. CE-induced IBS at CH13 (BA10, right middle frontal gyrus) was lower for female targets than for male targets, while no gender difference in AE was detected. GC change at CH13 during CE was lower in the sad condition for male targets than for female targets, while no gender difference in AE was discovered. These observations suggest that AE and CE activate affective bonds but that CE was more effective for regulating sadness in female targets, revealing different neural patterns of cognitive and affective sadness regulation in couples.

Key words: affective engagement; cognitive engagement; couples; Granger causality; hyperscanning; interpersonal emotion regulation.

Introduction

Sadness, one of the basic human emotions, is a natural and evolutionary response to loss or failure to achieve a goal (Beck and Bredemeier 2016), which is linked to interoceptive feelings and psychological pain (Adolfi et al. 2017). However, persistent sadness might develop into a psychiatric disorder, e.g. depression (Woody and Gibb 2015; Kovács et al. 2016). Sadness is also involved in interpersonal communication of intimate individuals, i.e. parent–child dyads, friends, and couples (Zaid et al. 2021). Especially in couples, sadness is the negative emotion most easily anticipated by oneself and one's partner, which makes the regulation of sadness in couples especially important (Jitaru and Turliuc 2022). Moreover, sadness regulation is related to insecure attachment (Feeney 1995) and resolution of interpersonal conflicts (Sanford 2007), which can help couples maintain a high-quality romantic relationship (Croyle and Waltz 2002).

Emotion regulation (ER) is the process through which individuals modify the intensity, duration, and quality of their emotional experience (Gross and Thompson 2007). ER has 2 roles: regulator and target. Intrapersonal ER involves the regulator and target being the same person; in interpersonal ER (IER), these roles are played by different people. Most previous ER research has focused on intrapersonal ER, revealing associated functional networks, e.g. the frontoparietal control network, salience network, and visceromotor network (Phillips et al. 2008; Koole et al. 2015; Arias et al. 2020). Recently, IER has attracted research attention, such as parent–child (Reindl et al. 2018), teacher-student (Sun et al. 2021), and friend relationships (Kwon and López-Pérez 2022). However, there is little research on IER in couples (Jitaru and Turliuc 2022). Studies that have examined IER in couples have reported that the regulator's outside viewpoint helps to minimize target distress more effectively than intrapersonal ER (Levy-Gigi and Shamay-Tsoory 2017) and that positive humor regulates momentary affect in couples by changing their feelings of psychological intimacy (Horn et al. 2019). These studies focused on habitual behaviors in daily life or nonexperimental contexts. Recently, the dyadic partner-schema model indicated an underlying pathway linking potential partner-schema structures to distress and depressed emotions in couples (Wilde and Dozois 2019); this study examined the pathological cognitive scheme but overlooked affective bonds in healthy couples. Therefore, research on the interpersonal regulation of sadness in healthy couples is needed.

Under the classification by Niven et al. (2009), affective engagement (AE) refers to the regulator directly engaging with the target's feelings, while cognitive engagement (CE) refers to the regulator engaging with the target's thoughts to change their emotions. Using this classification, López-Pérez (2018) found that AE had a higher perceived efficacy for sadness, whereas CE led to anxiety/stress in healthy adults. Moreover, Jitaru and Turliuc (2022) used thematic analysis (instructing participants to read a positive or negative vignette and imagine that they were the main character) and discovered that couples tended to "put their own feelings first" or use CE to regulate their own or their partner's emotions. However, little is known about how AE and CE regulate sadness in couples.

Recently, some work has explored social brain networks as the mechanism underlying IER. An fMRI study asked healthy

Received: October 14, 2022. **Revised:** February 24, 2023. **Accepted:** February 25, 2023

participants to regulate their own or another person's emotions and reported that activated brain regions overlapped between intrapersonal ER and IER; however, the social network was activated to a greater extent during IER than during intrapersonal ER, including the medial prefrontal cortex (BA10) (Hallam et al. 2014). Another fMRI study found that participants' emotions were regulated more successfully by supporting sentences and a picture from their best friends than by intrapersonal ER or assistance from strangers, leading to greater activation of the social cognition network (e.g. superior/middle frontal gyrus [MFG] and salience network) (Morawetz et al. 2021). These single-brain studies have shown that social closeness boosts intrapersonal ER but have not fully revealed the neural mechanisms underlying IER in real social interactions.

By contrast, hyperscanning can measure the activity in multiple brains simultaneously (Holper et al. 2012; Babiloni and Astolfi 2014). Specifically, fNIRS hyperscanning has higher temporal resolution than fMRI and less vulnerability to motion artifacts than EEG, rendering it well suited for studying social interactions in natural settings (Redcay and Schilbach 2019; Gamliel et al. 2021; Jiang et al. 2021). According to attachment theory (Carter 2014; Feldman 2017), affective bonds in couples can be defined as the emotional tie or bond of affection experienced by people towards their partners, whose key feature is biobehavioral synchrony (i.e. behavioral synchrony and brain-to-brain synchrony) (Feldman 2012). Similarly, a study found that interbrain synchronization (IBS) in the frontopolar cortex (BA10) indicated a neural mechanism underlying the emotional connection between parents and children during cooperation; this IBS was associated with the development of adaptive ER in children (Reindl et al. 2018).

IBS has also been widely applied in couple studies since the affective bonds between individuals in a couple produce biobehavioral synchrony (Feldman 2012, 2017; Djalovski et al. 2021). A dozen fNIRS hyperscanning studies have determined that IBS is a stable indicator of the correlation of brain signals within couples using a variety of social interaction tasks such as presenting realistic problems (Duan et al. 2020), face-to-face conversations (Jiang et al. 2012; Osaka et al. 2014), and cooperation (Pan et al. 2017; Tang et al. 2020). In particular, couples showed the highest behavioral synchrony and lowest neural synchrony, while strangers displayed the opposite pattern during social-oriented empathy tasks (Djalovski et al. 2021). By contrast, Long et al. (2022) found that couples exhibited stronger neural synchrony than friends during discussion of conflictual topics. Considering that empathy is naturally integrated into IER through affective bonds in couples (Zaki 2020) and that discussing conflictual topics induced emotional valence-related INS increases in Long's study, further exploration of the neural mechanisms underlying IER in couples is needed.

However, few IBS studies have focused on the gender differences in task roles due to their paradigms, e.g. cooperative tasks (Pan et al. 2017; Tang et al. 2020) and group creativity processes (Duan et al. 2020). Long and her team (2021) found gender differences in time-lag neural synchrony, with women exhibiting greater sensitivity to communication within couples. Moreover, a recent behavioral review found that men usually suppress or reappraise sadness during intrapersonal ER because they tend to avoid the experience and expression of emotions, while women are accustomed to seeking emotional support or engaging in rumination (Zaid et al. 2021). Based on these studies, we wondered whether gender differences are present at the neural level during sadness IER in couples.

