



Exploring Empathic Responses to Others' Positive and Negative Experiences: Insights from Empathy Subprocesses

Xiao Wu^{1,2} · Xue-Jing Lu^{1,2} · Li-Bo Zhang^{1,2} ·
Si-Rui Huo³ · Ya-Zhuo Kong^{1,2} · Li Hu^{1,2} 

Received: 2 February 2025 / Accepted: 26 June 2025 / Published online: 25 October 2025
© Center for Excellence in Brain Science and Intelligence Technology, Chinese Academy of Sciences 2025

Abstract Empathy can be categorized into positive and negative empathy depending on the emotional valence experienced. When responding to others' emotions, empathy involves three key subprocesses: emotion recognition, affective empathy, and motivational empathy. However, how these subprocesses operate to realistic positive *versus* negative stimuli remains largely unexplored. To fill this gap, we selected 96 real-life events with detailed contextual information and collected functional magnetic resonance imaging data. We observed lower within-subject and between-subject behavioral and neural similarity for positive empathy than for negative empathy. Although positive and negative empathy partially shared neural mechanisms underlying emotion recognition—evident in overlapping encoding regions and functional connectivity (FC)—they diverged notably in affective and motivational empathy. Negative empathy involved more complex encoding schemes and more convergent FC than positive empathy. These findings deepen our understanding of empathy dynamics, highlighting its

multifaceted nature and the importance of distinguishing between positive and negative emotions in empathy research.

Keywords Positive empathy · Negative empathy · Intra-subject similarity · Inter-subject similarity · Empathic response

Introduction

Empathy is a multifaceted construct essential for social interactions, involving the process of identifying and responding to the emotions of others [1–3]. Empathy can be differentiated by emotional valence, ranging from positive to negative [4]. While both positive and negative empathy involve understanding and resonating with others' feelings, they differ significantly. Negative empathy typically refers to the ability to understand and resonate with others' pain, suffering, or distress, often eliciting emotional responses like discomfort, compassion, sympathy, or even empathic painful feelings. In contrast, positive empathy involves responding to others' joy, success, or positive experiences. While some people may feel happiness and share in others' joy, others might experience opposite feelings, such as envy, resentment, or indifference.

Empathy encompasses a range of subprocesses, including emotion recognition, affective empathy, and motivational empathy, which may be labeled differently by various scholars [5–9]. Emotion recognition involves recognizing and comprehending others' feelings explicitly [10]. Affective empathy refers to experiencing emotions similar to those of others or being emotionally stirred by others' emotions. [5] Motivational empathy denotes compassion and concern for others [7] or an internal altruistic drive that motivates empathic behaviors [8].

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12264-025-01517-x>.

✉ Ya-Zhuo Kong
kongyz@psych.ac.cn

✉ Li Hu
huli@psych.ac.cn

¹ State Key Laboratory of Cognitive Science and Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing 100101, China

² Department of Psychology, University of Chinese Academy of Sciences, Beijing 100049, China

³ Faculty of Psychology, Southwest University, Chongqing 400715, China

Previous studies have identified both shared and distinct brain activations associated with positive and negative empathy [11, 12]. However, the subprocesses of empathy were not considered, the context of stimuli (e.g., the characteristics of the individual presented and the event that triggered the emotional response) was not detailed, and an appropriate control condition was not considered [11, 12]. Treating empathy as a single construct may lead to mixed findings, hindering our understanding of the detailed mechanisms underlying positive and negative empathy. Specifically, the extent to which they are in common and at which subprocesses of empathy they exhibited distinctions have not been thoroughly explored, particularly concerning behavioral performance and underlying neural mechanisms.

From the perspective of empathy subprocesses, we hypothesize that positive and negative empathy may partly share the emotion recognition subprocess, such as face perception [13], and inferring others' mental states [14]. However, we anticipate greater divergence between positive and negative empathy in the affective and motivational empathy subprocesses, given that people may experience different emotions and exhibit distinct affective responses, which in turn may lead to different motivational tendencies [15]. While positive empathy often fosters a desire to celebrate and enhance others' well-being, it can also evoke contrasting emotions, such as envy, which is commonly observed in real-life contexts [16, 17]. In contrast, negative empathy, which entails understanding and sharing in others' distress, typically elicits more consistent emotional responses and motivates similar concerns, such as empathy for pain, where the distress experienced is more universally recognized and shared [18]. Therefore, we also hypothesize that negative empathy may involve more consistent processing than positive empathy. Specifically, the same individual may resonate more consistently with others' negative emotions compared to positive emotions (intra-subject similarity), and different individuals may respond more consistently to others' negative experiences than positive experiences (inter-subject similarity).

To test these hypotheses, we conducted a functional magnetic resonance imaging (fMRI) study using an event-related design, collecting ratings for the three empathy subprocesses. This study included 96 real-life events, comprising 32 positive, 32 negative, and 32 neutral events, sourced from online news and documentary films, each accompanied by detailed contextual information (i.e., the characteristics of the individual presented and the event that triggered the emotional response) and high-resolution images depicting facial expressions. Subsequently, we performed a series of statistical analyses to uncover the shared and distinct mechanisms between positive and negative empathy from the perspective of subprocesses, focusing on both intra-subject and inter-subject behavioral and neural similarities.

At the intra-subject level, we aimed to clarify the relationships among emotion recognition, affective empathy, and motivational empathy. To achieve this, we first performed multilevel correlation analyses on the ratings of the three empathy subprocesses. Given the temporal sequence of empathy subprocesses, where emotion recognition occurs first, followed by early affective resonance, and later motivational compassion [9], we explored whether ratings of affective empathy mediated the relationship between emotion recognition and motivational empathy. This was achieved separately for positive and negative stimuli using multilevel mediation analyses, followed by moderated mediation analyses to determine whether mediation effects differed significantly between positive and negative stimuli. For neural data, we performed parametric modulation (PM) analyses to identify brain regions encoding ratings for each empathy subprocess. Subsequently, whole-brain functional connectivity (FC) analyses were conducted using these identified regions as seeds to reveal the neural synchrony among brain regions. These analyses allowed us to compare neural responses to positive *versus* negative stimuli, revealing shared and distinct intra-subject neural patterns.

At the inter-subject level, we aimed to assess rating similarity across participants using inter-subject correlation (ISC) analyses. Specifically, ratings from different participants were compared to assess the degree of similarity among participants exposed to the same stimuli. For neural data, beta values extracted from brain regions encoding empathy ratings were compared across participants to assess the inter-subject neural similarity. Additionally, the behavioral and neural inter-subject similarity was compared between positive and negative empathy to reveal shared and distinct inter-subject neural patterns. Altogether, the present study would provide evidence showing how the subprocesses of positive and negative empathy operate in response to real-life contexts, which contributes to a more comprehensive model of empathic responses.

Materials and Methods

Participants

To determine the necessary sample size for identifying differences in empathic responses to others' positive and negative experiences, we performed a power analysis for *t*-tests using G*Power 3.1.9.7 [19, 20]. The statistical power was set at 0.8, with an effect size of 0.5 and a significance level of 0.05. The analysis suggested a minimum sample size of 34 for detecting the main effects between two dependent means. Consequently, we recruited 35 right-handed healthy participants (17 males; age: 22.03 ± 2.30 years; education duration: 16.06 ± 2.37 years) for this study, accounting

for incomplete data from one male participant (see section MRI Data Acquisition and Preprocessing for details). No significant differences in age and education duration were observed between males and females (both $P > 0.05$). All participants met MRI safety criteria and had no history of neurological disorders, pain disorders, depression, anxiety, or insomnia. Each participant provided written informed consent and received monetary compensation for their participation. The study protocol was approved by the Ethics Committee of the Institute of Psychology, Chinese Academy of Sciences, China.

Experimental Materials

A total of 96 diverse real-life experiences were carefully selected, with 32 in each condition: positive, negative, and neutral (Fig. 1A). These materials were sourced from online news and documentary films published between 2015 and 2023. Initially, 120 experiences (40 per condition) were collected, and 96 were ultimately chosen based on the evaluation provided by an independent sample of participants ($n = 30$, 15 males; see Supplementary Materials for details). The

description of the protagonist and the event preserved essential background information, such as the protagonist attending literacy training (an illiterate person in the mountains), while maintaining a concise length (protagonist: 5.30 ± 1.97 Chinese characters; event: 8.15 ± 2.85 Chinese characters; see examples in Table S1 and full list at <https://osf.io/npbrg>). The Chinese character length for the protagonist and the event was matched among the three conditions (Table S2). Each stimulus also included a high-resolution image ($1,920 \times 860$ pixels) showcasing facial expressions. Positive stimuli were uplifting events with happy facial expressions, such as a slum-dwelling youth accessing clean tap water for the first time (Fig. 1A). Negative stimuli presented distressing circumstances with sad facial expressions, for example, a young woman facing the removal of her uterus due to a rare disease. Neutral stimuli depicted everyday occurrences with neutral facial expressions, such as an agricultural park worker performing routine tasks. These stimuli in each condition featured protagonists from diverse age groups (2/3 were adults, and 1/3 were children or elderly), nationalities (2/3 were Chinese and 1/3 were non-Chinese), and genders (2/3 were females and 1/3 were males). Age group,

