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# Brains in sync, friends in empathy: interbrain neural mechanisms underlying the impact of interpersonal closeness on mutual empathy

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Many everyday empathetic experiences arise within our social interactions and depend significantly on interpersonal closeness. However, the interbrain processes underlying social-oriented empathy by interpersonal closeness remain unclear. To address this gap, we conducted a dyadic social judgement task with dyads of friends and strangers, where targets received social evaluative feedback and empathizers observed the scenario in different experimental trials. Results showed that dyads of friends exhibited greater affect sharing than strangers when witnessing their partners being accepted or rejected. This was supported by the more pronounced event-related potential similarity in friends during the 340–840 ms post-feedback window, mediating the link between interpersonal closeness and affect sharing. Furthermore, witnessing emotional feedback elicited greater interbrain neural synchronization of brain $\alpha$-oscillation between the empathizer's left prefrontal cortex and the target's left temporoparietal junction in dyads of friends compared with those of strangers. This empathy-related synchronization was associated with mutual affect sharing within dyads of friends but not within dyads of strangers. Our findings highlight the sensitivity of empathy to interpersonal closeness, which links to sustained attention and detailed evaluation in social scenarios, along with functional communication between brain regions for mentalizing and emotional regulation. These insights have therapeutic potential for improving social functioning and relationship satisfaction.

## 1. Introduction

Empathy is a complex and multifaceted process involving the understanding and sharing of others' feelings, essential for effective social interaction and relationships. Most theories define empathy with both cognitive and affective components: cognitive empathy involves empathizers identifying targets' emotional states, while affective empathy involves empathizers vicariously responding with the same emotions as the targets [1]. As an alternative measurement framework, Coll *et al*. [2] proposed viewing empathy as a process with at least two constituent parts: emotion identification (the accuracy of an empathizer identifying the target's state) and affect sharing (the degree to which the empathizer's state matches the identified target's state). This framework suggests that affect sharing is best measured by the extent to which the empathizer's felt emotion compares to the identified emotion in the target, even if the felt emotion differs from the target's actual feeling. This contrasts with the traditional viewpoint, where the target's actual emotion is deemed as the reference for judging the empathizer's state, better characterizing the cognitive processes of empathy, especially in the context of interpersonal interaction.

## (a) Empathy for social experiences

Neuroimaging studies have shown that both first-hand painful experiences and observing others' physical pain consistently activate the dorsal anterior cingulate cortex (dACC) and anterior insula (aINS), regions associated with the affective component of pain [3–6]. These findings suggest that empathizers form affective links with targets, allowing them to vicariously 'feel' another person's distress. However, empathy also extends to various social experiences in daily interactions [7–9]. Negative social experiences, such as rejection or exclusion, can threaten fundamental psychological needs (e.g. self-esteem, belonging and control) and elicit emotional distress, while positive social experiences, such as inclusion and support, are associated with pleasant feelings and psychological wellbeing [10,11]. Therefore, understanding the neural basis of empathy in social contexts is crucial for understanding social behaviour, interpersonal relationships and wellbeing.

Studies have shown similarities in brain activation when empathizing with social exclusion and experiencing physical pain, particularly in the dACC and aINS, suggesting overlapping neural mechanisms [12,13]. Recent studies have expanded our understanding of empathy for positive and negative social experiences, such as witnessing others' joy or distress [7,14,15]. For instance, Taiwo *et al*. [15] found that the frontopolar medial prefrontal cortex (PFC) is activated in both empathetic happiness and sadness, with empathetic happiness engaging a broader network of prefrontal regions. These findings highlight the neural mechanisms of empathy for different social emotions and the importance of considering the valence of social experiences in empathetic processing.

## (b) Interpersonal closeness modulates empathy

According to the perception-action model of empathy [16], witnessing or imagining another person's experience activates our internal representations of that experience, leading to similar physiological and sensory responses. This model suggests that familiarity or closeness with another individual enhances empathetic responses by enabling us to develop richer representations of their internal states. Studies have shown stronger empathetic responses and activations in the dACC and aINS when observing the pain of close individuals compared with strangers [6,17–20]. Specifically, empathy tends to be higher for cultural in-groups than out-groups [6,20], and imagining a loved one versus a stranger enhances empathy-related brain responses [18].

Familiarity and closeness also enhance empathy in social contexts. For instance, observing friends being socially excluded activates brain regions associated with personal exclusion (dACC and aINS) and self-referential thinking (medial PFC) more than observing strangers' exclusion [21–23]. Similarly, Ma *et al*. [24] found that self-other overlap boosts empathetic responses to others' gains and losses. These findings suggest that closer relationships lead to heightened empathetic neural responses to others' social experiences. Indeed, familiarity and closeness with an individual allow for a richer and fine-grained psychological representation of that person's experience in specific social situations [25], leading to stronger empathy.

## (c) Interbrain neural synchronization in empathy

Unlike traditional neuroimaging methods, which focus on single-brain activities, hyperscanning records neural activities from multiple individuals simultaneously during real-time interactions [26,27]. Interbrain neural synchronization (INS) was then proposed to describe coordinated brain activities between individuals during social cognition and communication, indicating functional connectivity and information exchange [28–30]. Using functional near-infrared spectroscopy, electroencephalography (EEG) or functional magnetic resonance imaging (fMRI), hyperscanning allows researchers to study INS during a variety of social interactions. For instance, EEG hyperscanning by Dumas *et al*. [28] showed increased phase synchronization in $\alpha$-$\mu$, $\beta$ and $\gamma$-bands during social imitation, with $\alpha$-$\mu$ rhythm most robustly distinguishing behavioural synchronization from non-synchronization in the centroparietal regions of interacting partners. Similarly, fMRI hyperscanning by Bilek *et al*. [31] revealed neural synchronization in the temporoparietal junction (TPJ) during cooperative tasks, suggesting possible information flow during dyadic interaction.

Empathy, a two-person process, involves mutual emotional resonance, making hyperscanning ideal for studying interbrain mechanisms underlying empathy [30,32,33]. INS quantifies neural alignment between empathizers and targets, offering insights into the neural basis of empathy [34–37]. For example, Goldstein *et al*. [35] found that hand-holding during pain increased INS in the $\alpha$-band, correlating with analgesia and empathetic accuracy. Peng *et al*. [36] showed that shared painful experiences enhanced sensorimotor $\alpha$-oscillation synchronization, strengthening social bonds and prosocial behaviour. Additionally, empathy during distressing or troubling events elicited $\alpha$, $\beta$ and $\gamma$-band synchronization in sensorimotor and bilateral temporal areas [34]. These studies highlight the potential roles of INS in empathy. However, the interbrain mechanisms of empathy for social experiences (e.g. social acceptance or rejection) and how they are influenced by interpersonal closeness remain unclear.

## (d) The present study

While studies have explored single-brain mechanisms in empathizers, the interbrain mechanisms elucidating how interpersonal closeness shapes empathy in social situations remain to be established. To address this gap, the present study investigates whether and how interbrain mechanisms involved in empathy for positive and negative social experiences are influenced by interpersonal closeness. A dyadic social judgement paradigm was used to gauge empathy for social experiences between targets and empathizers. In this task, social feedback from fictitious 'peers' (dislike, neutral or like) was randomly directed to one participant of a dyad (targets) in different experimental trials, while the other participant observed the situation (empathizers). Two experiments ($n$ = 108 dyads) were conducted to assess the impact of interpersonal closeness on empathy in social contexts. Experiment 1 tested the dyadic social judgement paradigm's ability to elicit positive and negative empathy and examined how interpersonal closeness affects empathetic ratings. Experiment 2 simultaneously recorded behavioural and neural reactivities to explore the interbrain mechanisms underlying how interpersonal closeness shapes empathy.