Granger causality analysis (GCA) can be used to determine the directionality of dyadic interactions and is widely adopted in fNIRS hyperscanning studies, e.g. interactions between strangers (Sciaraffa et al. 2021), teachers and students (Pan et al. 2018), and couples (Pan et al. 2017; Duan et al. 2020; Tang et al. 2020). In particular, a fNIRS hyperscanning study revealed stronger directional synchronization in couples from women to men in cooperation tasks (Pan et al. 2017). By contrast, 2 other studies with couples found no gender difference in directional synchronization in a button-press cooperative task (Tang et al. 2020) and a realistic problem task (Duan et al. 2020). Because of the mutual information flow between the regulator and the target during IER, it is important to explore gender differences in its coupling directionality.

This study aimed to apply fNIRS hyperscanning to investigate the underlying neural mechanisms of IER in romantic couples. To this end, we recruited participants into 2 groups: heterosexual couple (C-C) dyads and heterosexual stranger (S-S) dyads. Each dyad had individuals assigned to serve as the regulator and the target during the IER task (Fig. 1). Previous studies have revealed a relationship between affective bonds and evaluation of romantic partners (McNulty et al. 2013; Ha and Hampton 2022). Therefore, we hypothesized that AE and CE, acting separately through affective bonds, would evoke different responses in couples. First, we predicted that both AE and CE would be more effective for couples than for strangers. Second, we predicted that female targets in romantic relationships might have more neural responses to IER than male targets for both AE and CE.

Methods

Participants

A total of 142 healthy participants, including 31 C-C dyads (31 males and 31 females; 19.13 ± 1.47 years) and 40 S-S dyads (40 males and 40 females, 19.03 ± 1.23 years), were recruited by advertising at several colleges in Hengyang. No significant differences between these groups were found in terms of age ($t(118) = 0.76$, $P = 0.44$). All participants had normal or corrected-to-normal vision and normal auditory function and had not taken part in any similar experiments before. All couples in C-C dyads had been together for more than a month. In S-S dyads, participants were unfamiliar with each other before the experiment, and the (lack of) relationship in both types of dyads was confirmed by the Measurement of Perceived Relationship Quality Components (PRQC, Fletcher et al. 2000). There was a significant difference in the closeness of C-C dyads and S-S dyads according to the PRQC, which was in accordance with their self-reports ($t(118) = 19.19$, $P < 0.001$). Of all participants, 6 dyads were used for the pilot experiment and were not included in the final analysis, and 5 dyads were excluded because of equipment failure, program failure, or missing data. Detailed information on the participants is provided in Table 1. All participants provided written informed consent before the experiment and received 30 RMB for their participation after the experiment. The study protocol was approved by the Ethics Committee of Hengyang Normal University.

Measurements

Assessment of relationship

To confirm their self-reported relationship type, all participants were asked to complete the PRQC. The PRQC assesses relationship quality based on 6 components: satisfaction, commitment, intimacy, trust, passion, and love (Fletcher et al. 2000). In our study, we mainly focused on the intimacy and trust subscales to distinguish couple and stranger relationships (Wu 2017). The scale had strong reliability in our study (Cronbach's $\alpha = 0.971$).

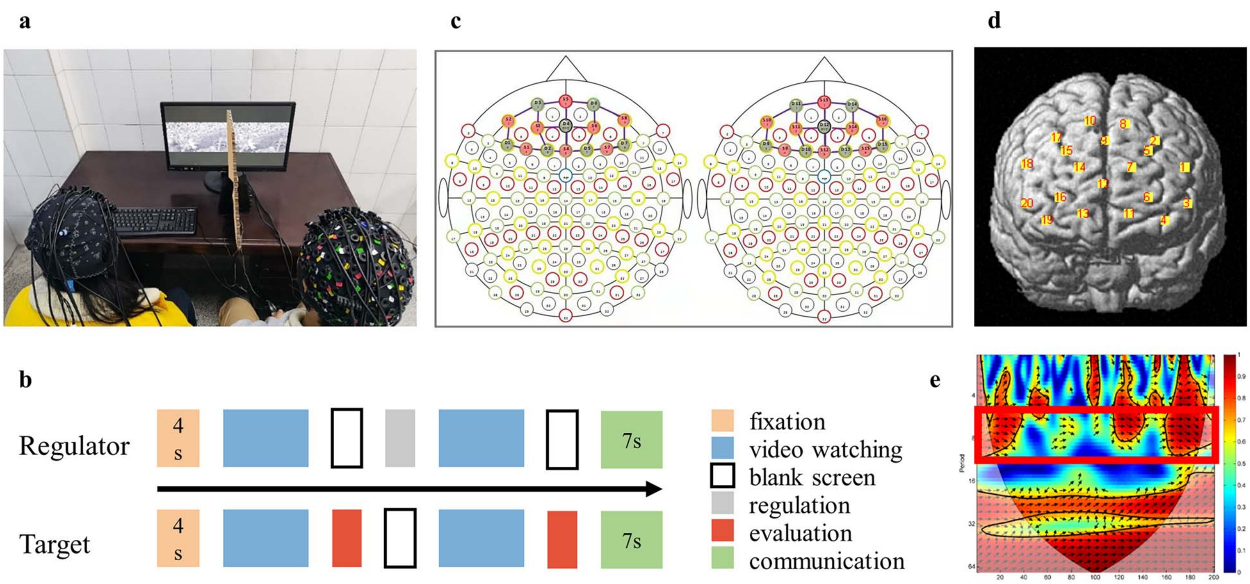

Fig. 1. The experimental design. a) The experimental setup. b) The experimental procedure of a trial. Each trial began with a fixation of 4 s and then both the regulator and target watched a video at the same time. After watching the video, the target evaluated his or her sadness; next, the regulator read the IER sentence. Subsequently, they watched the same video, the target evaluated his or her sadness again, and they communicated for 7 s at the end. c) The montage provided by NIRx Medical Technologies; sources are depicted as red dots, detectors are depicted as green dots. d) The MNI standard brain space estimation of 20 channels by NIRS-SPM. e) The frequency band of interest. This WTC graph is based on HbO signals from CH12 in a representative C-C dyad. The red rectangle highlights the frequency band of interest: 0.08–0.20 Hz (5–12 period).

Table 1. Demographic characteristics of participants.

	C-C dyad	S-S dyad
Length of relationships (days)	417.79 (448.05)	-
Age (in years)		
Men	19.47 (1.63)	19.50 (1.28)
Women	19.00 (1.02)	18.60 (1.10)
Handedness		
Men	29 right-handed, 1 left-handed	29 right-handed, 1 left-handed
Women	30 right-handed	30 right-handed
Gender of the target		
Male	11	14
Female	19	16

Note: Means (SDs) are provided for 2 groups. C-C dyad: couple dyad; S-S dyad: stranger dyad.