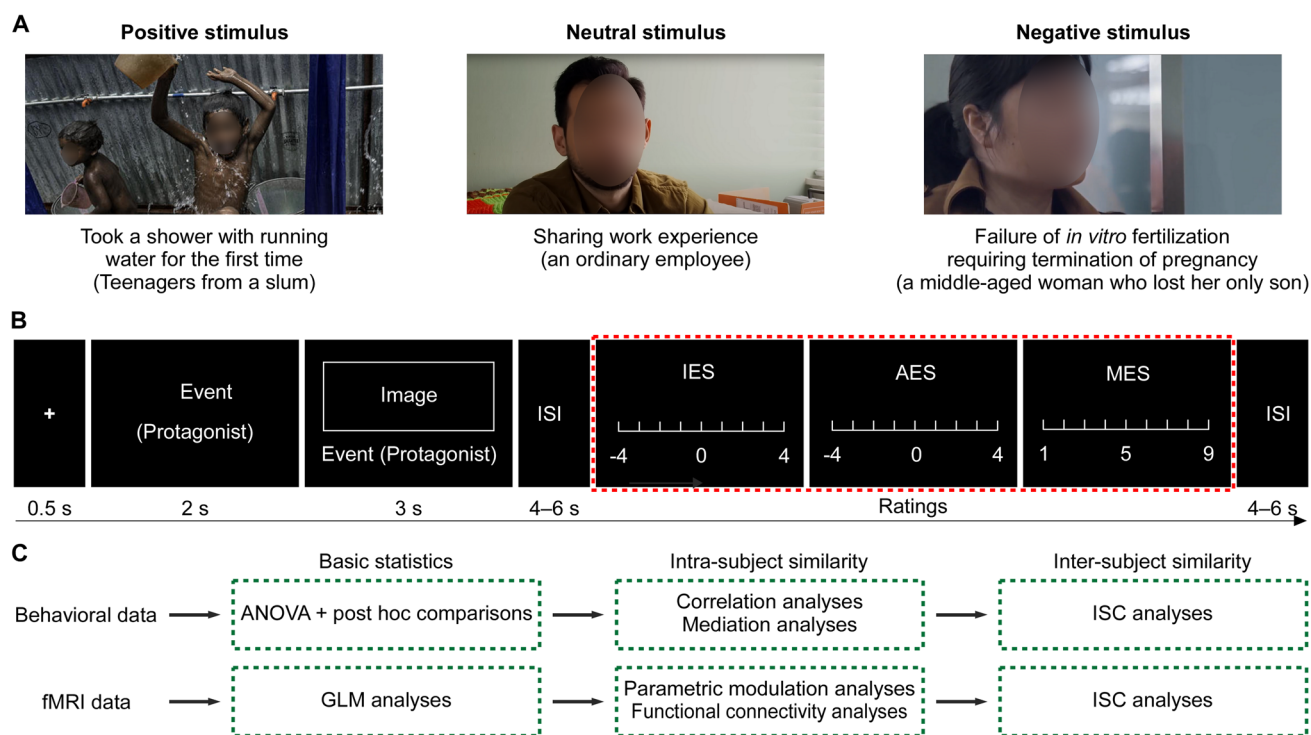


Fig. 1 Overview of stimuli (A), experimental design (B), and analysis pipeline (C). **A** Representative stimuli depicting positive, neutral, and negative real-life experiences. **B** Each stimulus sequence began with a 0.5-s white fixation cross, followed by a 2-s text screen and a 3-s image screen. After a jittered ISI of 4–6 s, participants were prompted to rate three questions, yielding the IES, AES, and MES, respectively. Another jittered ISI of 4–6 s preceded the next trial.

C Analysis pipeline for this study. After basic statistical analyses, advanced analyses were performed to explore intra-subject similarity and inter-subject similarity for both behavioral and fMRI data. IES, identified emotion score; AES, affective empathy score; MES, motivational empathy score; ANOVA, analysis of variance; ISC, inter-subject correlation; ISI, inter-stimulus interval.

nationality, and gender were matched among the three conditions (Table S3).

Experimental Design

The fMRI experiment consisted of two positive runs, each containing 16 positive stimuli and 8 neutral stimuli, and two negative runs, each with 16 negative stimuli and 8 neutral stimuli. The positive and negative runs were separated by a resting-state scan of ~7 min to minimize potential emotional interference, with the order of positive and negative runs counterbalanced for males and females. Stimuli with different real-life experiences were presented in a pseudo-random order, with each beginning with a 0.5-s white cross, followed by a 2-s text screen, and then a 3-s image screen (Fig. 1B). The text screen provided two parts of contextual information: the upper part describing the event, and the lower part describing the protagonist. The image screen displayed the accordant image (reduced to $1,440 \times 645$ pixels) at the center of the screen ($1,920 \times 1,080$ pixels), with contextual information reappearing at the bottom in a smaller font. Participants were instructed to primarily focus on the image, referring to the text when necessary. Moreover, participants were required to imagine themselves being present at the scene of the event when viewing the image. In order to introduce variability in the timing of stimulus presentations, jittered inter-stimulus intervals (ISIs) ranging from 4 to 6 s [21] were implemented, both between consecutive stimuli and between the image screen and the subsequent rating process.

After each stimulus, participants were asked to rate the following three questions: (1) What is the emotional state of the protagonist? (2) What emotion do you feel for them? (3) To what extent do you feel warmth, kindness, concern, or compassion? These questions have been similarly used in previous studies, yielding the self-reported measures of identified emotion score (IES), affective empathy score (AES), and motivational empathy score (MES), respectively [22, 23]. Notably, the motivational dimension is interpreted differently between positive and negative empathy. While “warmth” and “kindness” are used to represent the motivational dimension for positive empathy, “concern” and “compassion” are used for negative empathy [23]. These differences were explained to participants, and they were instructed to rate on question #3 if any of the words matched their states. Ratings for the first two questions were made on a 9-point scale ranging from -4 to 4 (-4 = “very sad”, 0 = “neutral”, 4 = “very happy”), while the third question was rated on a scale from 1 to 9 (1 = “very little”, 5 = “neutral”, 9 = “very much”). During the rating procedure, participants used two buttons operated with the left hand to adjust their ratings (one for leftward and one for rightward movement), and one of two buttons in the right hand to confirm

their ratings. Each question began at the neutral position, and there was no time limit for completing the ratings. The average response time was 2.63 ± 1.71 s for IES, 2.34 ± 1.49 s for AES, and 2.70 ± 1.64 s for MES. The experimental paradigm was designed and implemented using the PsychoPy software (Open Science Tools Ltd., <https://www.psychopy.org/>).

To ensure data quality during the experimental procedures, several strategies were employed. First, all data were collected in the morning to ensure that participants were in a good physiological state and to minimize the potential influence of daily distractions. Second, participants received a detailed explanation of the fMRI procedures, including clarification on the presence of black screens (shown during ISI) and the importance of maintaining a relaxed state during these ISIs. Third, the ISI used in this study ranged from 4 to 6 s, which has been shown to yield reliable effects [21]. Fourth, we confirmed with all participants whether they had made any errors in their ratings after the fMRI scanning and corrected them immediately. Fifth, post-tests were conducted for each participant immediately after the experiment. Participants rated their level of concentration during the task on a 9-point scale (1 = “very unfocused”, 9 = “very focused”), as well as their capability to imagine themselves being present at the scene of the event (1 = “very incapable”, 9 = “very capable”). Overall, participants reported high levels of concentration (8.37 ± 0.68) and capability (8.23 ± 0.64). Additionally, participants were asked to complete an image appearance test, determining whether 30 images (10 positive, 10 negative, and 10 neutral images; half appeared in the task while the other half did not) had appeared during the task. Importantly, participants were not informed in advance about the content of the test to prevent them from memorizing the images. Participants who scored $< 60\%$ accuracy on the test would be excluded from further analyses, but none failed to meet this criterion. The average accuracy of the image appearance test was $90.20\% \pm 7.60\%$ (ranging from 70 to 100%), indicating good task performance by the participants.

MRI Data Acquisition and Preprocessing

MRI data were collected using a Discovery MR 750 3.0T scanner (General Electric Healthcare, Milwaukee, USA) with a 32-channel head coil at the Magnetic Resonance Imaging Research Center, Institute of Psychology, Chinese Academy of Sciences, China. T1-weighted structural images were obtained using a magnetization prepared-rapid acquisition gradient echo (MP-RAGE) pulse sequence (240 sagittal slices, flip angle [FA] = 7° , field of view [FOV] = $256 \text{ mm} \times 256 \text{ mm}$, matrix size = 320×320 , slice thickness = 0.8 mm). Task fMRI images were obtained using a Gradient Echo pulse sequence with

Hyperband acceleration (60 oblique slices, TR [repetition time] = 800 ms, TE [echo time] = 30 ms, FA = 60°, FOV = 216 mm × 216 mm, matrix size = 90 × 90, slice thickness = 2.4 mm, hyperband slice = 6, no slice spacing). Note that the first five subjects were scanned with a TR of 750 ms, and the remaining participants were scanned with a TR of 800 ms to prevent reaching the upper limit of the scanner. Fieldmap images were obtained before task fMRI images (TE short = 4.9 ms, TE long = 7.4 ms).