## 2. Material and methods

### (a) Participants

A total of 60 dyads of female college students (aged 20.47 ± 0.15 years, mean ± s.e.m.) participated in experiment 1 (behavioural experiment), while another 48 dyads (aged 20.84 ± 0.23 years) took part in experiment 2 (EEG experiment). None of the participants reported any cardiovascular or neurological diseases, acute or chronic pain, psychiatric disorders or current use of medication. Participants were assigned to dyads categorized into two groups: strangers (females meeting for the first time) and friends (females considering each other as one of their top five 'best friends' but not romantically involved). Data from one dyad in experiment 1 and two dyads in experiment 2 were excluded owing to failure to follow experimental instructions. Thus, data from 59 dyads (30 dyads of friends, 29 dyads of strangers) in experiment 1 and 46 dyads (22 dyads of friends, 24 dyads of strangers) in experiment 2 were included in the formal analysis. Before the experiments, written informed consent was obtained from each participant in accordance with the Declaration of Helsinki. The experimental procedures were approved by the Ethics Committee of the Shenzhen University Medical School.

### (b) General experimental procedure

Before the experiment, participants completed self-report questionnaires on general demographics, the interpersonal reactivity inventory to measure trait empathy [38], and the rejection sensitivity questionnaire to assess sensitivity to social rejection [39]. A dyadic social judgement paradigm was used to evaluate their reactions to social acceptance and rejection directed at themselves or their partners. Participants visited the laboratory twice: the first time for the cover story and the second time to receive social evaluations made towards themselves or their partners.

During the first visit, participants were told they were part of an inter-college study on first impressions among peers. They viewed 180 neutral-expression portrait photos of peers and rated them as liked, disliked or neutral based on their first impressions. Participants were then photographed with a neutral expression and told that peers from other colleges would also evaluate their photos. About one week after the cover story, participants in dyads were informed that peers had given first impressions of their photographs and that they would view the feedback together. To evoke positive emotions from receiving social acceptance feedback and negative emotions from social rejection, participants were made to believe that the evaluative feedback was from 'peers'. However, unbeknownst to the participants, the feedback was fictitious, and their photographs were not genuinely evaluated by these 'peers'. Ensuring participants believed the authenticity of the social feedback was crucial, as genuine feelings were necessary for the study. Hence, deception was inevitable in this paradigm.

Upon arriving at the laboratory, each participant first completed the inclusion of other in the self (IOS) scale to measure how close they felt to their partner [40]. The IOS scale involves choosing one of seven pairs of circles (ranging from just touching to almost completely overlapping) to describe their relationship with their partner. During the dyadic social judgement task, each pair of participants sat face-to-face in front of two separate computer screens (as shown in figure 1*a*). This set-up ensured real social interaction as they performed the task in each other's presence, but the separate screens allowed individualized ratings according to instructions displayed on their own screens. Participants were instructed not to talk throughout the experiment. To minimize potential negative consequences, all participants were debriefed after the completion of the formal experiment. They were informed that their portraits were not judged by any peers and that the feedback they received was fictitious. The aim of the study and the reason for the cover story were also explained to the participants, and an apology was made for the deception.

### (c) Dyadic social judgement paradigm

The study followed a 2 (interpersonal closeness: friends versus strangers) × 3 (social feedback: like versus neutral versus dislike) experimental design. A within-dyad control with neutral feedback assessed whether behavioural or neural synchronization stemmed from processing the same stimuli or affective interplay. A between-dyad control with strangers tested if empathy-related responses depended on interpersonal closeness. This experimental setting allowed for investigating how empathy for positive and negative social experiences is influenced by target-empathizer closeness.

As shown in figure 1*b*, the task involved two target stimuli: a down arrow indicated feedback directed to the self, and an up arrow indicated feedback directed to the partner. There were three types of social feedback: a *tick* for liked, a *bar* for neutral and a *cross* for disliked. Feedback, unknown to participants, was randomly generated and presented in a pseudorandom order, with equal numbers for each condition (six conditions: two feedback targets × three social feedback types). The experiment included 30 trials per condition, totalling 180 trials, administered in three blocks of 60 trials each, with 2–3 min breaks between

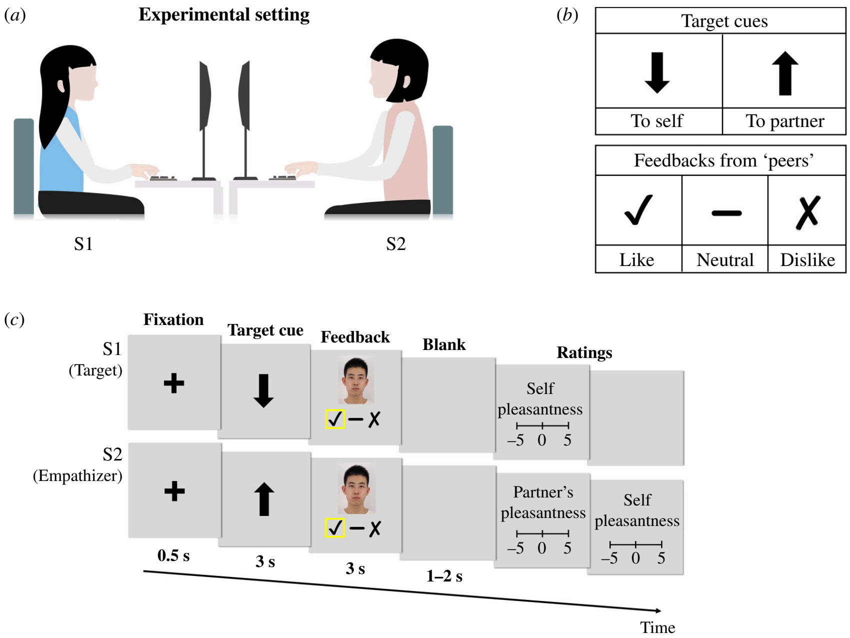


**Figure 1.** Schematic illustration of the experimental procedure. (*a*) Illustration of the dyadic experimental setting. Two participants in a dyad (S1 and S2) sat opposite each other with monitors and keyboards placed in front of them. (*b*) Types of target stimuli and feedback from peers**.** There were two types of target stimuli, with up-directed and down-directed arrows indicating whether the feedback was directed towards the self or the partner, respectively. Feedback from 'peers' was of three types: like, neutral or dislike. (*c*) Trial structure of the dyadic social judgement task**.** In the example trial, S1 was the feedback target, and S2 was the empathizer. The trial began with a 0.5 s fixation, followed by a 3 s cue indicating the target of the upcoming feedback evaluation. Next, the portrait of the peer and the feedback directed towards the target were presented for 3 s, with the feedback highlighted using a yellow rectangle. After a blank screen for 1–2 s, the target provided a rating of their emotional experience, while the empathizer provided two ratings: one for estimating the partner's emotional experience and one for their own perceived emotional experience. These ratings were made on predefined numerical scales (−5 = extreme unpleasantness, 0 = neutral, 5 = extreme pleasantness).

blocks. Trials were pseudorandomly ordered so each block contained 10 trials per condition. Participants completed training trials before the formal task.

The structure of a single trial is shown in figure 1*c*. Each trial began with a 0.5 s fixation, followed by a 3 s target cue indicating the target of the upcoming social evaluation. Then, the peer's portrait and their feedback towards the target (self or partner) were displayed, highlighted by a yellow rectangle. The target then rated the pleasantness of the feedback, while the empathizer provided two ratings: their estimation of the partner's pleasantness and their own. Ratings were made on an 11-point numeric rating scale (NRS; −5 for extreme unpleasantness, 0 for neutral, 5 for extreme pleasantness).

## (d) Dyad-level empathetic ratings

Two outcome measures of empathetic reactivity within the dyad, emotion identification and affect sharing, were assessed for each trial [2,41]. Emotion identification refers to the accuracy with which one can discern another's feelings and was calculated as the absolute difference between the target's self-rating and the empathizer's rating of the target's state (|target's self-rating – empathizer's rating of the target's state|). A lower score signifies greater accuracy in emotion identification. Affect sharing represents the instantiation of the state of others in self that was driven by identifying other's state, which was computed as the difference between the empathizer's self-rating and the empathizer's rating of the target's state (empathizer's self-rating – empathizer's rating of the target's state). A higher score indicates a greater extent of affect sharing, reflecting a more substantial emotional response in the empathizer triggered by cognitive appraisal of the other's state [41]. Given that pleasantness ratings were assigned to 'like' feedback and unpleasantness ratings to 'dislike' feedback, these ratings were oppositely directed to the NRS. To facilitate comparisons between conditions, we converted the ratings for the 'dislike' condition to their opposites. For each dyad, empathetic ratings were calculated by averaging single-trial ratings across epochs within the same experimental condition, resulting in two empathetic ratings (emotion identification and affect sharing) for three conditions (like, neutral and dislike). We also computed differences in empathetic reactivity (Δemotion identification and Δaffect sharing) by subtracting the corresponding index under the dislike or like conditions from the neutral condition.