Assessment of ER ability

All participants were asked to complete the Regulatory Emotional Self-Efficacy (RESE) scale and the Interpersonal Emotion Regulation Questionnaire (IERQ) to evaluate ER ability (Caprara et al. 2008; Hofmann et al. 2016). The RESE scale measures perceived self-efficacy in managing negative emotions and in expressing positive affect (POS; Cronbach's $\alpha = 0.781$, Caprara et al. 2008). The RESE scale includes 3 components: POS, managing despondency distress (DES), and perceived self-efficacy in managing anger (ANG) (Cronbach's α: POS, 0.780; DES, 0.709; ANG, 0.768).

The IERQ was used to evaluate IER preference (Cronbach's $\alpha = 0.879$, Hofmann et al. 2016). It includes the 4 following subscales: enhancing positive affect (EPA), perspective-taking (PT), soothing (S), and social modeling (SM) (Cronbach's α: EPA, 0.822; PT, 0.803; S, 0.754; SM, 0.759).

Materials

Video materials

To elicit emotional responses in the laboratory, we first selected video materials following previous studies and generated 24 video clips (12 negative and 12 neutral) with similar length, intelligibility, and discreteness (Gross and Levenson 1995; Xu et al. 2010). Then, 40 healthy Chinese university students rated the arousal and valence of each video on the emotional arousal scale and the Positive and Negative Affect Schedule (Gross and Levenson 1995; Xu et al. 2010). During this process, we used 13 positive videos similar to our materials to alleviate the participants' negative emotions and to keep them in a steady emotional state. Finally, we selected 16 videos (8 sad videos, 8 neutral videos) among which the sad videos elicited sadness (sad videos: $F(7, 384) = 0.64$, $P = 0.74$; neutral videos: $F(7, 384) = 1.60$, $P = 0.12$) and significantly differed in elicited sadness from neutral videos ($F(1, 774) = 517.53$, $P < 0.001$). All the videos were closely matched in valence (sad videos: Cronbach's $\alpha = 0.93$; neutral videos: Cronbach's $\alpha = 0.94$; all videos: Cronbach's $\alpha = 0.93$). In addition, all videos were between 9.00 and 18.00 s in length, with an average length of 13.57 s (all videos: 13.57 ± 2.68 s; sad videos: 13.29 ± 2.98 s; neutral videos: 13.86 ± 2.54 s).

Sentence materials of IER

Based on the IER classification (Niven et al. 2009) and some IER examples (López-Pérez et al. 2016, López-Pérez 2018), we generated 8 IER sentences (4 AE sentences and 4 CE sentences) that were accurately translated into Mandarin Chinese and adapted to apply to general situations; thus, they could be applied to all sad videos. Six dyads volunteered to participate in the pilot experiment to ensure that these sentences were effective. The generated IER sentences had a significant effect on sadness regulation, and the effects differed between AE and CE sentences (AE: $t(47) = 4.08$, $P < 0.001$; CE: $t(47) = 2.83$, $P = 0.007$). An example AE sentence is “You’re doing great,” and a CE sentence is “You could talk to your friends to feel better.”

Procedure and tasks

Upon arrival, participants of each dyad were asked to finish their preexperiment tests and then were guided to sit in front of a computer screen. They sat side by side, separated by a distance of 30 cm, and an opaque cardboard was placed in the middle of the screen to prevent the participants from seeing each other’s screen (Fig. 1a). This setup with a split screen enabled each participant in the dyad to perform different tasks. Before the experience, participants were allowed to introduce themselves, communicate, and decide which role they would take during a period of 30 min. During this period, the experimenter guided the participants to communicate and further confirm their relationship. During the introduction, couples reported having held hands, kissed, and even exhibiting other intimate behaviors; thus, the experimenter was able to observe greater intimacy between couples. Once both participants felt ready, they could skip the remaining time and start the experiment.

During the experiment, participants were first given a comprehensive overview of the whole experiment, and specific instructions were displayed on the screen. Once both participants in each dyad fully understood the task, they were given a practice trial to familiarize themselves with the experiment. Then, the formal experiment began. The formal experiment consisted of 2 blocks, each containing 32 trials. A 1-min break was provided between the blocks to allow participants to rest and relax between sustained attention to screens. During the break, participants were advised to close their eyes and relax their minds. Each block contained the same number of sad and neutral videos displayed in a random order. Thus, the IER sentences and videos were paired at random. In both C-C or S-S dyads, male and female targets viewed all videos twice, while male and female regulators read all sentences.

In each trial (Fig. 1b), a fixation cross was first presented in the middle of both halves of the screen for 4,000 ms, and then participants watched a video together. Next, the target evaluated his or her sadness on a 7-point Likert scale ranging from 1 (“not at all”) to 7 (“very much”). After the evaluation, the regulator was instructed to read aloud the IER sentence presented on his or her half of the screen during a period of 5,000 ms. Then, both participants watched the same video clips again, and the target evaluated his or her sadness again. Finally, a blank interval was presented for 7,000 ms to allow participants to simply express their feelings to their partners. During the experiment, participants were instructed to communicate at a natural volume as usual and refrain from physical contact.

fNIRS data acquisition

An fNIRS device (NIRScout, NIRx Medical Technologies, Berlin, Germany) with a sample rate of 7.8125 Hz was employed to record raw data at 2 wavelengths (760 and 850 nm). Two sets of customized optodes (8 sources and 8 detectors, 20 measurement channels) were placed over the PFC of two participants per montage by NIRx (Fig. 1c). One was used for male participants within a dyad, and the other was used for female participants within a dyad. The distance of each source-detector pair was set at 30 mm. Each optode set was placed over the PFC of the participant following the international 10–20 system (Ramstrand et al. 2020; Dybvik and Steinert 2021). This montage covered the anterior frontal lobe and more specifically included Brodmann areas 8, 9, 10, 11, 44, 45, 46, and 47 (Ramstrand et al. 2020; Dybvik and Steinert 2021). An estimation of the locations of 20 channels in the Montreal Neurological Institute (MNI) space was generated with NIRS-SPM for each participant (Fig. 1d) (Yamazaki et al. 2020; Dybvik and Steinert 2021).