MRI data were mainly preprocessed using the SPM 12 toolbox (Statistical Parametric Mapping, the Wellcome Trust Centre for Neuroimaging, <http://www.fil.ion.ucl.ac.uk/spm>). For task fMRI images, the initial 12 volumes from each run were removed to ensure the scanner signal stability. Voxel-displacement maps (VDM) were computed from fieldmap images for each run. Task fMRI images were then realigned and unwrapped using the VDM files as the phase maps while registering to the mean task fMRI image. The structural image was corrected for intensity non-uniformity using the N4BiasFieldCorrection tool in ANTs (Advanced Normalization Tools) 2.5.1 [24], coregistered to the mean task fMRI image, and then segmented into gray matter, white matter, and cerebrospinal fluid. Task fMRI images were normalized to the Montreal Neurological Institute (MNI) space using the deformation field obtained during segmentation, resampled to 2 mm × 2 mm × 2 mm isotropic voxels, and then smoothed with a 4 mm full-width half-maximum Gaussian kernel.

Regarding head motion, 33 out of 35 participants were able to maintain it within 2.4 mm translation and 2.4° rotation in any direction throughout each run. One female participant exhibited a single large head motion spike in the interval between stimuli, and the data were retained and included in subsequent analyses. One male participant exhibited head motion exceeding 2.4 mm during the last 3 min of a run. Consequently, the data collected during this period (10 trials with 7 negative and 3 neutral stimuli) were discarded, while the remaining data from this participant were retained for analyses that do not require equal trial counts among participants, e.g., analysis of variance (ANOVA), correlation analysis, general linear model (GLM), and PM analysis, but were excluded from ISC and FC analyses.

Data Analyses

The overall analysis pipeline is demonstrated in Fig. 1C. After conducting basic statistical analyses of behavioral and fMRI data, we focused on exploring the intra-subject similarity for each subprocess of empathic responses and the inter-subject similarity among participants.

Behavioral Analyses

All ratings were normalized by dividing by the maximal score (4 for IES and AES, and 9 for MES), resulting in IES and AES being scaled to the [−1, 1] range, and MES to the [0, 1] range. For each type of ratings (IES, AES, or MES), one-way repeated-measures ANOVA (positive, negative, and neutral) was performed. When significant differences were observed, *post hoc* pairwise comparisons were conducted. To account for multiple comparisons, Greenhouse-Geisser correction was applied to the ANOVA analyses, and false discovery rate (FDR) correction was used for the *post hoc* paired-sample *t*-tests. To explore whether the variance of ratings differed among conditions, we calculated the SD for each type of rating in each condition per participant and compared the SD between positive and negative stimuli using paired-sample *t*-tests.

To enable a more direct comparison between positive and negative empathy, the IES and AES for negative stimuli were reversed to ensure consistency in the direction of the scores (i.e., larger values represented larger responses). Multilevel correlation analyses were conducted to explore pairwise correlations among IES, AES, and MES for each stimulus type. Then, Fisher's *Z*-transformed correlation coefficients among IES, AES, and MES were calculated for each subject and compared among stimulus types using one-way repeated-measures ANOVA and *post hoc* paired-sample *t*-tests.

We explored whether AES mediated the relationship between IES and MES using multilevel mediation analyses for positive and negative stimuli separately. To further distinguish their differences after accounting for the mediation effect of AES, we combined both stimulus types and used stimulus type as a moderator (positive = 1, negative = 0). We tested all possible models based on the moderated paths: (1) IES → MES, (2) IES → AES, (3) AES → MES, (4) IES → AES and IES → MES, (5) AES → MES and IES → MES, (6) IES → AES and AES → MES, and (7) all three paths combined. The model fit was assessed using the following criteria: (1) the significance of χ^2 test $P > 0.05$, (2) the normed χ^2 , i.e., the ratio of χ^2 to degree of freedom (df) < 2, [25] (3) the root mean square error of approximation (RMSEA) ≤ 0.06, (4) standardized root mean square residual (SRMR) ≤ 0.08, and (5) both the comparative fit index (CFI) and the Tucker-Lewis index (TLI) ≥ 0.95 [26]. Standardized path coefficients (β), 95% confidence intervals (CI), and *P*-values were reported for both direct and indirect effects. Person-mean centering was applied before parameter estimation, and parameter estimates were calculated using maximum likelihood with robust standard errors to account for the data's non-normality. The “correlation” package was used for multilevel correlation analyses [27, 28], the “pingouin” package was used for ANOVA analyses and *post hoc* comparisons [29], and the “Mplus v8.3”

(<https://www.statmodel.com/>) was used for multilevel mediation analyses.

Inter-subject similarity was assessed using inter-subject correlation (ISC) analysis, which calculates the linear correlations between each pair of subjects and derives summary statistics from these correlations [30–34]. Specifically, the ratings for each stimulus type were sorted in the same order (i.e., identical stimulus order) across subjects. Then, Pearson correlations between subjects were calculated to generate an inter-subject correlation matrix for each type of rating. The overall ISC value was obtained by calculating the median of the lower triangle in each ISC matrix [35]. The *P*-value was obtained by comparing the ISC to a null distribution generated through subject-wise bootstrapping of the pairwise similarity matrices 10,000 times and evaluating the proportion of samples from the distribution larger than the observed ISC. Furthermore, the lower triangle of the ISC matrices was compared across stimulus types using the non-parametric Wilcoxon signed-rank tests. FDR correction was applied to account for multiple comparisons. The “nltools” package (<https://cosanlab.github.io/nltools>) was used for ISC analyses.

GLM Analyses for fMRI Data

First-level analyses were performed with the image screen as the trial onset, with six realignment parameters and a constant term per run included as regressors of no interest (referred to as GLM#1). Three *t*-contrast maps were generated for the three stimulus types at the first level, and one-sample *t*-tests were performed on each *t*-contrast to explore the brain’s activation and deactivation under each condition. *T*-contrast maps comparing different stimulus types, i.e., Positive *versus* Neutral, Negative *vs* Neutral, and Positive *vs* Negative, were summarized at the group level using one-way ANOVA—within-subject. Conjunction analyses were conducted to explore shared responses between the Positive *versus* Neutral and Negative *vs* Neutral comparisons. To account for multiple comparisons, thresholds of voxel-level $P < 0.001$ and cluster-level FDR corrected $P < 0.05$ were applied. These criteria were also applied in subsequent fMRI analyses unless specified otherwise. The image screen was used as the trial onset since brain responses to facial expressions are faster and more direct than those to words [36]. However, we also used the text screen as the trial onset to verify the statistical results. All fMRI analyses were performed using SPM12.

PM Analyses for fMRI Data

PM analyses were performed to identify brain regions that correlated with ratings for positive, neutral, and negative stimuli, respectively. In the first-level analyses, a single regressor was specified to model the onset of positive, neutral, or negative stimuli, with the corresponding ratings serving as parametric modulators for IES, AES, and MES, respectively (referred to as GLM#2). At the group level, one-sample *t*-tests were applied to identify brain regions that were either positively or negatively correlated with the ratings. Given high correlations among the ratings, a stringent threshold was applied at the cluster level, i.e., FDR corrected $P < 0.016$ ($0.05/3 \approx 0.016$). Additionally, conjunction analyses were conducted to explore shared brain regions encoding both positive and negative stimuli. Please note that SPM automatically de-means the parametric modulator by default.

FC Analyses for fMRI Data

FC analyses were performed to explore intra-subject neural similarity between different brain regions using the beta-series correlation method, which has been shown to be more effective for event-related designs compared to standard psychophysiological interaction (PPI) and generalized PPI analyses [37]. To perform FC analyses, an additional first-level analysis was conducted (referred to as GLM#3). In GLM#3, one regressor was modeled for each single trial, generating a beta map for each trial that allowed the exploration of trial-by-trial dynamic variability of neural responses. Then, beta maps for positive, negative, and neutral stimuli were isolated. Mean beta values of a pre-defined region of interest (ROI), i.e., the seed, were estimated, and Pearson correlation analyses were performed to correlate these values with beta values in every single voxel of the rest of the brain. The resulting correlation coefficients were Fisher’s *Z*-transformed to generate the corresponding *Z*-map. At the group level, *t*-contrasts (Positive *vs* Neutral or Negative *vs* Neutral) were generated to identify regions with stronger FC for positive or negative stimuli compared to neutral stimuli. Notably, significant brain regions from the PM analyses were defined as ROIs. ROI masks were created using the “Marsbar” toolbox [38], and beta-series correlation analyses were performed using the modified MATLAB code based on SPM scripts from Andrew Jahn and Derek Nee [39].

ISC Analyses for fMRI Data

ISC analyses were performed to explore inter-subject neural similarity. Significant brain regions identified from the PM analyses served as ROIs, and trial-by-trial mean beta values were extracted for each ROI from GLM#3. Like

the ISC analyses for behavioral data, beta values were first ordered according to the same stimulus sequence across subjects. Then, a pairwise Pearson correlation matrix was constructed, and the ISC value was computed as the median of the lower triangle of the ISC matrix. The P -value was determined by comparing the ISC value to a null distribution. Furthermore, the beta value ISC matrices for positive and negative stimuli were compared using the non-parametric Wilcoxon signed-rank test, with FDR corrections applied to account for multiple comparisons.