## (e) Dual-electroencephalography data acquisition and pre-processing

The experimental procedure in experiment 2 closely followed that of experiment 1. In addition to completing the experimental tasks, both participants in each dyad wore EEG caps while receiving feedback. Neuroelectric activity from both participants was recorded simultaneously and continuously during the dyadic social judgement task. Data acquisition used a 64-channel BrainAmp standard amplifier (Brain Products GmbH, Germany; passband: 0.01–100 Hz; sampling rate: 1000 Hz) to allow for millisecond-range synchronization between the two EEG recordings. The system included two BrainCap helmets, each equipped with 32 passive Ag/AgCl electrodes arranged according to the international 10–20 system. The FCz electrode served as the reference for recording, and the impedance of all electrodes was maintained below 10 kΩ. Stimuli were presented simultaneously to both participants on their respective monitors, which were connected to the same server.

Continuous EEG data were pre-processed using EEGLAB [42], an open-source toolbox within the MATLAB environment (The MathWorks, Inc., USA). A bandpass finite impulse response (FIR) filter, ranging from 0.1 to 40 Hz, was applied. EEG epochs, time-locked to feedback onset, were extracted using a 3500 ms analysis window (500 ms pre-stimulus to 3000 ms post-stimulus) and baseline-corrected using the pre-stimulus interval through a subtraction approach. EEG epochs were visually inspected, and those with transient jumps in isolated EEG channels were manually removed. Corresponding epochs from the partners' EEG data were also excluded to ensure alignment within the dyad. Consequently, 3.44 ± 0.60 epochs were rejected, representing less than 3% of the total EEG epochs. The remaining epochs were subjected to independent component analysis (ICA) [43], where components associated with ocular movements (e.g. blinks and saccades) and muscle artefacts were identified and removed. Following ICA and an additional baseline correction, EEG trials were re-referenced to the average reference. Finally, a visual inspection was conducted to assess data quality.

## (f) Dual-electroencephalography data processing

We employ both event-related potential (ERP) similarity and INS measurements to achieve a comprehensive understanding of the neural mechanisms underlying empathy. These methods offer distinct yet complementary insights into empathetic processes. Dyad-level ERP similarity evaluates the consistency of ERP response patterns within a dyad, akin to traditional single-brain studies of empathy [44,45]. By contrast, INS measures the alignment of neural oscillations between targets and empathizers in response to positive or negative social feedback. This approach aligns with prior hyperscanning research, which has observed significant INS during empathetic interactions [34–37].

### (i) Dyad-level event-related potential similarity calculation

Dyad-level ERP similarity was computed to assess the degree to which empathizers and targets exhibit similar ERP patterns when processing social feedback. The underlying assumption is that if empathizers experience emotions similar to those of the targets, their ERP patterns during social feedback processing will also be similar. We anticipated that ERP similarity would be higher for emotional feedback compared with neutral feedback. This analytical approach quantified how dyad-level ERP similarity was influenced by the type of social feedback and the interpersonal closeness between targets and empathizers.

The process of calculating dyad-level ERP similarity is illustrated in the electronic supplementary material, figure S1, which involves: (i) computing correlation coefficients of ERPs between targets and empathizers across channels (i.e. similarity in the spatial distribution of ERPs) for each trial and time point, resulting in time-varying correlation coefficients for each trial; (ii) applying Fisher's $r$-to-$z$ transformation to the correlation coefficients to normalize their distribution; (iii) averaging the correlation coefficients across trials for each dyad to obtain condition-specific ERP similarities; (iv) performing one-sample $t$-tests on the averaged similarities across conditions at each time point, with significance levels adjusted using the Bonferroni method, to identify time windows with significant ERP similarity; (v) averaging ERP similarities within the identified time windows across trials for each feedback type; and (vi) comparing dyad-level ERP similarity using a two-way repeated measures analysis of variance (ANOVA) with interpersonal closeness and social feedback as factors.

### (ii) Dyad-level interbrain neural synchronization calculation

INS was calculated to evaluate the phase alignment of EEG oscillations between targets and empathizers during the processing of social feedback. The premise is that if empathizers experience emotions similar to those of the targets, their neural activities will be more synchronized, reflecting functional connectivity and communication during empathy [28,29,46]. We anticipated greater INS for emotional feedback compared with neutral feedback. Given the role of $\alpha$-band synchronization in empathy [35,36], INS was measured in the $\alpha$-band (8–13 Hz) using circular correlation (CCorr), a method that assesses the covariance of phase variance between two data streams and is considered robust against coincidental synchronization [47].

Initially, the pre-processed EEG data were bandpass filtered within the 8–13 Hz range using an FIR filter. We then estimated the instantaneous phase using the Hilbert transform and calculated CCorr between electrode pairs within each dyad. For each dyad and trial, CCorr was computed within a 1 s window, with the average taken over the 3 s following feedback onset. These CCorr values were transformed using Fisher's $r$-to-$z$ transformation to ensure a normal distribution. The absolute values of the transformed CCorr were averaged across trials for each feedback type, resulting in three INS values (for dislike, neutral and like feedback) for each dyad and electrode pair. INS values range from 0 (no synchronization) to 1 (perfect synchronization) [35].

To improve region specification and interpretability, rather than comparing each electrode pair individually (30 electrodes × 30 electrodes), we selected regions of interest (ROI). The scalp was divided into six ROIs [34,37]: left PFC (lPFC: (Fp1, F3 and F7), right PFC (rPFC: Fp2, F4, F8), left sensorimotor cortex (lSMC: FC1, FC5 and C3), right sensorimotor cortex (rSMC: FC2, FC6 and C4), left TPJ (lTPJ: P3, P7 and CP5), and right TPJ (rTPJ: P4, P8 and CP6). This approach resulted in 36 (6 ROIs × 6 ROIs) comparisons. INS for each pair of ROIs was calculated by averaging the INS values across all electrode pairs within those ROIs [37]. This yielded 36 INS values for each dyad and feedback type, which were analysed using a two-way ANOVA with feedback type and interpersonal closeness as factors. Significance levels for each main effect and interaction were adjusted using the Bonferroni method.

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**Table 1.** Demographic and psychometric characteristics of dyads in experiments 1 and 2. (Data are expressed using mean ± s.e.m. Statistics were obtained using independent-sample *t*-tests.)

| | experiment 1 | | | experiment 2 | | |
|---|---|---|---|---|---|---|
| | friends | strangers | statistics | friends | strangers | statistics |
| dyads | $n = 30$ | $n = 29$ | | $n = 22$ | $n = 24$ | |
| age (years) | 20.48 ± 0.31 | 20.40 ± 0.19 | $t_{57} = 0.24$ | 20.84 ± 0.38 | 20.77 ± 0.42 | $t_{44} = 0.12$ |
| interpersonal reactivity inventory | | | | | | |
| perspective taking | 13.68 ± 0.33 | 13.10 ± 0.39 | $t_{57} = 1.14$ | 13.50 ± 0.52 | 14.75 ± 0.33 | $t_{44} = -1.50$ |
| fantasy | 16.23 ± 0.44 | 15.95 ± 0.62 | $t_{57} = 0.38$ | 16.05 ± 0.71 | 16.50 ± 0.50 | $t_{44} = -0.53$ |
| empathetic concern | 16.72 ± 0.36 | 16.52 ± 0.50 | $t_{57} = 0.33$ | 16.43 ± 0.48 | 16.06 ± 0.39 | $t_{44} = 0.60$ |
| personal distress | 11.83 ± 0.49 | 10.86 ± 0.54 | $t_{57} = 1.34$ | 12.30 ± 0.64 | 11.48 ± 0.61 | $t_{44} = 0.93$ |
| rejection sensitivity questionnaire | 8.68 ± 0.42 | 9.60 ± 0.39 | $t_{57} = -1.60$ | 10.52 ± 0.68 | 9.37 ± 0.57 | $t_{44} = 1.30$ |
| IOS | 5.00 ± 0.19 | 1.34 ± 0.09 | $t_{57} = 16.85$[a] | 3.59 ± 0.22 | 1.35 ± 0.09 | $t_{44} = 9.66$[a] |

[a] $p < 0.001$.