fNIRS data analysis

Preprocessing

To determine the signal-to-noise performance of the channels, we calculated the relative coefficient of variation (CV, in %) of the raw data. The channels with a CV > 15% were rejected, and the remaining channels with a CV of trials <5% were retained for future analyses (Schmitz et al. 2005; Schneider et al. 2011; Piper et al. 2014). Then, the signals were preprocessed in MATLAB (MathWorks, Inc., Natick, MA, USA) with the Homer2 function (Huppert et al. 2009). We converted intensity to optical density (Huppert et al. 2009) and performed a cubic spline correction of the motion artifact to remove motion artifacts (Scholkmann et al. 2010). In addition, no filtering or detrending procedures were applied to the data for task-related IBS analysis in accordance with previous studies (Cui et al. 2012; Cheng et al. 2015; Dai et al. 2018; Zheng et al. 2018). We applied a bandpass filter (0.01–0.2 Hz) to the data for GCA and converted the data to concentrations using the modified Beer–Lambert law (Sassaroli and Fantini 2004). Finally, we group-averaged the oxygenated and deoxygenated hemoglobin concentrations by the Homer2 block averaging function hmrBlockAvg, with tRange: [−5, 20], which was synchronized via marks placed in the data at the onset of each video. In our study, we focused on oxygenated hemoglobin (HbO) signals due to their high change sensitivity (Hoshi 2007) and their wide use in fNIRS hyperscanning studies (Cui et al. 2012; Baker et al. 2016; Nozawa et al. 2016; Feng et al. 2020).

IBS frequency band

To assess the relationship between HbO time series, we used the WTC toolbox in MATLAB (Grinsted et al. 2004). Following the visual inspection of WTC graphs (Fig. 1e) and the literature, we identified the frequency band of 0.08–0.25 Hz as the most sensitive for our task. Data >0.20 Hz (0.20–0.25 Hz) was excluded to prevent an effect of respiration (0.20–0.30 Hz) (Xue et al. 2018). Ultimately, the frequency band of 0.08–0.20 Hz was chosen as the frequency band of interest in this study.

IBS evaluation

We used the MATLAB function “coherence” to compute the brain synchronization (coherence) of the 20 paired channels across conditions and calculated the task-related IBS. However, unlike most previous studies, our task-related IBS was not defined as the mean coherence in the task condition minus the mean coherence in the rest state (Cui et al. 2012; Cheng et al. 2015; Baker et al. 2016; Xue et al. 2018). Instead, we calculated the coherence in each video-watching condition (sad videos or neural videos) and compared the 2 video-watching coherences in the same trial in the 4 conditions (AE in the sad condition, CE in the sad condition, AE in the neutral condition, and CE in the neutral condition). We chose this method following some neuroimaging studies indicating that appropriate task conditions usually provide a better baseline than rest states (Stark and Squire 2001; Reindl et al. 2018). Finally, we converted task-related IBS into Fisher z-statistics and replaced bad channel values with the mean IBS values (Chang and Glover 2010; Cui et al. 2012; Cheng et al. 2015).

Granger causality analysis

We used GCA to examine the directionality between time series of neural data. GCA is a standard statistical tool that can be used to calculate the directionality of system components and has been successfully applied in neuroscience (Luo et al. 2013). In our study, we applied GCA for all conditions in all channels by HERMES (Niso et al. 2013) (http://hermes.ctb.upm.es/). Our GCA was carried out by using a model order of 3, which was estimated by selecting 100 random vectors in HERMES (Niso et al. 2013). This model order was fixed across all data because all data underwent the same treatments. The GC in the 2 groups (C-C dyads and S-S dyads) of participants in both directions (regulator→target & target→regulator) was computed. During this analysis, we did not consider any time delay. Finally, we converted GC values into Fisher z-statistics and replaced bad channel values with the mean GC values for further analysis.

Statistical analysis

All statistical analyses were carried out using SPSS 22.0 (IBM, New York, NY, USA), with the alpha level set at 0.05 (2-tailed). For self-report measurements, we first performed a reliability analysis to examine the quality of the tests in our study. Then, we conducted independent-samples *t*-tests to confirm that there were no significant differences between C-C dyads and S-S dyads except in relationship closeness. Behavioral performance was defined as the sadness evaluation of targets after watching each video. We conducted a preliminary 2 (GROUP: C-C or S-S dyad) × 2 (target GENDER: male or female) × 2 (VIDEO: sad or neutral) × 2 (REGULATION: AE or CE) × 2 (TIME: before or after regulation) ANOVA on behavioral performance with GROUP and GENDER as between-participant factors and VIDEO, REGULATION, and TIME as within-participant factors. We also conducted a 2 (GROUP: C-C or S-S dyad) × 2 (target GENDER: male or female) × 2 (VIDEO: sad or neutral) × 2 (REGULATION: AE or CE) Greenhouse–Geisser-corrected ANOVA on IBS, with GROUP and GENDER as between-participant factors and VIDEO and REGULATION as within-participant factors. For GC values, we first calculated the "GC change" (GC value before regulation—GC value after regulation in the same trial), similar to the calculation of IBS. Then, we performed 2 (GROUP: C-C or S-S dyad) × 2 (target GENDER: male or female) × 2 (VIDEO: sad or neutral) × 2 (REGULATION: AE or CE) × 2 (DIRECTION: regulator→target or target→regulator) Greenhouse–Geisser adjusted ANOVAs on synchronous channels, with GROUP and GENDER as between-participant factors and VIDEO, REGULATION, and DIRECTION as within-participant factors. Finally, Pearson correlation analyses were performed to determine the relationship between brain data and behavioral indices.

Results

Subjective measurements

The results of subjective measurements showed that participants of different dyad types had no differences in RESE, $t(118) = 1.65$, $P = 0.102$, or IER preference, $t(118) = -0.36$, $P = 0.716$, although the dyads differed in closeness, $t(118) = 19.16$, $P < 0.001$, which meant they were highly matched (Table 2). No differences were found in RESE, $t(118) = 0.37$, $P = 0.710$, IER preference, $t(118) = -0.72$, $P = 0.473$, or closeness, $t(118) = -1.28$, $P = 0.202$, according to target gender.

Behavioral performance

The 2 × 2 × 2 × 2 × 2 ANOVA revealed a significant main effect of VIDEO, $F(1, 416) = 1138.67$, $P < 0.001$, $\eta_p^2 = 0.73$, TIME, $F(1, 416) = 8.29$, $P = 0.004$, $\eta_p^2 = 0.20$, GROUP, $F(1, 416) = 9.18$, $P = 0.003$, $\eta_p^2 = 0.22$ (Fig. 2a), and GENDER, $F(1, 416) = 12.35$, $P < 0.001$, $\eta_p^2 = 0.29$ (Fig. 2b) on the sadness evaluation. Significant VIDEO × TIME, $F(1, 416) = 22.66$, $P < 0.001$, $\eta_p^2 = 0.52$, and VIDEO × GENDER interactions, $F(1, 416) = 16.97$, $P < 0.001$, $\eta_p^2 = 0.39$ were also observed. The simple effect analysis of the VIDEO × TIME interaction revealed that the sadness evaluation in the sad condition was obviously lower after regulation ($M = 3.93$, $SE = 0.07$) than before regulation ($M = 4.10$, $SE = 0.07$), $P < 0.001$; however, no such difference was found in the neutral condition, $P = 0.342$. In addition, simple effect analysis of the VIDEO × GENDER interaction (Fig. 2c) revealed that the sadness evaluation ($M = 4.32$, $SE = 0.09$) in the sad condition was significantly higher when the target was male than when the target was female ($M = 3.70$, $SE = 0.11$), $P < 0.001$; however, no such difference was found in the neutral condition, $P = 0.917$ (Bonferroni- and Greenhouse–Geisser-corrected).