Results

Behavioral Results

Significant differences were observed in IES, AES, and MES among positive, negative, and neutral stimuli (IES: $F_{(2,68)} = 1,353.76$; AES: $F_{(2,68)} = 370.44$; MES: $F_{(2,68)} = 182.25$;

all $q_{FDR} < 0.001$; Fig. 2A and Table S4), indicating robust differences in stimulus valence. Furthermore, the variance (SD) in IES, AES, and MES showed no difference between positive and negative stimuli (all $P > 0.05$), suggesting that these ratings' variations were comparable between positive and negative stimuli.

Multilevel correlation analyses revealed significant correlations between IES and AES (positive: $r = 0.51$, neutral: $r = 0.68$, negative: $r = 0.69$; all $q_{FDR} < 0.001$), IES and MES (positive: $r = 0.26$, neutral: $r = 0.20$, negative: $r = 0.47$; all $q_{FDR} < 0.001$), as well as AES and MES (positive: $r = 0.56$, neutral: $r = 0.29$, negative: $r = 0.64$; all $q_{FDR} < 0.001$). The correlations among these scores were significantly weaker for positive stimuli compared to negative stimuli [$r(\text{IES}, \text{AES})$: $t_{(33)} = -4.27$, $q_{FDR} < 0.001$, Hedges' $g = -0.76$; $r(\text{IES}, \text{MES})$: $t_{(34)} = -5.00$, $q_{FDR} < 0.001$, $g = -1.02$; $r(\text{AES}, \text{MES})$: $t_{(33)} = -2.24$, $q_{FDR} = 0.032$, $g = -0.48$; Fig. 2B and Table S5], suggesting more consistent responses toward others' negative experiences

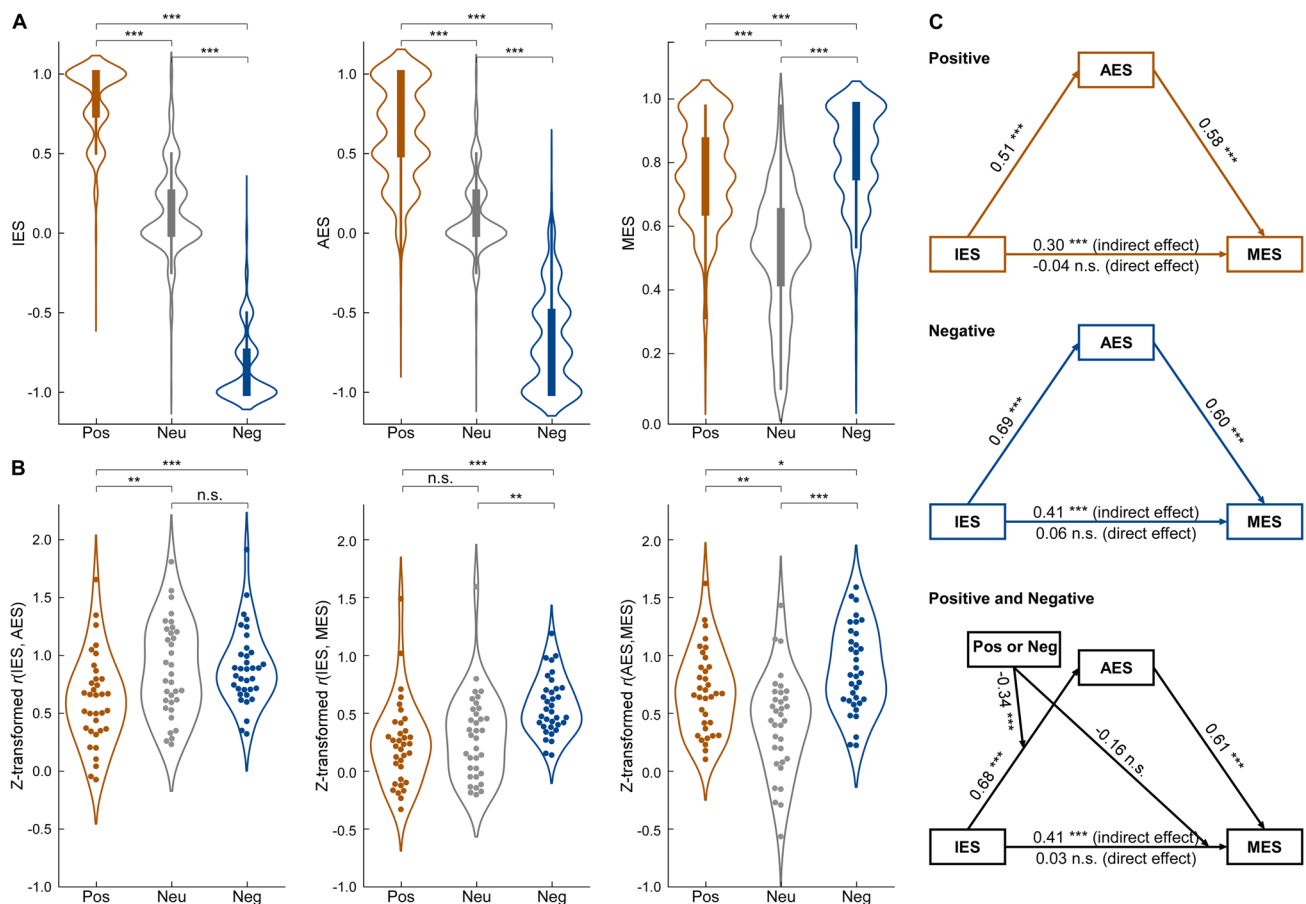


Fig. 2 Behavioral results. **A** Comparisons of IES, AES, and MES among positive (Pos), neutral (Neu), and negative (Neg) stimuli. **B** Comparisons of Fisher Z-transformed correlation coefficients among different ratings (IES, AES, and MES). **C** Results of multilevel mediation analyses for the relationships among IES, AES, and MES. IES,

identified emotion score; AES, affective empathy score; MES, motivational empathy score; pos, positive; neu, neutral; neg, negative; * $q_{FDR} < 0.05$, ** $q_{FDR} < 0.01$, *** $q_{FDR} < 0.001$ in panels **A** and **B**, *** $P < 0.001$ in panel **C**; n.s., not significant.

than positive experiences at the behavioral level. Please note that one subject rated the AES at 0 for all neutral stimuli, resulting in one less degree of freedom for AES-related correlation analyses.

Exploratory multilevel mediation analyses revealed that AES completely mediated the relationship between IES and MES for both positive and negative stimuli (positive: $\beta = 0.30$, 95% CIs = [0.21, 0.38], $P < 0.001$; negative: $\beta = 0.41$, 95% CIs = [0.32, 0.51], $P < 0.001$; Fig. 2C). The direct effect of IES on MES, after controlling for the mediator, was not significant (positive: $\beta = -0.04$, 95% CIs = [-0.14, 0.06], $P = 0.411$; negative: $\beta = 0.06$, 95% CIs = [-0.04, 0.15], $P = 0.257$). Mediation analyses involving both positive and negative stimuli showed that the model where the stimulus type moderated the paths between IES and AES, and between IES and MES, fitted best ($P = 1.000$, $\chi^2/df < 0.001$, RMSEA < 0.001 , SRMR < 0.001 , CFI = 1.000, TLI = 1.000; Table S6). AES completely mediated the relationship between IES and MES ($\beta = 0.41$, 95% CIs = [0.38, 0.51], $P < 0.001$), with a significantly weaker mediation effect for positive stimuli compared to negative stimuli (unstandardized β difference = -0.14, 95% CIs = [-0.21, -0.06], $P = 0.001$). The stimulus type significantly moderated the direct effect from IES to AES ($\beta = -0.34$, 95% CIs = [-0.51, -0.16], $P < 0.001$), but not on the direct effect from IES to MES ($\beta = -0.16$, 95% CIs = [-0.35, 0.04], $P = 0.114$). These results indicated that others' positive events induced less similar empathic responses compared to negative events, and individuals' affective responses showed a weaker effect on the relationship between recognizing others' emotions and motivational empathy for positive events than negative ones.

ISC analyses indicated significant inter-subject similarity in IES (positive: ISC = 0.09, $q_{FDR} = 0.008$; neutral: ISC = 0.29, $q_{FDR} < 0.001$; negative: ISC = 0.41, $q_{FDR} < 0.001$), AES (positive: ISC = 0.08; neutral: ISC = 0.18; negative: ISC = 0.31; all $q_{FDR} < 0.001$), and MES (positive: ISC = 0.19; neutral: ISC = 0.24; negative: ISC = 0.23; all $q_{FDR} < 0.001$) for all stimulus types (Fig. 3). Wilcoxon signed-rank tests showed the inter-subject similarity was significantly weaker for positive stimuli compared to negative stimuli (IES: $z = -15.84$, AES: $z = -15.36$, MES: $z = -3.44$; all $q_{FDR} < 0.001$; Table S7). This indicated that even though different individuals responded in a similar way to others' positive and negative experiences, the similarities were significantly weaker for positive experiences compared to negative experiences.