### (g) Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics 26 (IBM Corp., USA). Scores from the questionnaires assessing trait empathy, rejection sensitivity and interpersonal closeness were compared between dyads of friends and strangers using independent samples *t*-tests. To evaluate differences in dyadic empathetic reactivity between friends and strangers, behavioural outcomes (emotion identification and affect sharing) and neural outcomes (ERP similarity and INS) during the dyadic social judgement task were analysed using two-way ANOVA. The between-participant variable was interpersonal closeness (friends versus strangers), and the within-participant variable was social feedback (dislike versus neutral versus like). When a significant interaction was found, further analyses were conducted to compare empathy-related reactivity between strangers and friends using independent samples *t*-tests, focusing on the differences between emotional and neutral feedback conditions (e.g. Δaffect sharing and ΔINS). Additionally, Pearson correlation analyses were performed to explore the relationship between empathy-related behavioural and neural activities. Finally, mediation analyses were conducted to examine the mediating role of empathy-related neural reactivity [48,49]. Mediation effects were considered significant if the 95% confidence intervals (CI) calculated from 5000 bootstrapping samples did not include zero.

## 3. Results

### (a) Dyad-level empathetic ratings

The demographic characteristics, as well as scores on the questionnaires assessing trait empathy and rejection sensitivity, were well-matched between dyads of friends and strangers ($ps > 0.05$ for all comparisons; table 1). The scores on the IOS were significantly higher in dyads of friends compared to those of strangers (experiment 1: $t_{57} = 16.85$, $p < 0.001$, Cohen's $d = 4.39$; experiment 2: $t_{44} = 9.66$, $p < 0.001$, Cohen's $d = 2.85$). It demonstrated a higher level of interpersonal closeness within dyads of friends.

Dyad-level empathetic ratings of experiment 1 are shown in figure 2*a*. Analysis of emotion identification during the dyadic social judgement task revealed a significant main effect of interpersonal closeness ($F_{1,57} = 5.44$, $p = 0.023$, $\eta_p^2 = 0.09$). It is manifested as dyads of friends generally had higher accuracy in identifying each other's emotional states than those of strangers. However, the main effect of social feedback or the interaction was not significant. Analysis of affect sharing revealed a significant interaction between interpersonal closeness and social feedback ($F_{2,114} = 6.16$, $p = 0.003$, $\eta_p^2 = 0.10$). Post hoc analyses showed that when witnessing the partner receiving dislike or like feedback, dyads of friends had greater Δaffect sharing (dislike: $t_{57} = 2.80$, $p = 0.007$, Cohen's $d = 0.73$; like: $t_{57} = 3.28$, $p = 0.002$, Cohen's $d = 0.85$). These results indicated that interpersonal closeness increases mutual emotion identification regardless of social feedback type, as well as affect sharing for social feedback with either positive or negative emotional valence. Pearson correlation analyses across dyads of friends and strangers revealed that dyads with greater interpersonal closeness had more accurate emotion identification for social feedback across types ($r_{59} = -0.29$, $p = 0.027$), as well as greater Δaffect sharing ($r_{59} = 0.42$, $p < 0.001$) for emotional social feedback. It thus confirmed the association between interpersonal closeness and mutual empathetic reactivities.

Dyad-level empathetic ratings of experiment 2 are shown in figure 2*b*. Replicating results in experiment 1, Δaffect sharing for social feedback with either dislike or like were greater for dyads of friends than those of strangers (dislike: $t_{44} = 4.47$, $p < 0.001$, Cohen's $d = 1.32$; like: $t_{44} = 4.27$, $p < 0.001$, Cohen's $d = 1.26$). Correlation analysis also replicated the positive association between interpersonal closeness and Δaffect sharing ($r_{46} = 0.47$, $p = 0.001$). However, we did not observe significant differences in the

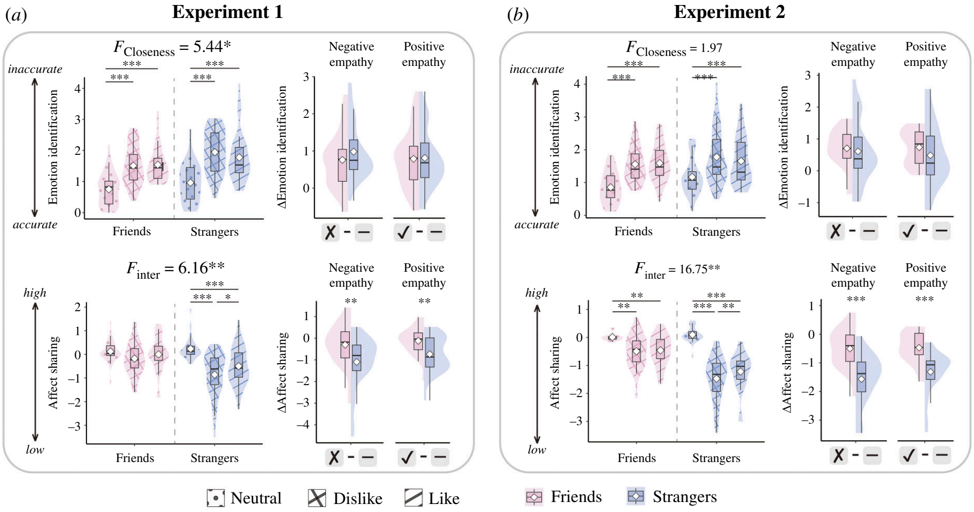


**Figure 2.** Effects of interpersonal closeness on dyadic empathetic reactivity. Dyad-level empathetic reactivities to social feedback in experiment 1 (*a*) and experiment 2 (*b*). Emotion identification and affect sharing in response to social feedback were compared between dyads of friends and strangers. In both experiments, empathy-related affect sharing, quantified as Δaffect sharing in response to social like or dislike (subtracted from those in response to neutral feedback), was greater among dyads of friends than among strangers. In experiment 1, emotion identification was generally more accurate in dyads of friends than in dyads of strangers, regardless of the type of social feedback. Boxes show where 50% of the data lies, and whiskers indicate outlier boundaries. The horizontal lines and diamonds in the boxes represent medians and means, respectively. $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

emotion identification between dyads of friends and strangers. Overall, behavioural data in experiment 2 mostly replicated the association between interpersonal closeness and mutual empathetic reactivities.

## (b) Dyad-level event-related potential similarity

The time course of ERP similarity between targets and empathizers is shown in figure 3*a*. As revealed by point-by-point one-sample *t*-tests, targets and empathizers had significant ERP similarity within the time window of 340–840 ms. The averaged ERP similarity within this time window was significantly modulated by the interaction between interpersonal closeness and social feedback ($F_{2,88} = 3.56$, $p = 0.032$, $\eta_p^2 = 0.08$). Post hoc analyses showed that when encountering dislike feedback, ΔERP similarity was greater in dyads of friends than those of strangers ($t_{44} = 2.74$, $p = 0.009$, Cohen's $d = 0.81$). Hence, interpersonal closeness increases the similarity of ERP in the dyad of targets and empathizers, particularly when confronting negative social feedback.

Correlation analysis across all dyads revealed that ΔERP similarity to emotional feedback was significantly correlated with Δaffect sharing ($r_{46} = 0.42$, $p = 0.004$). The mediation model also confirmed that ΔERP similarity partially mediated the interpersonal closeness (friends versus strangers) effect on Δaffect sharing (a*b = 0.15, s.e. = 0.09, 95% CI = [0.01, 0.36]). This result suggests that ERP similarity between the target and empathizer when witnessing emotional feedback from 'peers' partially explained the link between interpersonal closeness and affect sharing.