Task-related IBS

The 4-way ANOVA yielded significant REGULATION × GROUP interactions in CH12, $F(1, 56) = 9.81$, $P = 0.003$, $\eta_p^2 = 0.15$, and CH13, $F(1, 56) = 4.01$, $P = 0.050$, $\eta_p^2 = 0.17$ as well as a significant REGULATION × GENDER interaction in CH13, $F(1, 56) = 4.80$, $P = 0.033$, $\eta_p^2 = 0.18$. The simple effect analysis of the REGULATION × GROUP interaction in CH12 showed that the IBS of C-C dyads was lower in the AE condition ($M = -0.21$, $SE = 0.13$) than in the CE condition ($M = 0.19$, $SE = 0.12$), $P = 0.022$; by contrast, the IBS of S-S dyads was higher in the AE condition ($M = 0.21$, $SE = 0.12$) than in the CE condition ($M = -0.15$, $SE = 0.11$), $P = 0.017$ (Fig. 3a). The simple effect analysis of the REGULATION × GROUP interaction in CH13 showed that IBS in the CE condition was higher in C-C dyads ($M = 0.18$, $SE = 0.09$) than in S-S dyads ($M = -0.11$, $SE = 0.09$), $P = 0.031$, while no such difference was found in the AE condition, $P = 0.316$ (Fig. 3b). Furthermore, the simple effect analysis of the REGULATION × GENDER interaction in CH13 showed that the IBS in the CE condition was lower when the target was male ($M = -0.14$, $SE = 0.08$) than when the target was female ($M = 0.21$, $SE = 0.10$), $P = 0.011$; no such difference was found in the AE condition, $P = 0.365$ (FDR and Greenhouse–Geisser-corrected).

Directional coupling

The 5-way ANOVA on GC in CH12 revealed 2 significant 3-way interactions: a VIDEO × GROUP × GENDER interaction, $F(1, 56) = 4.96$, $P = 0.030$, $\eta_p^2 = 0.14$, and a VIDEO × GROUP × REGULATION interaction, $F(1, 56) = 4.77$, $P = 0.033$, $\eta_p^2 = 0.12$. Simple effect analyses were performed and revealed 2 main results. First, the GC change in the neutral condition was lower in C-C dyads ($M = -0.39$, $SE = 0.19$) than in S-S dyads ($M = 0.20$, $SE = 0.16$) when the target was female, $P = 0.025$; no such difference was observed when the target was male, $P > 0.239$. Second, the GC change in the AE condition was lower in C-C dyads ($M = -0.38$, $SE = 0.14$) than in S-S dyads ($M = 0.29$, $SE = 0.13$), $P = 0.001$ in the neutral condition; no such difference was observed in the sad condition, $P > 0.438$.

The 5-way ANOVA on GC in CH13 revealed a main effect of GROUP, $F(1, 56) = 7.09$, $P = 0.018$, $\eta_p^2 = 0.23$, and a significant 4-way interaction of <u>GROUP</u> × <u>VIDEO</u> × <u>REGULATION</u> × GENDER (Fig. 4), $F(1, 56) = 5.44$, $P = 0.023$, $\eta_p^2 = 0.18$; there were no other main effects or interactions ($P > 0.05$). The simple effect analysis

Table 2. Descriptive statistics for the psychological measurements.

	Whole sample		C-C dyads		S-S dyads	
	M	SD	*M*	SD	*M*	SD
PRQC score	25.92	13.48	37.58	4.02	14.27	8.52
RESE score	42.62	5.69	43.47	5.78	41.77	5.52
IERQ score	64.43	11.22	64.05	11.97	64.80	10.50

Note: PRQC: Perceived Relationship Quality Components scale; RESE: Regulatory Emotional Self-efficacy scale; IERQ: Interpersonal Emotion Regulation Questionnaire; C-C dyads: couple dyads; S-S dyads: stranger dyads; *M*: mean value.

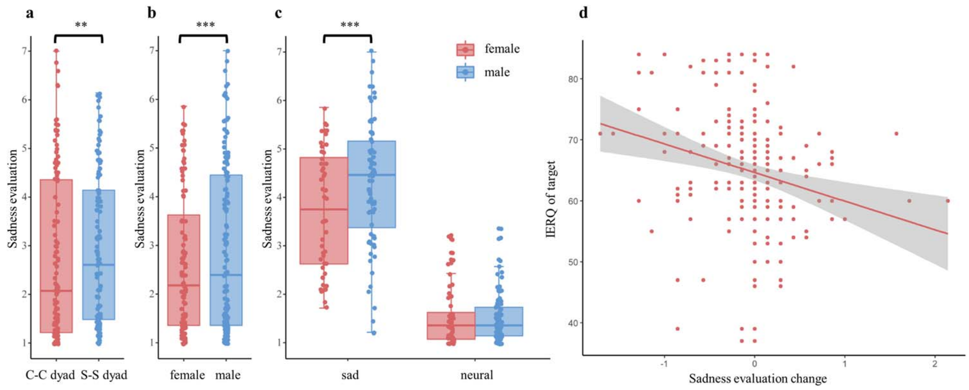

Fig. 2. Behavioral results. a) The main effect of group. b) The main effect of gender. c) The interaction effect of video and gender. d) The correlation between sadness evaluation change and IERQ scores of targets. C-C dyad: couple dyad; S-S dyad: stranger dyad. Error bars indicate standard errors. $^{**}P < 0.01$; $^{***}P < 0.001$ (Bonferroni- and Greenhouse–Geisser-corrected).