GLM Analysis Results

GLM results for each condition were summarized in Table S8. Compared to neutral stimuli, positive and negative stimuli evoked stronger blood oxygenation level-dependent

(BOLD) responses in 5,411 overlapping voxels (positive: 10,571 voxels, negative: 10,123 voxels) and weaker responses in 2,170 overlapping voxels (positive: 5,428 voxels, negative: 4,453 voxels). Overlapping regions with stronger responses were found in the bilateral superior temporal sulcus (STS), medial prefrontal cortex (mPFC), medial precuneus, and left dorsolateral superior frontal gyrus (dlSFG). In contrast, overlapping regions with weaker responses were identified in the bilateral anterior insula (aINS), bilateral triangular part of the inferior frontal gyrus (IFGtri), bilateral inferior parietal gyrus (IPG), and corpus callosum, among others (Fig. 4A–C and Table S9). The Positive vs Neutral contrast also showed stronger responses in the right dlSFG, left hippocampal and parahippocampal gyrus, and right hippocampal gyrus (Fig. 4A and Table S10). The negative vs neutral contrast showed stronger responses in the left middle insula (mINS), right mINS extending into posterior insula (pINS), right supplementary motor area (SMA), supracallosal anterior cingulate cortex (ACC), and middle cingulate cortex (MCC) (Fig. 4B and Table S11). A direct comparison between positive and negative stimuli showed that positive stimuli elicited stronger responses in 3,290 voxels, located in the bilateral occipital gyrus, fusiform gyrus, parahippocampal gyrus, and left dlSFG. In contrast, negative stimuli induced stronger responses in the right hemisphere, including the aINS, pINS, and Rolandic operculum (420 voxels; Fig. 4D and Table S12). These observations suggested that there are shared and distinct brain responses between positive and negative empathy. Unthresholded contrast maps are available at <https://neurovault.org/collections/19481/>. GLM analyses with the text screen as the trial onset yielded similar results (Fig. S1).

PM Analysis Results

For positive stimuli, bilateral IFGtri, left SMA, left precentral gyrus, the mPFC, left aINS, left postcentral gyrus, and left caudate showed a negative correlation with IES, while the left cuneus exhibited a positive correlation with MES (Fig. 5A and Table 1 upper part). No significant correlations were observed for AES. For negative stimuli, the right fusiform gyrus exhibited a positive correlation with IES, while bilateral IFGtri, left SMA, left precentral gyrus, the left middle temporal gyrus (MTG), and MCC showed a negative correlation with IES. Bilateral conjunction of the middle occipital gyrus (MOG) and MTG (MOTG) and right supramarginal gyrus (SMG) were positively correlated with both IES and AES. The left SMG, right mINS, and right MOG were also positively correlated with AES. The right angular gyrus and left MTG were negatively correlated with both AES and MES. The right inferior frontal gyrus (IFG) and right dlSFG were negatively correlated with MES (Fig. 5B

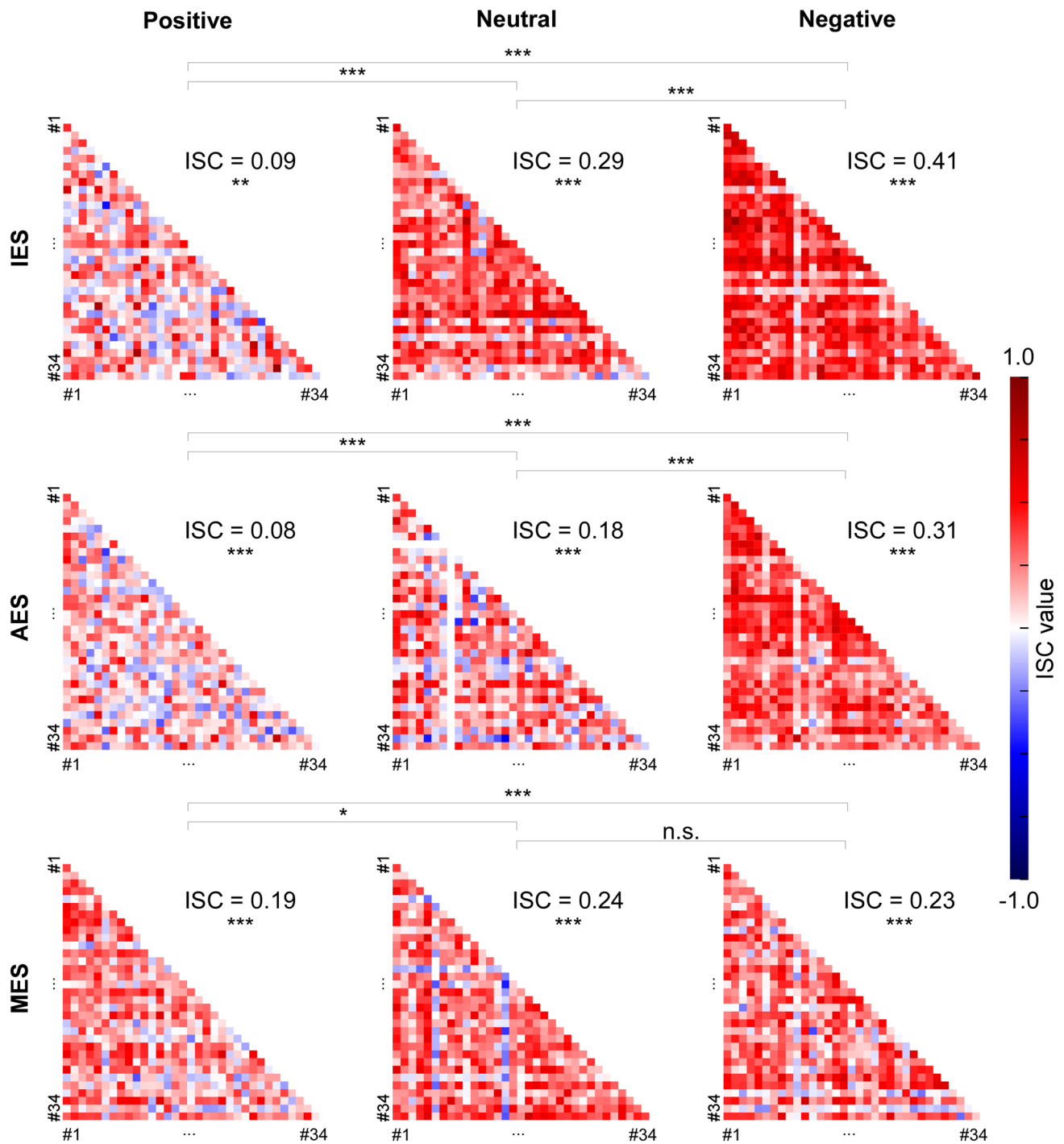


Fig. 3 ISC matrices for IES, AES, and MES across different stimulus types. ISC, inter-subject correlation; IES, identified emotion score; AES, affective empathy score; MES, motivational empathy score. * $q_{FDR} < 0.05$, ** $q_{FDR} < 0.01$, *** $q_{FDR} < 0.001$, n.s., not significant.

and Table 1 lower part). For neutral stimuli, no significant result was observed.

Conjunction analyses showed that the right IFGtri, left SMA, and left precentral gyrus negatively encoded IES for both positive and negative empathy. However, no shared encoding schemes were observed for AES or MES. In short,

shared and distinct encoding schemes were observed for IES in response to positive and negative stimuli; encoding schemes for AES were only observed in response to negative stimuli; more encoding schemes were observed for negative stimuli compared to positive ones.