## (c) Dyad-level interbrain neural synchronization

With the definitions of ROIs (figure 4*a*), the statistics of INS values for each pair of ROIs are shown in the electronic supplementary material, figure S2. The INS between the neural activities from the empathizer's lPFC and the target's lTPJ was significantly modulated by the interaction between interpersonal closeness and social feedback ($F_{2,88} = 7.92$, $p_{\text{Bonferroni}} = 0.002$, $\eta_p^2 = 0.15$; figure 4*a*), which passed the Bonferroni correction. Post hoc analyses revealed that dyads of friends had greater ΔINS when encountering dislike ($t_{44} = 3.54$, $p < 0.001$, Cohen's $d = 1.04$) or like ($t_{44} = 3.39$, $p = 0.001$, Cohen's $d = 1.00$) feedback. It demonstrates interpersonal closeness increases the interbrain synchronization between targets and empathizers when they are exposed to emotional social feedback.

Correlation analyses revealed that ΔINS was significantly associated with Δaffect sharing in dyads of friends ($r_{22} = 0.45$, $p = 0.035$), but not in dyads of strangers ($r_{24} = -0.22$, $p = 0.297$). Mediation analysis confirmed that INS partially mediated the effects of emotional social feedback on affect sharing within dyads of friends ($a^*b = 0.16$, s.e. = 0.11, bias-corrected 95% CI = [0.01, 0.46]), but not within those of strangers ($a^*b = 0.10$, s.e. = 0.12, bias-corrected 95% CI = [−0.13, 0.34]). Therefore, the observed affect sharing while exposed to emotional social feedback was accounted by the enhanced INS in dyads of friends.

# 4. Discussion

Using a dyadic social judgement paradigm and EEG hyperscanning, our study examined how interpersonal closeness affects mutual empathetic responses to positive and negative social feedback, along with the associated interbrain mechanisms. We

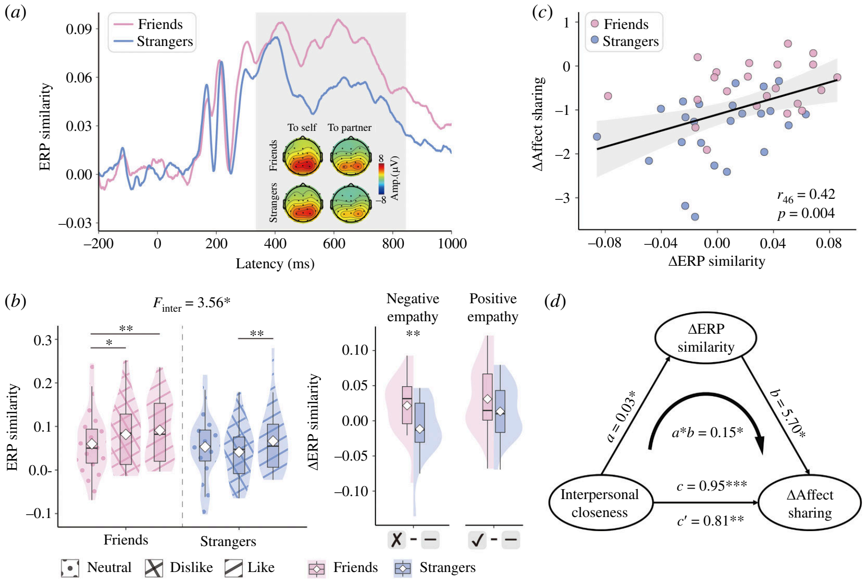


**Figure 3.** Effects of interpersonal closeness on dyad-level ERP similarity. (*a*) The time course of ERP similarity in dyads of friends and strangers. ERPs were elicited by social feedback (dislike, neutral or like), and the correlation coefficients between their ERP response patterns served as an index of similarity. Point-by-point one-sample *t*-tests revealed significant similarities in neural reactivity between dyads within the time window of 340–840 ms. (*b*) Comparisons of dyad-level ERP similarity within 340–840 ms between dyads of friends and strangers. The ΔERP similarity in response to dislike feedback was greater for dyads of friends than for those of strangers. Boxes represent the interquartile range, whiskers indicate outlier boundaries and the horizontal lines and diamonds in the boxes represent the medians and means, respectively. (*c*) The correlation between ΔERP similarity and Δaffect sharing. A positive and significant correlation was observed between ΔERP similarity and Δaffect sharing in response to either dislike or like feedback across all dyads. (*d*) The mediation model linking interpersonal closeness, ΔERP similarity, and Δaffect sharing. Interpersonal closeness enhances affect sharing in response to witnessing others receiving social dislike or like by modulating ERP similarity between the dyads. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

found that dyads of friends generally demonstrated better emotion identification and greater affect sharing in response to emotional social feedback compared with dyads of strangers. This was supported by more pronounced ERP similarity in dyads of friends during the 340–840 ms post-feedback time window, which mediated the link between interpersonal closeness and affect sharing. Moreover, friends witnessing each other being socially accepted or rejected showed greater INS of $\alpha$-oscillations between the empathizer's lPFC and the target's lTPJ, which was linked to mutual affect sharing. This suggests that affect sharing in dyads of friends is associated with INS in brain regions involved in understanding others' mental states and emotion regulation.

## (a) Dyad-level empathetic ratings

Dyads of friends demonstrated a higher degree of overlap between two circles representing 'self' and 'other,' indicating a more profound interconnectedness. In our study, a dyadic setting was used to evaluate mutual empathy. Each participant in the dyad assumed a specific role: targets received real-time social feedback, while empathizers observed the situation unfold. Adopting a dual-person framework of empathy, our findings revealed that dyads of friends consistently exhibited more accurate emotion identification, regardless of the nature of the social feedback. Furthermore, they demonstrated greater affect sharing when witnessing emotional social feedback, whether positive or negative. In essence, dyads of friends not only recognized another person's emotions more accurately but also experienced these emotions more resonantly. This evidence underscores the impact of interpersonal closeness in facilitating both the cognitive and affective dimensions of social-oriented empathy. It suggests that an enhanced understanding of an individual fosters the construction of a more nuanced representation of their emotional experiences in social situations, further contributing to heightened affect sharing.

Our findings align with prior research highlighting the influence of interpersonal relationships on empathy. For instance, Stinson & Ickes [50] demonstrated that friends surpass strangers in accurately discerning each other's thoughts and feelings, attributing this to friends' proficiency in understanding their partners' thoughts and feelings regarding imagined events in different locations or times. Regarding the affective dimension of empathy, a higher level of interpersonal closeness predicts heightened distress at another's pain and increased activity in the dACC and aINS [6,18,21,22]. These brain regions constitute the shared distress network, which is automatically activated upon detecting distress in the targets. Greater interpersonal closeness allows for richer representations of the internal states of others, automatically triggering a corresponding emotional state in a more resonant manner. Indeed, while the mental states of similar individuals are relatively predictable (relying on one's own mental states for prediction), those of dissimilar individuals pose more challenges, leading to increased response uncertainty.