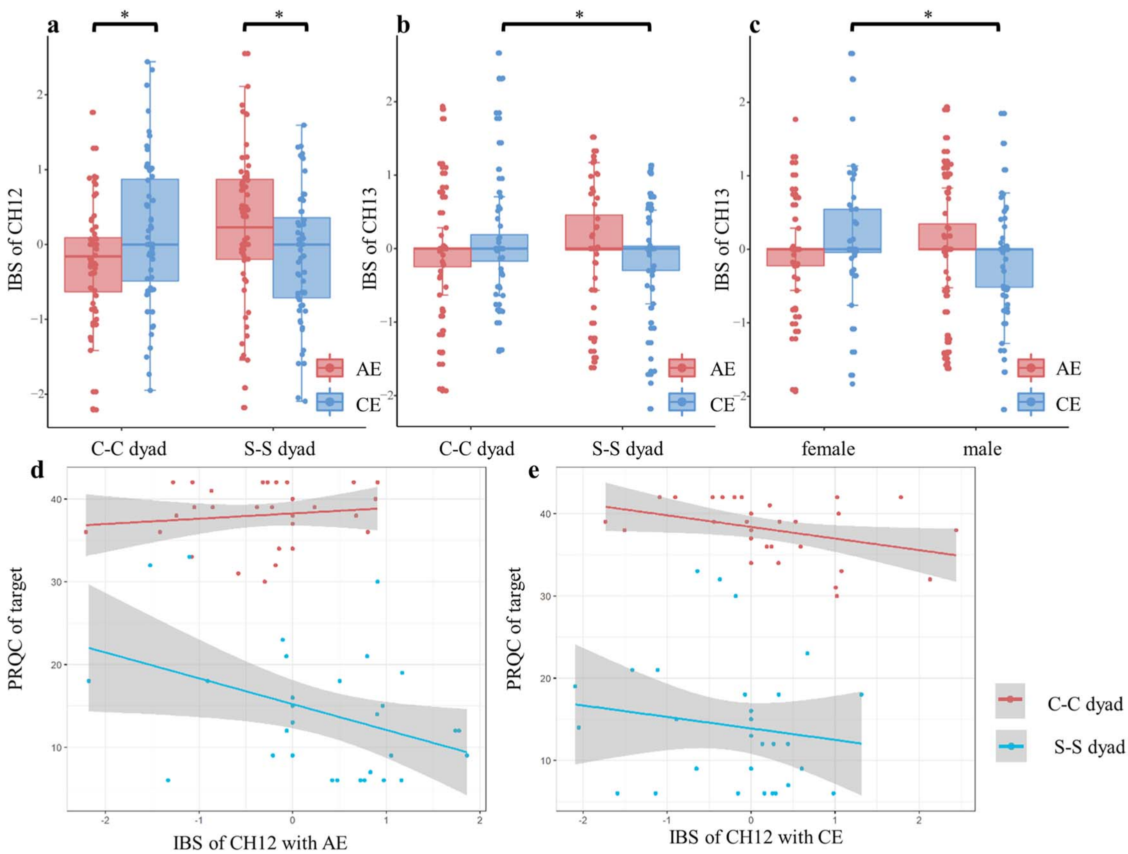

Fig. 3. Results of interbrain synchronization (IBS). a) The effect of the interaction between group and regulation on IBS in CH12. b) The effect of the interaction between group and regulation on IBS in CH13. c) The effect of the interaction between gender and regulation on IBS in CH13. d) The correlations of the IBS in CH12 with AE and PRQC scores of targets in the 2 groups. e) The correlations of the IBS in CH12 with the CE and PRQC scores of targets in the 2 groups. C-C dyad: couple dyad; S-S dyad: stranger dyad. Error bars indicate standard errors. * $P < 0.05$ (IBS: FDR- and Greenhouse–Geisser-corrected; correlations: Bonferroni-corrected). The red line denotes results of C-C dyads, while the blue line denotes results of S-S dyads.

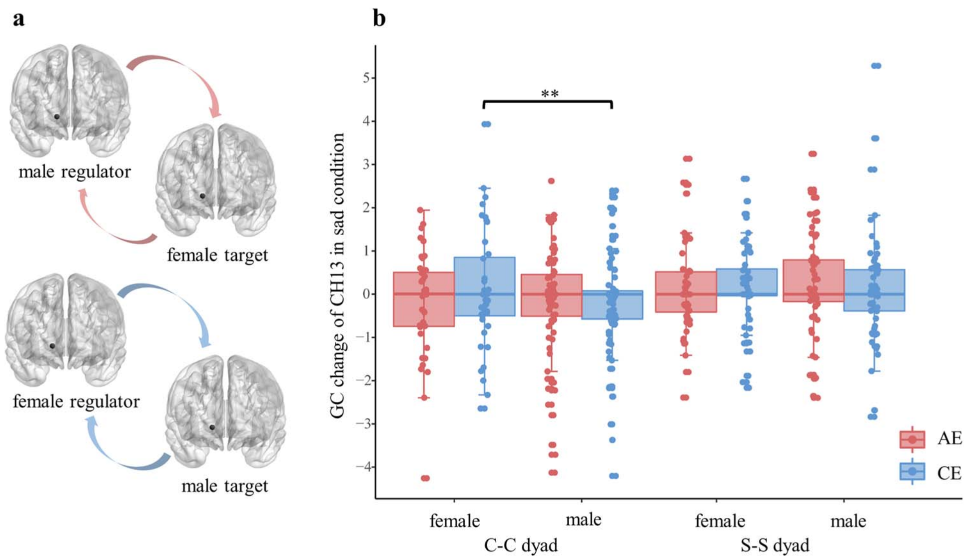

Fig. 4. Directional coupling results. a) Direction of GC values in CH13 when the target was female (top) or male (bottom) (i.e. regulator→target and target→regulator). b) The mean GC change in AE and CE in the sad condition in different dyads with male and female targets. C-C dyad: couple dyad; S-S dyad: stranger dyad. Error bars indicate standard errors. $^{**}P < 0.01$ (FDR- and Greenhouse–Geisser-corrected).

indicated that when couples used CE to regulate sadness in the sad condition, the GC change was lower when the target was male ($M = -0.42$, $SE = 0.18$) than when the target was female ($M = 0.46$, $SE = 0.26$), $P = 0.008$; no such difference was observed in the neutral condition, $P > 0.05$.

Brain–behavior association

To simplify calculations, we converted behavioral performance into "sadness evaluation change," calculated as the first sadness evaluation–the second sadness evaluation in the same trial, such as IBS and GC change. Then, we performed Pearson correlation analyses to determine the associations among IBS in CH12 or CH13, GC change in CH12 or CH13, change in evaluated sadness, and subjective measurements. In all subjects, sadness evaluation change was negatively correlated with the EPA score (subscale of the IERQ) ($r = -0.27$, $P < 0.001$), PT score (subscale of the IERQ) ($r = -0.18$, $P = 0.023$), SM score (subscale of the IERQ) ($r = -0.21$, $P = 0.001$), and IERQ total score ($r = -0.22$, $P = 0.001$) of the target (Fig. 2d).