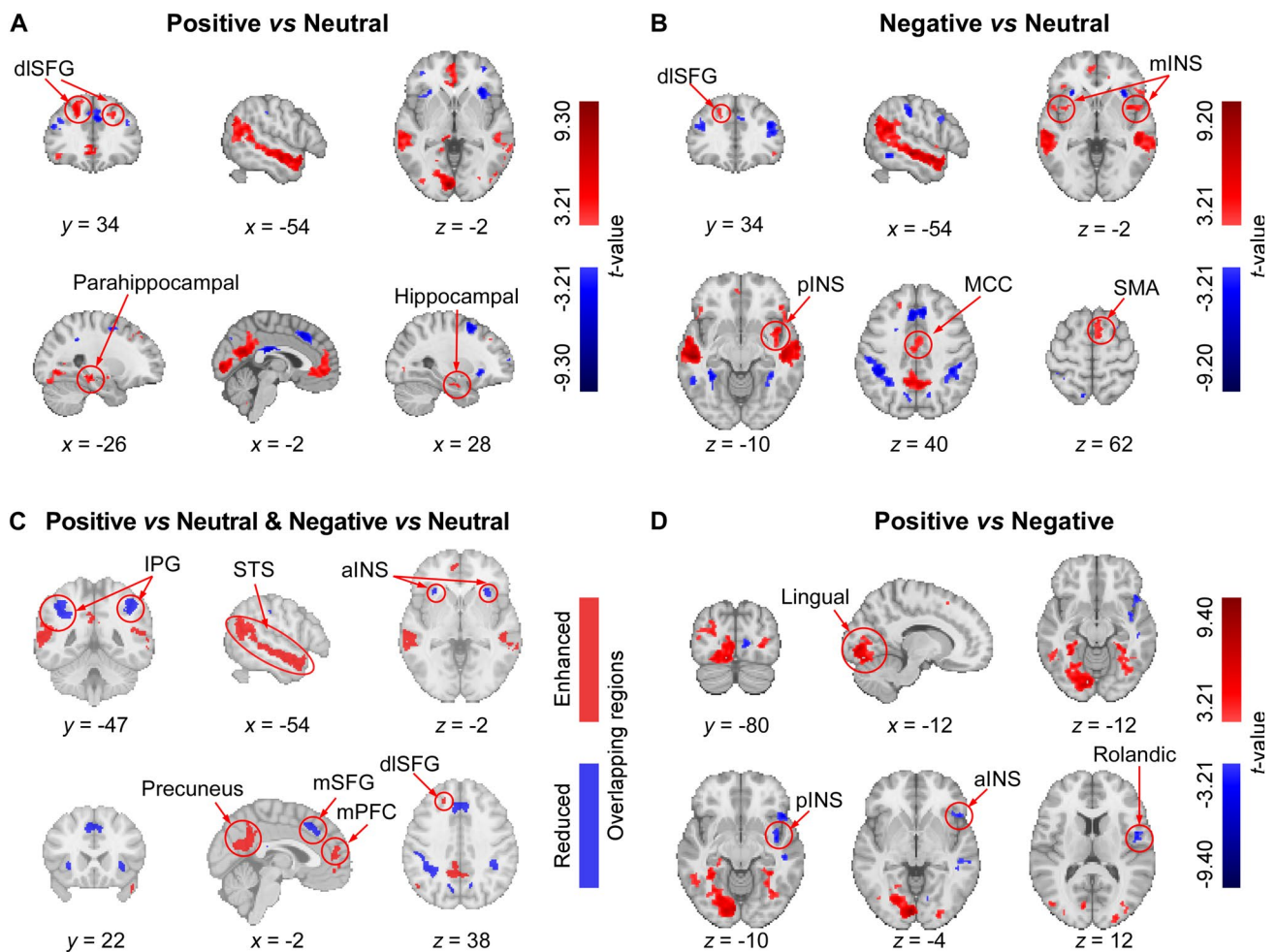


Fig. 4 GLM results. **A** Brain responses for the Positive vs Neutral contrast. **B** Brain responses for the Negative vs Neutral contrast. **C** Overlapping brain responses for both Positive vs Neutral contrast and Negative vs Neutral contrast. Red indicates stronger shared responses, while blue denotes weaker shared responses. **D** Brain responses for

the Positive vs Negative contrast. dISFG, dorsolateral superior frontal gyrus; mINS, middle insula; pINS, posterior insula; MCC, middle cingulate cortex; SMA, supplementary motor area; IPG, inferior parietal gyrus; STS, superior temporal sulcus; aINS, anterior insula; mSFG, medial superior frontal gyrus; mPFC, medial prefrontal cortex.

FC Analysis Results

FC analysis results were summarized in Table S13. For both stimuli, stronger FC was observed only between the right IFG and left MOTG, which are IES-encoding brain regions. For positive stimuli, stronger FC was also observed in IES-encoding brain regions, specifically between the right IFG and right superior parietal gyrus (SPG). Moreover, stronger FC was observed in MES-encoding brain regions, including between the left cuneus and MCC, as well as the medial superior frontal gyrus (SFG).

For negative stimuli, stronger FC was also observed in IES-encoding brain regions, including between the left SMA and left postcentral gyrus, as well as between the MCC and right SMG/left postcentral gyrus. Notably, evident FC

results were observed in AES-encoding brain regions. Specifically, bilateral SMG and right mINS, which encoded AES, showed stronger FC with the right SMA and supracallosal ACC (Fig. 6). Moreover, the mINS showed stronger FC with several other brain regions, such as the left mINS, left cuneus, left cerebellum, MCC, and left middle frontal gyrus (MFG). No significant FC was observed in brain regions encoding MES in response to negative stimuli.

To summarize, stronger shared FC between positive and negative stimuli was only observed for IES-encoding brain regions (between the right IFG and left MOTG); a convergent FC network with several AES-encoding brain regions was observed for negative stimuli; FC results for MES-encoding brain regions were sparse.

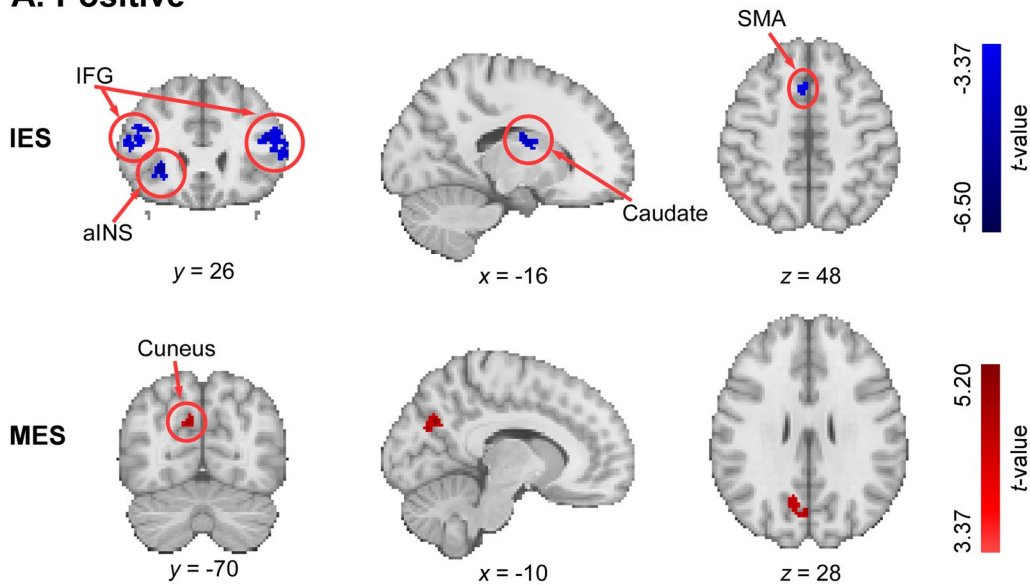
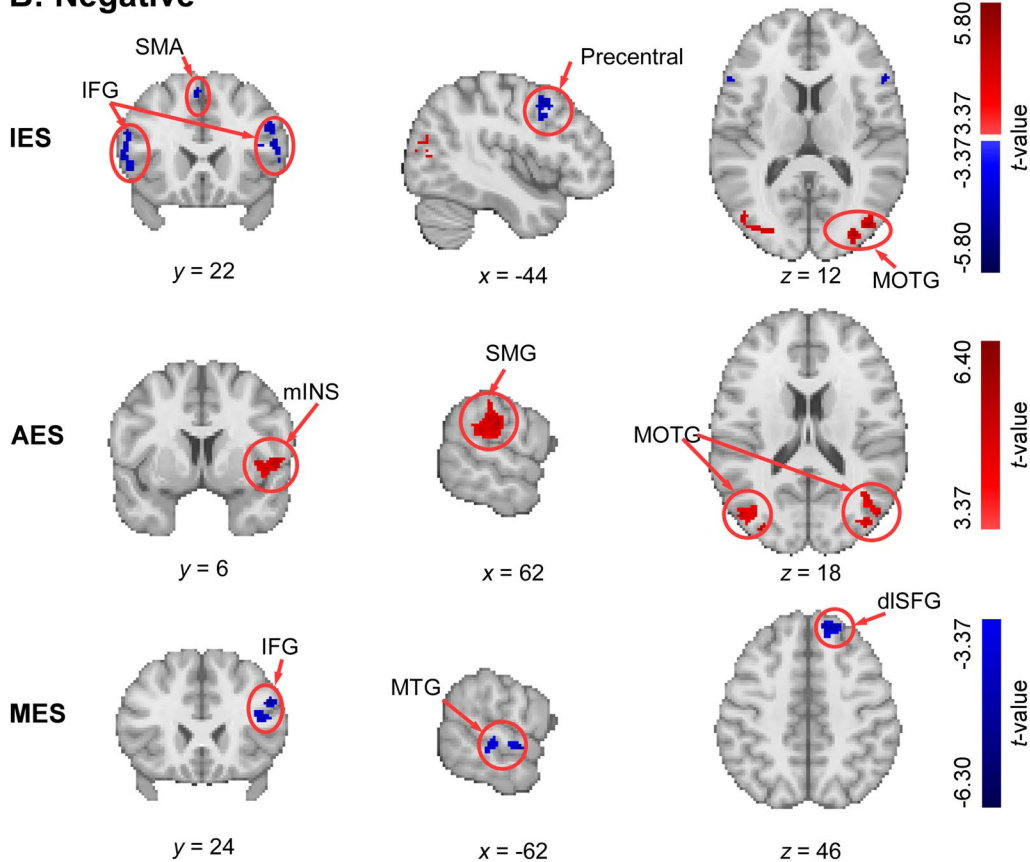
A: Positive**B: Negative**

Fig. 5 Results of parametric modulation analyses. PM analyses depicting brain regions significantly correlated with ratings for positive (A) and negative (B) stimuli. IES, identified emotion score; AES, affective empathy score; MES, motivational empathy score; IFG, inferior frontal gyrus; aINS, anterior insula; SMA, supplementary

motor area; MOTG, conjunction of the middle occipital gyrus and middle temporal gyrus; mINS, middle insula; SMG, supramarginal gyrus; MTG, middle temporal gyrus; dISFG, dorsolateral superior frontal gyrus.