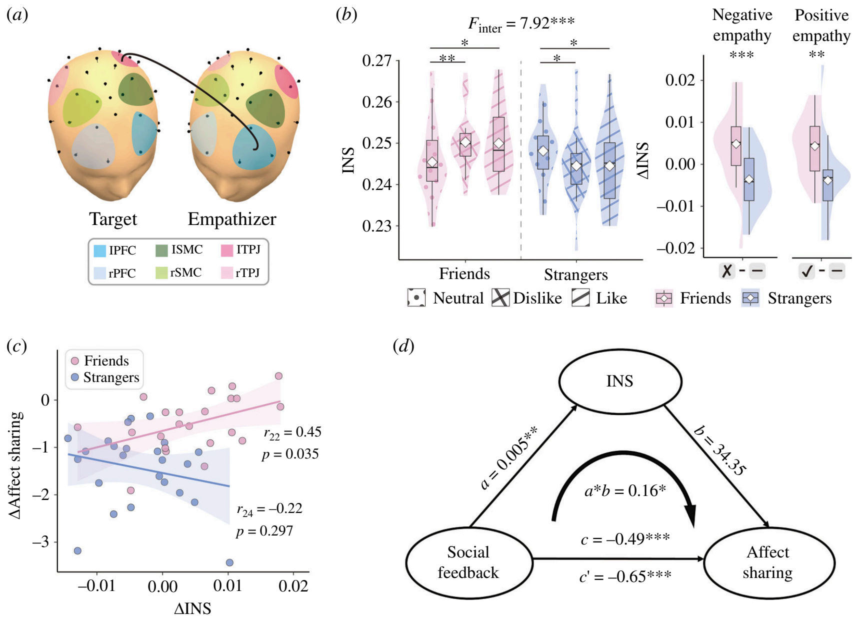


**Figure 4.** Effects of interpersonal closeness on INS. (*a*) ROI defined for calculating INS between the dyad of feedback target and empathizer. The black line links the empathizer's lPFC and the target's lTPJ, where INS was significantly modulated by the interaction of interpersonal closeness and social feedback. (*b*) Comparisons of INS in the lPFC-lTPJ in response to social feedback between dyads of friends and strangers. The empathy-related INS (ΔINS) in response to either dislike or like feedback in dyads of friends was significantly greater than in dyads of strangers. Boxes represent the interquartile range, whiskers indicate outlier boundaries and the horizontal lines and diamonds in the boxes represent the medians and means, respectively. (*c*) The correlation between INS and affect sharing in response to emotional feedback. A significant and positive correlation between ΔINS and Δaffect sharing was observed among dyads of friends but not those of strangers. (*d*) The mediation model linking social feedback, INS and affect sharing. Presenting emotional social feedback elicits enhanced empathy-related INS, leading to greater affect sharing in dyads of friends. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

## (b) Dyad-level neural reactivities

Beyond self-report measures of empathy, experiment 2 involved the simultaneous recording of neural reactivities of targets and empathizers during the task. Our results revealed that dyads of targets and empathizers generally exhibited similar ERP reactivity within 340–840 ms following the onset of social feedback. This neural reactivity corresponds to the late positive potential (LPP), predominantly distributed over central-parietal electrodes, a phenomenon frequently observed in the cognitive processing of emotional information [51]. The LPP has been demonstrated to be sensitive to the emotional valence and social significance of stimuli [52,53], associated with sustained attention and cognitive evaluation of emotional stimuli [51]. The LPP component is commonly observed in empathy paradigms (e.g. observing depictions of painful situations) and is linked to the top-down controlled process of empathy [54]. Our results indicated that the alignment of LPP activity was more extensive in dyads of friends than in strangers when encountering emotional feedback. Crucially, this neural alignment mediated the link between interpersonal closeness and affect sharing. Hence, LPP alignment can be considered a dual-brain mechanism illustrating how familiarity or closeness with another individual modulates affect sharing in social-oriented empathy. The enhanced alignment of the LPP component within dyads of friends probably reflects more simultaneous sustained attention allocation and elaborative evaluation following the detection of social feedback.

In addition to dyad-level ERP similarity, INS offers insights into the phase alignment of EEG $\alpha$-oscillations during the dyadic social judgement task. To distinguish whether INS arises from shared stimuli processing or affect sharing, we used a neutral condition as a within-dyad control. If INS merely reflects shared stimuli processing, it would be similar across different social feedback types. However, if it reflects affect sharing, it would be greater for emotional feedback compared with neutral feedback. Results showed that emotional feedback triggered significant INS between the empathizer's lPFC and the target's lTPJ in dyads of friends, partially explaining the mutual affect sharing elicited by emotional social feedback. However, an opposite pattern was observed in dyads of strangers, with decreased INS following emotional feedback compared with neutral feedback. Hence, the inclusion of within-dyad neutral feedback control and between-dyad stranger control, along with the correlation between INS and affect sharing, allowed us to conclude that observed INS facilitates affect sharing in dyads of friends.

The TPJ is a pivotal brain region involved in social cognition processes, implicated in mentalizing about others' mental states [55,56] and making judgements from another person's perspective [57]. Targets receiving social acceptance or rejection may engage the TPJ to interpret social cues and signals from peers and to process self-reflection on social attributes [58]. Meanwhile, the PFC is particularly vital to empathetic processing and regulation of empathetic behaviours [59]. Witnessing pain or suffering in the target can induce emotional and psychological discomfort in the empathizer, and the PFC appears to modulate this personal distress [60], through cognitive reappraisal or attention modulation. Empathizers witnessing their partners being socially accepted or rejected may engage the PFC to regulate their emotional responses through cognitive reappraisal or reinterpretation of the emotional stimuli. Hence, the observed INS between the target's TPJ and the empathizer's PFC may suggest functional communication between regions involved in understanding others' mental states and regulating affective responses to social acceptance or rejection.

While further research is needed to establish causality between INS and affect sharing [61], the observed interbrain mechanisms suggest potential targets for enhancing empathy and interpersonal connections. Recent studies show that dual-brain transcranial alternating current stimulation (tACS) can improve interbrain synchronization and social learning [62,63]. Targeting PFC-TPJ synchronization through tACS could benefit individuals with atypical empathetic responses, such as those with autism spectrum disorder [64,65] and schizophrenia [66], improving social interactions and quality of life. Additionally, these findings have implications for enhancing empathy in professional settings, such as patient-clinician and counsellor-client interactions, potentially improving therapeutic outcomes and relationship satisfaction. Further studies are necessary to explore and confirm the efficacy of these interventions.

### (c) Limitations

While our study provides valuable insights into the neural mechanisms of affect sharing in empathy, it has several limitations. First, we only recruited female participants, which limits the generalizability of our findings. This decision was based on reported gender differences in empathy [45,67], but broader applicability will require more diverse samples. Second, using two separate 32-channel EEG systems to record empathizers' and targets' neural activities offers low spatial resolution, making it difficult to pinpoint specific brain regions involved in INS during affect sharing. Techniques with higher spatial resolution, such as dense-array EEG systems, would be beneficial for localizing synchronized brain activities related to empathy. Third, our design focused on eliciting affect sharing without direct interaction or cooperation between participants. Therefore, the INS we measured mainly reflects affect sharing related to empathy, not the complex processes of realistic empathetic interactions. Future studies should validate the observed empathy-related INS by using experimental paradigms that involve more direct and interactive empathetic processes.

## 5. Conclusion

Through the integration of the dyadic social judgement paradigm and EEG hyperscanning, we illustrated the facilitating impact of interpersonal closeness on mutual empathy in social contexts. Dyads of friends exhibited heightened accuracy in emotion identification and increased affect sharing in response to emotional social feedback, accompanied by greater alignment in late ERP responses associated with sustained attention and elaborate processing of emotional social feedback. Notably, empathy-related INS between the target's TPJ and the empathizer's PFC was observed only in dyads of friends, which also tracked their mutual affect sharing elicited by emotional social feedback. These findings offer valuable insights into the significance of interpersonal closeness on empathy in social contexts and hold the potential for informing the development of therapeutic approaches aimed at enhancing social functioning and relationship satisfaction.

Ethics. Written informed consent in accordance with the Declaration of Helsinki was obtained from each participant before the experiment. All the experimental procedures were approved by the Ethics Committee of the Shenzhen University Medical School (approval number: PN-202200070).

Data accessibility. Data and codes can be found on the OSF platform [68].