Second, the IBS in CH12 with the AE condition was negatively correlated with the PRQC scores of the target in S-S dyads ($r = -0.38$, $P = 0.034$), and the IBS in CH12 with the CE condition was negatively correlated with the PRQC scores of the target in C-C dyads ($r = -0.37$, $P = 0.041$). No difference was detected in other conditions ($P > 0.434$) (Fig. 3d and e).

Third, the GC change in CH13 (in the target→regulator direction, with the CE condition) was significantly correlated with the DES score (subscale of the RESE) of the target in C-C dyads (Fig. 5b), for both male ($r = 0.59$, $P = 0.012$) and female targets ($r = 0.61$, $P = 0.027$); no such correlation was observed in S-S dyads (Fig. 5c and d) or in the AE condition ($P > 0.229$) (Fig. 5a). In C-C dyads, the GC change in CH13 in the regulator→target direction after CE was negatively correlated with the EPA score (subscale of the IERQ) of the regulator when the target was male ($r = -0.48$, $P = 0.048$); no such correlation was observed when the target was female ($P = 0.978$) (Fig. 5e).

In S-S dyads, the GC change in CH13 in the regulator→target direction after CE was positively correlated with the ANG score (subscale of the RESE scale) of the regulator when the target was male ($r = 0.57$, $P = 0.016$), and no correlation was observed when the target was female ($P = 0.451$) (Fig. 5f). Correlations in C-C dyads are presented in Fig. 6. Further correlation results are provided in the Supplementary Material (Supplementary Figs. 1–6).

Discussion

This study used the fNIRS hyperscanning technique to explore the underlying neural mechanisms of using AE and CE to regulate a partner's sadness in couples. The results showed that these 2 IER strategies were more effective for couples than for strangers. Moreover, there was a gender difference in that IER strategies were more effective in regulating female targets' sadness. Similarly, in when CE was applied, increased neural activity, including changes in IBS and GC, were observed when male participants regulated their female partners' sadness. These findings suggest gender differences in the neural patterns of couples during IER, which are discussed below.

First, previous studies have demonstrated that viewing a photograph of one's lover reduces pain while receiving thermal stimulation. Consistent with these studies, we found reduced sadness after IER in couples compared to strangers, which means that IER was more effective for couples. From an evolutionary perspective, the affective bonds between individuals in a couple could help them regulate sadness more effectively through biobehavioral synchrony (Phillips et al. 2008; Koole et al. 2015; Djalovski et al. 2021). However, there is another possibility. Regulating a stranger's emotion is not typical in Chinese culture, which might lead to weakened influences on alleviating sadness in stranger dyads compared to couple dyads. In our study, we did not measure subjective feelings about providing or receiving IER and could not determine that weakened sadness evaluation was due to subjective feelings about IER, the unnaturalness of the task, or both. Future studies should employ IER in more kinds of interpersonal relationships to address these questions.

Second, a gender difference was observed in that female targets had lower sadness evaluations than male targets. According to previous studies, women are sensitive to emotions (Zaid et al. 2021), while men tend to avoid expressing or experiencing emotions (Tamres et al. 2002. Therefore, it seems that both AE and CE work better for female targets. However, our neural evidence