Table 1 Parametric modulation analysis results for positive and negative stimuli

Stimulus type	ROI index	Cluster size	Cluster <i>P</i> (FDR)	Hemisphere	Brain regions	<i>t</i> -value	Peak MNI coordinates (mm)		
							<i>X</i>	<i>Y</i>	<i>Z</i>
Positive	<i>IES</i> (–)								
	1	112	< 0.001	L	aINS	6.49	– 30	24	– 2
	2	483	< 0.001	L	Triangular and opercular parts of IFG, and the precentral gyrus	5.97	– 44	8	24
	3	340	< 0.001	R	Triangular part of IFG	5.24	46	24	22
	4	60	0.008	L	Postcentral gyrus	5.15	– 60	– 8	34
	5	84	0.002	M	mPFC	5.14	8	44	48
	6	67	0.006	L	Caudate	4.94	– 18	– 8	22
	7	64	0.006	L	Precentral gyrus	4.90	– 4	0	58
Negative	8	64	0.006	L	SMA	4.50	– 6	16	46
	<i>MES</i> (+)								
	9	105	< 0.001	L	Cuneus	5.17	– 12	– 68	30
	<i>IES</i> (+)								
	1	151	< 0.001	L	MOTG	5.80	– 32	– 84	16
	2	207	< 0.001	R	MOTG	5.48	42	– 82	14
	3	130	< 0.001	R	SMG	5.09	58	– 32	24
	4	69	0.006	R	Fusiform gyrus	4.79	28	– 44	– 14
	<i>IES</i> (–)								
	5	88	0.001	L	SMA	5.58	– 4	20	52
	6	102	< 0.001	L	Triangular part of IFG	5.24	– 52	18	4
	7	201	< 0.001	L	MTG	5.01	– 56	– 34	2
	8	123	< 0.001	L	Precentral gyrus	4.83	– 42	12	46
	9	59	0.005	R	Triangular and opercular part of IFG	4.60	50	14	28
	10	71	0.002	M	MCC	4.58	6	28	38
	11	73	0.002	R	Triangular part of IFG	4.52	54	26	14
	<i>AES</i> (+)								
	12	369	< 0.001	L	MOTG	6.00	– 50	– 74	16
	13	99	< 0.001	L	SMG	5.70	– 62	– 30	34
	14	421	< 0.001	R	SMG	5.65	66	– 34	32
	15	80	0.002	L	MTG	5.19	– 42	– 58	0
	16	154	< 0.001	R	mINS	5.12	52	6	– 2
	17	90	< 0.001	R	MOG	5.11	42	– 82	14
	18	90	< 0.001	R	MOTG	4.92	50	– 74	18
	<i>AES</i> (–)								
19	247	< 0.001	R	Angular gyrus	6.35	50	– 56	34	
20	88	0.002	L	MTG	4.89	– 46	– 42	0	
<i>MES</i> (–)									
21	259	< 0.001	L	MTG	6.29	– 48	– 42	0	
22	80	0.003	R	Triangular and opercular part of IFG	5.41	46	24	28	
23	194	< 0.001	R	dlSFG	5.35	18	36	40	
24	77	0.003	R	Triangular part of IFG	5.20	44	30	18	
25	248	< 0.001	R	Angular gyrus	5.11	50	– 58	32	

L, left; R, right; M, medial; aINS, anterior insula; IFG, inferior frontal gyrus; mPFC, medial prefrontal cortex; SMA, supplementary motor area; SMG, supramarginal gyrus; MOTG, conjunction of the middle occipital gyrus and middle temporal gyrus; MTG, middle temporal gyrus; mINS, middle insula; MOG, middle occipital gyrus; MTG, middle temporal gyrus; dISFG, dorsolateral superior frontal gyrus. The “ROI Index” column indicates the sequence of the ROIs used in the following ISC analyses.

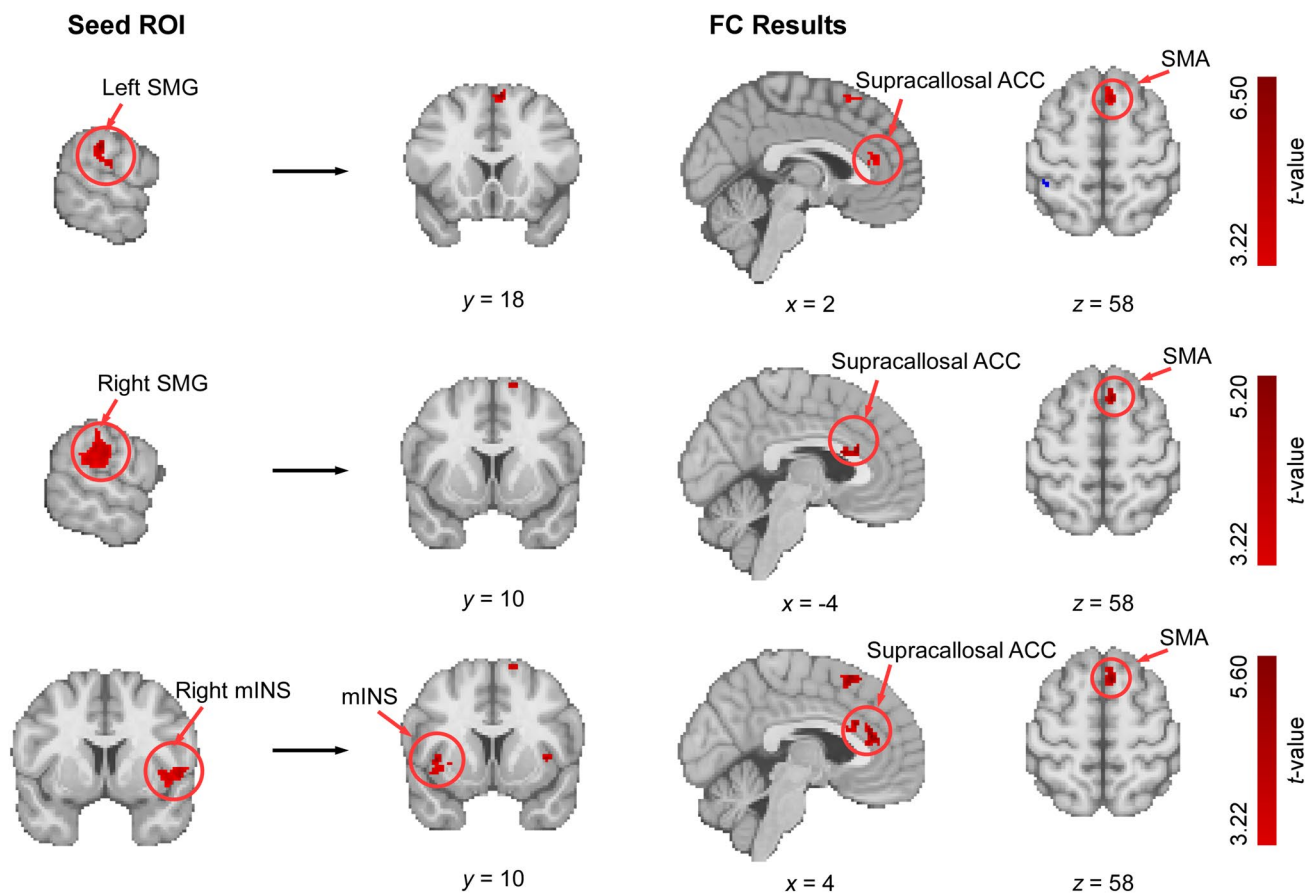


Fig. 6 Stronger FC in AES-encoding brain regions to negative stimuli. Significant brain regions encoding AES, identified from PM analyses, in response to negative stimuli, exhibited robust FC with the supracallosal ACC and right SMA. FC, functional connectivity; AES,

affective empathy score; PM, parametric modulation; SMG, supra-marginal gyrus; ACC, anterior cingulate cortex; SMA, supplementary motor area; mINS, middle insula.

ISC Analyses Results

Inter-subject neural similarity was explored using mean beta values within ROIs identified from PM analyses (Fig. 7 and Table S14). Both stimuli showed significant ISC among a series of brain regions, including bilateral MOTG, right fusiform gyrus, left IFGtri, left MTG, left precentral gyrus, and right MOG. Two additional brain regions, i.e., the left cuneus and right IFGtri, showed significant ISC for negative stimuli only. Wilcoxon signed-rank tests showed that the ISC values were significantly higher for negative stimuli compared to positive stimuli in bilateral MOTG and right MOG. Intuitively, this observation suggested higher inter-subject neural similarity in response to others' negative experiences compared to positive ones.