Data is available in the electronic supplementary material [69].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. C.L.: data curation, formal analysis, investigation, software, visualization, writing—original draft, writing—review and editing; X.L.: conceptualization, data curation, writing—review and editing; W.L.: conceptualization, investigation, software, writing—review and editing; W.Z.: investigation, writing—review and editing; W.P.: conceptualization, formal analysis, funding acquisition, supervision, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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## References

1. Cuff BMP, Brown SJ, Taylor L, Howat DJ. 2016 Empathy: a review of the concept. *Emot. Rev.* **8**, 144–153. (doi:10.1177/1754073914558466)
2. Coll MP, Viding E, Rütgen M, Silani G, Lamm C, Catmur C, Bird G. 2017 Are we really measuring empathy? Proposal for a new measurement framework. *Neurosci. Biobehav. Rev.* **83**, 132–139. (doi:10.1016/j.neubiorev.2017.10.009)
3. Jackson PL, Meltzoff AN, Decety J. 2005 How do we perceive the pain of others? A window into the neural processes involved in empathy. *Neuroimage* **24**, 771–779. (doi:10.1016/j.neuroimage.2004.09.006)
4. Lamm C, Batson CD, Decety J. 2007 The neural substrate of human empathy: effects of perspective-taking and cognitive appraisal. *J. Cogn. Neurosci.* **19**, 42–58. (doi:10.1162/jocn.2007.19.1.42)
5. Singer T, Seymour B, O'Doherty J, Kaube H, Dolan RJ, Frith CD. 2004 Empathy for pain involves the affective but not sensory components of pain. *Science* **303**, 1157–1162. (doi:10.1126/science.1093535)

6. Xu X, Zuo X, Wang X, Han S. 2009 Do you feel my pain? Racial group membership modulates empathic neural responses. *J. Neurosci.* **29**, 8525–8529. (doi:10.1523/JNEUROSCI.2418-09.2009)
7. Depow GJ, Francis Z, Inzlicht M. 2021 The experience of empathy in everyday life. *Psychol. Sci.* **32**, 1198–1213. (doi:10.1177/0956797621995202)
8. Masten CL, Morelli SA, Eisenberger NI. 2011 An fMRI investigation of empathy for 'social pain' and subsequent prosocial behavior. *Neuroimage* **55**, 381–388. (doi:10.1016/j.neuroimage.2010.11.060)
9. Zaki J, Weber J, Bolger N, Ochsner K. 2009 The neural bases of empathic accuracy. *Proc. Natl Acad. Sci. USA* **106**, 11382–11387. (doi:10.1073/pnas.0902666106)
10. Kiecolt-Glaser JK, Gouin JP, Hantsoo L. 2010 Close relationships, inflammation, and health. *Neurosci. Biobehav. Rev.* **35**, 33–38. (doi:10.1016/j.neubiorev.2009.09.003)
11. Pressman SD, Jenkins BN, Moskowitz JT. 2019 Positive affect and health: what do we know and where next should we go? *Annu. Rev. Psychol.* **70**, 627–650. (doi:10.1146/annurev-psych-010418-102955)
12. Eisenberger NI, Lieberman MD, Williams KD. 2003 Does rejection hurt? An fMRI study of social exclusion. *Science* **302**, 290–292. (doi:10.1126/science.1089134)
13. Eisenberger NI, Lieberman MD. 2004 Why rejection hurts: a common neural alarm system for physical and social pain. *Trends Cogn. Sci.* **8**, 294–300. (doi:10.1016/j.tics.2004.05.010)
14. Andreychik MR. 2019 I like that you feel my pain, but I love that you feel my joy: empathy for a partner's negative versus positive emotions independently affect relationship quality. *J. Soc. Pers. Relat.* **36**, 834–854. (doi:10.1177/0265407517746518)
15. Taiwo Z, Bezdek M, Mirabito G, Light SN. 2021 Empathy for joy recruits a broader prefrontal network than empathy for sadness and is predicted by executive functioning. *Neuropsychology* **35**, 90–102. (doi:10.1037/neu0000666)
16. Preston SD, de Waal FBM. 2002 Empathy: its ultimate and proximate bases. *Behav. Brain Sci.* **25**, 1–20; (doi:10.1017/s0140525x02000018)
17. Bucchioni G, Lelard T, Ahmaidi S, Godefroy O, Krystkowiak P, Mouras H. 2015 Do we feel the same empathy for loved and hated peers? *PLoS One* **10**, e0125871. (doi:10.1371/journal.pone.0125871)
18. Cheng Y, Chen C, Lin CP, Chou KH, Decety J. 2010 Love hurts: an fMRI study. *Neuroimage* **51**, 923–929. (doi:10.1016/j.neuroimage.2010.02.047)
19. Grynberg D, Konrath S. 2020 The closer you feel, the more you care: positive associations between closeness, pain intensity rating, empathic concern and personal distress to someone in pain. *Acta Psychol.* **210**, 103175. (doi:10.1016/j.actpsy.2020.103175)
20. Hein G, Silani G, Preuschoff K, Batson CD, Singer T. 2010 Neural responses to ingroup and outgroup members' suffering predict individual differences in costly helping. *Neuron* **68**, 149–160. (doi:10.1016/j.neuron.2010.09.003)
21. Beeney JE, Franklin RG, Levy KN, Adams RB. 2011 I feel your pain: emotional closeness modulates neural responses to empathically experienced rejection. *Soc. Neurosci.* **6**, 369–376. (doi:10.1080/17470919.2011.557245)
22. Meyer ML, Masten CL, Ma Y, Wang C, Shi Z, Eisenberger NI, Han S. 2013 Empathy for the social suffering of friends and strangers recruits distinct patterns of brain activation. *Soc. Cogn. Affect. Neurosci.* **8**, 446–454. (doi:10.1093/scan/nss019)
23. Meyer ML, Masten CL, Ma Y, Wang C, Shi Z, Eisenberger NI, Lieberman MD, Han S. 2015 Differential neural activation to friends and strangers links interdependence to empathy. *Cult. Brain* **3**, 21–38. (doi:10.1007/s40167-014-0023-7)
24. Ma Q, Shen Q, Xu Q, Li D, Shu L, Weber B. 2011 Empathic responses to others' gains and losses: an electrophysiological investigation. *Neuroimage* **54**, 2472–2480. (doi:10.1016/j.neuroimage.2010.10.045)
25. Thornton MA, Mitchell JP. 2017 Consistent neural activity patterns represent personally familiar people. *J. Cogn. Neurosci.* **29**, 1583–1594. (doi:10.1162/jocn_a_01151)
26. Czeszumski A, Eustergerling S, Lang A, Menrath D, Gerstenberger M, Schuberth S, Schreiber F, Rendon ZZ, König P. 2020 Hyperscanning: a valid method to study neural inter-brain underpinnings of social interaction. *Front. Hum. Neurosci.* **14**, 39. (doi:10.3389/fnhum.2020.00039)
27. Dumas G, Lachat F, Martinerie J, Nadel J, George N. 2011 From social behaviour to brain synchronization: review and perspectives in hyperscanning. *I.R.B.M.* **32**, 48–53. (doi:10.1016/j.irbm.2011.01.002)
28. Dumas G, Nadel J, Soussignan R, Martinerie J, Garnero L. 2010 Inter-brain synchronization during social interaction. *PLoS One* **5**, e12166. (doi:10.1371/journal.pone.0012166)
29. Hasson U, Ghazanfar AA, Galantucci B, Garrod S, Keysers C. 2012 Brain-to-brain coupling: a mechanism for creating and sharing a social world. *Trends Cogn. Sci.* **16**, 114–121. (doi:10.1016/j.tics.2011.12.007)
30. Valencia AL, Froese T. 2020 What binds us? Inter-brain neural synchronization and its implications for theories of human consciousness. *Neurosci. Conscious.* **2020**, niaa010. (doi:10.1093/nc/niaa010)
31. Bilek E *et al*. 2015 Information flow between interacting human brains: identification, validation, and relationship to social expertise. *Proc. Natl Acad. Sci. USA* **112**, 5207–5212. (doi:10.1073/pnas.1421831112)
32. Hari R, Sams M, Nummenmaa L. 2016 Attending to and neglecting people: bridging neuroscience, psychology and sociology. *Phil. Trans. R. Soc. B* **371**, 20150365. (doi:10.1098/rstb.2015.0365)
33. Main A, Walle EA, Kho C, Halpern J. 2017 The interpersonal functions of empathy: a relational perspective. *Emot. Rev.* **9**, 358–366. (doi:10.1177/1754073916669440)
34. Djalovski A, Dumas G, Kinreich S, Feldman R. 2021 Human attachments shape interbrain synchrony toward efficient performance of social goals. *Neuroimage* **226**, 117600. (doi:10.1016/j.neuroimage.2020.117600)
35. Goldstein P, Weissman-Fogel I, Dumas G, Shamay-Tsoory SG. 2018 Brain-to-brain coupling during handholding is associated with pain reduction. *Proc. Natl Acad. Sci. USA* **115**, E2528–E2537. (doi:10.1073/pnas.1703643115)
36. Peng W, Lou W, Huang X, Ye Q, Tong RY, Cui F. 2021 Suffer together, bond together: brain-to-brain synchronization and mutual affective empathy when sharing painful experiences. *Neuroimage* **238**, 118249. (doi:10.1016/j.neuroimage.2021.118249)
37. Schwartz L, Levy J, Endevelt-Shapira Y, Djalovski A, Hayut O, Dumas G, Feldman R. 2022 Technologically-assisted communication attenuates inter-brain synchrony. *Neuroimage* **264**, 119677. (doi:10.1016/j.neuroimage.2022.119677)
38. Davis MH. 1983 Measuring individual differences in empathy: evidence for a multidimensional approach. *J. Pers. Soc. Psychol.* **44**, 113–126. (doi:10.1037/0022-3514.44.1.113)
39. Downey G, Feldman SI. 1996 Implications of rejection sensitivity for intimate relationships. *J. Pers. Soc. Psychol.* **70**, 1327–1343. (doi:10.1037/0022-3514.70.6.1327)
40. Aron A, Aron EN, Smollan D. 1992 Inclusion of other in the self scale and the structure of interpersonal closeness. *J. Pers. Soc. Psychol.* **63**, 596–612. (doi:10.1037/0022-3514.63.4.596)
41. Santiesteban I, Gibbard C, Drucks H, Clayton N, Banissy MJ, Bird G. 2021 Individuals with autism share others' emotions: evidence from the continuous affective rating and empathic responses (CARER) task. *J. Autism Dev. Disord.* **51**, 391–404. (doi:10.1007/s10803-020-04535-y)
42. Delorme A, Makeig S. 2004 EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* **134**, 9–21. (doi:10.1016/j.jneumeth.2003.10.009)