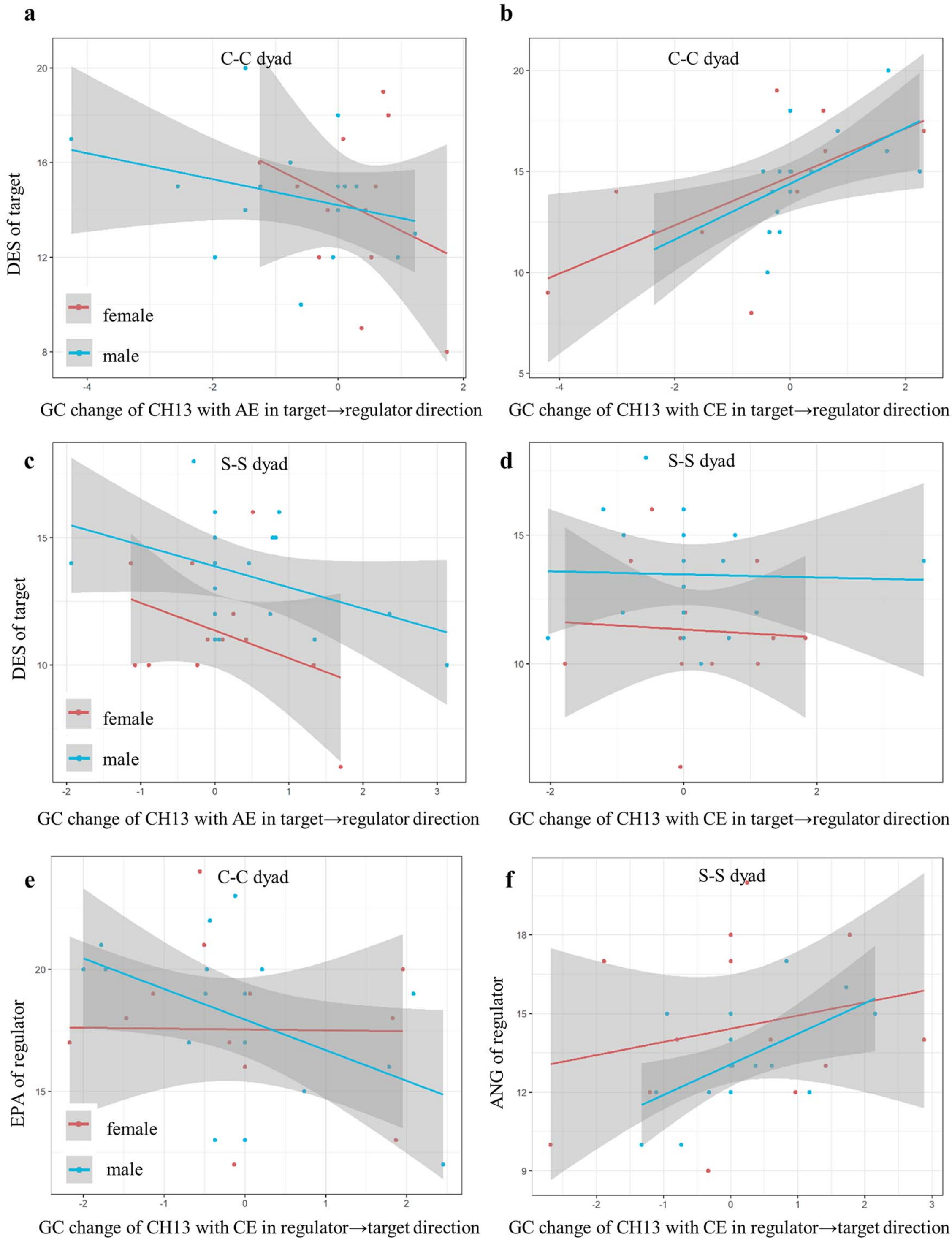

Fig. 5. Correlational results of GCA. a) The correlation between GC changes in CH13 in the target→regulator direction after AE and DES scores of targets in C-C dyads. b) The correlation between GC changes in CH13 in the target→regulator direction after CE and DES scores of targets in C-C dyads. c) The correlation between GC change in CH13 in the target→regulator direction after AE and DES scores of targets in S-S dyads. d) The correlation between GC changes in CH13 in the target→regulator direction after CE and DES scores of targets in S-S dyads. e) The correlation between GC changes in CH13 in the regulator→target direction after CE and EPA scores of regulators in C-C dyads. f) The correlation between GC changes in CH13 in the regulator→target direction after CE and ANG scores of regulators in S-S dyads. C-C dyad: couple dyad; S-S dyad: stranger dyad. The red line displays data of dyads with female targets, and the blue line displays data of dyads with male targets.

that the IBS in CH13 (BA10, r-MFG) was lower in female targets than in male targets after CE and that no gender difference was detected after AE further indicates differences in the neural mechanisms by which CE is triggered in targets of different genders. This result also indicates that the r-MFG (a key node of the frontoparietal network) is engaged in explicit ER tasks and can inhibit the salience network to enhance awareness of sadness (McRae et al. 2008; Hallam et al. 2014; Arias et al. 2020).

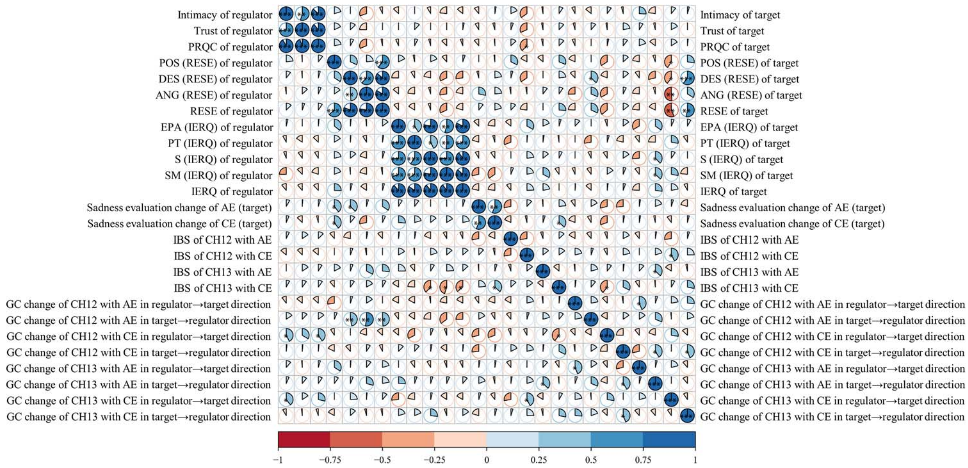

Fig. 6. Correlational results in C-C dyads. Data in the matrix below the diagonal line (lower triangle) are the regulator results, while data in the matrix above the diagonal line (upper triangle) are the target results. IBS: interpersonal brain synchronization. The color bar indicates the Pearson correlation coefficient. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. Bonferroni-corrected.

Third, our GCA provided more details about this gender difference. We found that the GC change in CH13 after CE was lower in the sad condition when the target was male than when the target was female, while no gender difference was discovered after AE. When the target was male, CE was more effective in regulating sadness. This might be because men usually avoid expressing and experiencing emotions and tend to use regulation strategies that do not expose emotions in intrapersonal ER, such as cognitive reappraisal (McRae et al. 2008). Thus, male partners consciously use cognitive strategies, while female partners use CE during sadness IER. In our study, the couples were college students in the early stage of their romantic relationships, which is the time when men exert themselves, attempt to appear favorably, and seek sexual partners (Pan et al. 2017). Therefore, when men used CE to help regulate their female partner's sadness, the opposite result was observed. Alternatively, there is another potential explanation. According to the study of Long and her coworkers (2021), women in romantic relationships may be better at predicting the subsequent actions of their male partners. This means that after realizing that their partner is sad, female regulators can use CE in a more tailored way than strangers, such as speaking in a softer tone.

Fourth, after AE was used with male targets in couples, the IBS in CH13 was positively correlated with the ANG scores of both female regulators and male targets. For female targets, the IBS in CH13 after AE was negatively correlated with the ANG scores of male regulators. These correlations provide indirect evidence of gender differences in neural patterns after AE in couples. Additionally, after CE was applied in couples, the GC change in CH13 in the regulator→target direction was positively related to the felt intimacy of the regulator, while the GC change in CH13 in the target→regulator direction was positively correlated with the DES score and RESE score of targets. There was a unique neural pattern without any gender difference when couples used CE to regulate their partners' emotions, and this pattern was correlated with managing the despondency distress of targets.

In our study, a major limitation was that our sample size in the C-C group was small and unequal (e.g. 11 vs. 19). During statistical analysis, we noticed that some data failed Mauchly's test of sphericity and therefore corrected all ANOVA data with the Greenhouse–Geisser method. However, it was difficult to ensure the normality of data and statistical power, given the small sample size; further research is needed to verify our results. Additionally, in our study, all the couples that we recruited had been together for more than a month and were differentiated from strangers according to measures of trust and intimacy. However, this may be too simple a method that overlooks some information. In the future, we may need a more precise definition of romantic relationships to separate them from other relationships.

In summary, our results partly resolved the debate over whether affective or cognitive regulation of sadness is more effective in couples. Although both AE and CE activated affective bonds in couples, CE seemed to be more effective for female targets. The findings mainly focus on gender differences in cognitive regulation in the process of IER and deepen our understanding of sadness IER in couples.

Acknowledgments

We are delighted to acknowledge help and advice from Prof. Hongjin Sun, Department of Psychology, Neuroscience and Behaviour, McMaster University, Canada.

CRediT authors statement

Wenhai Zhang (Conceptualization, Funding acquisition, Methodology, Supervision, Writing—original draft), Lanting Qiu (Data curation, Investigation, Visualization, Writing—original draft), Fanggui Tang (Funding acquisition, Resources), and Hong Li (Validation)

Supplementary material

Supplementary material is available at *Cerebral Cortex* online.

Funding

This study was funded by the Hunan Natural Science Foundation of China (2022JJ30099), the Educational Science Planning Research Achievements of Hunan Province (XJK18AJG002), the Research Project of Shanghai and Technology Commission (20dz2260300), and the Fundamental Research Funds for the Central Universities.

Conflict of interest statement: None declared.

Data and code availability

All data of the study are available from the corresponding author by request with no restrictions.

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