43. Jung TP, Makeig S, McKeown MJ, Bell AJ, Lee TW, Sejnowski TJ. 2001 Imaging brain dynamics using independent component analysis. *Proc. IEEE Inst. Electr. Electron. Eng.* **89**, 1107–1122. (doi:10.1109/5.939827)
44. Fan Y, Han S. 2008 Temporal dynamic of neural mechanisms involved in empathy for pain: an event-related brain potential study. *Neuropsychologia* **46**, 160–173. (doi:10.1016/j.neuropsychologia.2007.07.023)
45. Han S, Fan Y, Mao L. 2008 Gender difference in empathy for pain: an electrophysiological investigation. *Brain Res.* **1196**, 85–93. (doi:10.1016/j.brainres.2007.12.062)
46. Fries P. 2015 Rhythms for cognition: communication through coherence. *Neuron* **88**, 220–235. (doi:10.1016/j.neuron.2015.09.034)
47. Burgess AP. 2013 On the interpretation of synchronization in EEG hyperscanning studies: a cautionary note. *Front. Hum. Neurosci.* **7**, 881. (doi:10.3389/fnhum.2013.00881)
48. Montoya AK, Hayes AF. 2017 Two-condition within-participant statistical mediation analysis: a path-analytic framework. *Psychol. Methods* **22**, 6–27. (doi:10.1037/met0000086)
49. Preacher KJ, Hayes AF. 2008 Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behav. Res. Methods* **40**, 879–891. (doi:10.3758/brm.40.3.879)
50. Stinson L, Ickes W. 1992 Empathic accuracy in the interactions of male friends versus male strangers. *J. Pers. Soc. Psychol.* **62**, 787–797. (doi:10.1037/0022-3514.62.5.787)
51. Hajcak G, MacNamara A, Olvet DM. 2010 Event-related potentials, emotion, and emotion regulation: an integrative review. *Dev. Neuropsychol.* **35**, 129–155. (doi:10.1080/87565640903526504)
52. Hajcak G, Olvet DM. 2008 The persistence of attention to emotion: brain potentials during and after picture presentation. *Emotion* **8**, 250–255. (doi:10.1037/1528-3542.8.2.250)
53. Schupp HT, Schmälzle R, Flaisch T, Weike AI, Hamm AO. 2012 Affective picture processing as a function of preceding picture valence: an ERP analysis. *Biol. Psychol.* **91**, 81–87. (doi:10.1016/j.biopsycho.2012.04.006)
54. Coll MP. 2018 Meta-analysis of ERP investigations of pain empathy underlines methodological issues in ERP research. *Soc. Cogn. Affect. Neurosci.* **13**, 1003–1017. (doi:10.1093/scan/nsy072)
55. Saxe R, Kanwisher N. 2003 People thinking about thinking people. The role of the temporo-parietal junction in "theory of mind." *Neuroimage* **19**, 1835–1842. (doi:10.1016/s1053-8119(03)00230-1)
56. Samson D, Apperly IA, Chiavarino C, Humphreys GW. 2004 Left temporoparietal junction is necessary for representing someone else's belief. *Nat. Neurosci.* **7**, 499–500. (doi:10.1038/nn1223)
57. Aichhorn M, Perner J, Kronbichler M, Staffen W, Ladurner G. 2006 Do visual perspective tasks need theory of mind? *Neuroimage* **30**, 1059–1068. (doi:10.1016/j.neuroimage.2005.10.026)
58. Ma Y, Bang D, Wang C, Allen M, Frith C, Roepstorff A, Han S. 2014 Sociocultural patterning of neural activity during self-reflection. *Soc. Cogn. Affect. Neurosci.* **9**, 73–80. (doi:10.1093/scan/nss103)
59. Eslinger PJ. 1998 Neurological and neuropsychological bases of empathy. *Eur. Neurol.* **39**, 193–199. (doi:10.1159/000007933)
60. Ochsner KN, Silvers JA, Buhle JT. 2012 Functional imaging studies of emotion regulation: a synthetic review and evolving model of the cognitive control of emotion. *Ann. NY Acad. Sci.* **1251**, E1–24. (doi:10.1111/j.1749-6632.2012.06751.x)
61. Novembre G, Iannetti GD. 2021 Hyperscanning alone cannot prove causality. Multibrain stimulation can. *Trends Cogn. Sci.* **25**, 96–99. (doi:10.1016/j.tics.2020.11.003)
62. Lu H, Wang X, Zhang Y, Huang P, Xing C, Zhang M, Zhu X. 2023 Increased interbrain synchronization and neural efficiency of the frontal cortex to enhance human coordinative behavior: a combined hyper-tES and fNIRS study. *Neuroimage* **282**, 120385. (doi:10.1016/j.neuroimage.2023.120385)
63. Pan Y, Novembre G, Song B, Zhu Y, Hu Y. 2021 Dual brain stimulation enhances interpersonal learning through spontaneous movement synchrony. *Soc. Cogn. Affect. Neurosci.* **16**, 210–221. (doi:10.1093/scan/nsaa080)
64. Harmsen IE. 2019 Empathy in autism spectrum disorder. *J. Autism Dev. Disord.* **49**, 3939–3955. (doi:10.1007/s10803-019-04087-w)
65. Fatima M, Babu N. 2023 Cognitive and affective empathy in autism spectrum disorders: a meta-analysis. *Rev. J. Autism Dev. Disord.* 1–20. (doi:10.1007/s40489-023-00364-8)
66. Bonfils KA, Lysaker PH, Minor KS, Salyers MP. 2017 Empathy in schizophrenia: a meta-analysis of the interpersonal reactivity index. *Psychiatry Res.* **249**, 293–303. (doi:10.1016/j.psychres.2016.12.033)
67. Schulte-Rüther M, Markowitsch HJ, Shah NJ, Fink GR, Piefke M. 2008 Gender differences in brain networks supporting empathy. *Neuroimage* **42**, 393–403. (doi:10.1016/j.neuroimage.2008.04.180)
68. Lin C. 2024 Interbrain neural mechanisms underlying the impact of interpersonal closeness on mutual empathy. OSF (doi:10.17605/OSF.IO/7CDQW)
69. Lin C, Lin X, Lian W, Zhang W, Peng W. 2024 Data from: Brains in sync, friends in empathy: interbrain neural mechanisms underlying the impact of interpersonal closeness on mutual empathy. Figshare. (doi:10.6084/m9.figshare.c.7437383)