Discussion

By dissecting empathy into three subprocesses—emotion recognition, affective empathy, and motivational

empathy—the present study systematically examined positive and negative empathy and identified similarities and differences in both behavioral patterns and underlying neural mechanisms. First, significant correlations were observed among IES, AES, and MES, with AES completely mediating the relationship between IES and MES for both stimulus types. Second, GLM analyses on fMRI data revealed stronger shared responses in response to positive and negative stimuli than neutral stimuli in brain regions (i.e., the bilateral STS, precuneus, mPFC, and left dlSFG) that are responsible for understanding others' states and cognitive control. Positive stimuli also showed stronger responses in the right dlSFG, left hippocampal and parahippocampal gyrus, and right hippocampal gyrus than neutral stimuli. Negative stimuli also showed stronger responses in bilateral mINS, right pINS, right SMA, supracallosal ACC, and MCC than neutral stimuli. Third, PM analyses further identified shared brain regions (i.e., left SMA, right IFGtri, and left precentral gyrus) encoding IES for both positive and negative stimuli. However, AES-encoding brain regions (e.g.,

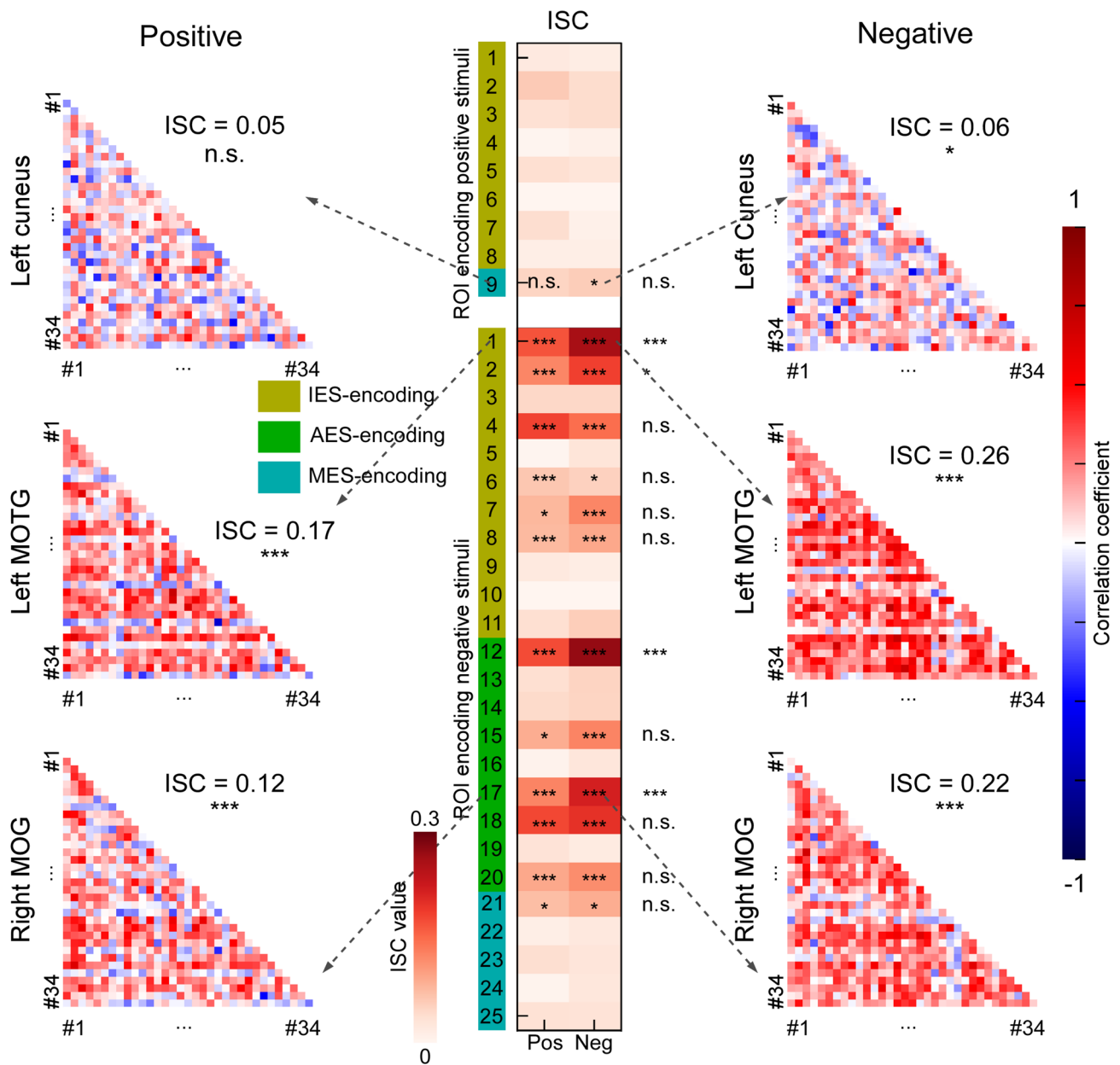


Fig. 7 Inter-subject neural similarity for positive and negative stimuli. The middle bar summarizes the ISC values for positive (left column) and negative (right column) stimuli, with brain regions identified from parametric modulation analyses as ROIs. The sequence of the ROIs, labeled to the left of the bar, corresponds to the order detailed in Table 1. Significance levels for comparisons between positive and negative ISC matrices are indicated to the right of the bar. Representative ISC matrices for positive and negative stimuli are dis-

played in the left and right panels, respectively, with the following brain regions: left cuneus (top), left MOTG (middle), and right MOG (bottom). MOTG, conjunction of the middle occipital gyrus and middle temporal gyrus; MOG, middle occipital gyrus; IES, identified emotion score; AES, affective empathy score; MES, motivational empathy score; ISC, inter-subject correlation. * $q_{FDR} < 0.05$, *** $q_{FDR} < 0.001$, n.s., not significant, $q_{FDR} > 0.05$.

bilateral MOTG, bilateral SMG, and right mINS) were only observed for negative stimuli. Fourth, shared stronger FC between positive and negative stimuli was observed for IES-encoding brain regions (between the right IFG and left MOTG), and only negative empathy exhibited a convergent FC network for AES-encoding brain regions (bilateral SMG

and right mINS showed stronger FC with the right SMA and supracallosal ACC). Fifth, significant inter-subject similarity of IES, AES, and MES was observed for both positive and negative stimuli across participants, but the similarity was significantly weaker in response to positive stimuli compared to negative stimuli at both behavioral and neural levels.

Responding to others' emotions involves a complex array of mental processes, including understanding others' states and emotions, sharing their feelings, and feeling motivated to act [40, 41]. These subprocesses of empathy are not mutually exclusive but function cohesively as an integrated response [23]. This is reflected in our findings, where significant correlations were observed among IES, AES, and MES for both positive and negative stimuli. Such correlations highlight the interdependence of empathy subprocesses, supporting the view that empathy functions as a dynamic and interconnected system rather than as isolated processes [42]. In particular, our results confirm that AES acts as a complete mediator between IES and MES for both stimulus types. This aligns with previous studies emphasizing the central role of affective empathy in translating emotional recognition into motivational outcomes [43, 44]. Affective empathy allows individuals to emotionally resonate with others, thereby increasing the likelihood of prosocial actions [45, 46]. However, this mediation effect was significantly weaker for positive stimuli compared to negative ones. This finding is further supported by ISC results, which showed that participants were significantly less consistent in their responses to positive stimuli than to negative ones. In line with previous studies [47], this suggests that an individual's emotions are less influenced by others' joy than by their distress, and that different individuals respond more similarly to the same negative experiences compared to the same positive experiences. In other words, although positive and negative empathy share similar subprocesses, there is a fundamental difference between the two [15], which may stem from the different variability in emotional responses to others' emotions. This discrepancy between positive and negative empathy likely reflects a broader societal focus on addressing suffering over celebrating success or well-being, potentially influencing the motivations underlying positive empathy. These insights would have important practical implications. For instance, given the consistent emotional resonance to negative events, these findings may help explain why negative content spreads more rapidly and widely online. Platforms could use such insights to adjust content moderation policies or develop algorithms that promote more balanced emotional engagement.

Notably, our behavioral findings were supported by neuroimaging evidence. GLM analyses revealed stronger shared responses in the bilateral STS, mPFC, and medial precuneus. These regions are known to be integral to the theory of mind network, which is involved in inferring others' mental states [48, 49]. This overlap in brain activations suggests that both positive and negative empathy engage similar neural mechanisms for understanding others' emotional states. However, distinct responses were observed for positive stimuli in the hippocampal gyrus and right dlSFG, along with broader activations in the left dlSFG compared to

negative stimuli. These regions are associated with cognitive control, with the dlSFG in particular being responsible for high-level cognitive functions [50]. This suggests that more complex, high-level cognitive processing could be involved when responding to others' positive emotions, as individuals may experience diverse feelings (even changes of feelings) during positive empathy processing. In contrast, negative empathy showed stronger responses in bilateral mINS, right pINS, and right SMA, which are also activated during physical pain and positively correlate with real-time pain intensity [51, 52]. The similarity of brain activation patterns between empathic responses to others' distress and one's own experience of distress suggests consistent and straightforward emotional processing during negative empathy. This finding is in good agreement with ISC results showing stronger inter-subject neural similarity for negative stimuli than positive stimuli. Distress tends to evoke more uniform emotional reactions across individuals, while responses to joy appear more individualized, potentially influenced by personal experiences or social norms regarding the expression of positive emotions.

Another key finding of this study is that positive and negative empathy partly share the emotion recognition subprocess but substantially differ in the affective empathy and motivational empathy subprocesses. This is supported by two lines of evidence. First, PM analyses revealed shared encoding schemes for IES between positive and negative stimuli in several brain regions, including the left SMA, left precentral gyrus, and right IFG. The left SMA, for instance, correlated with IES for both types of stimuli, suggesting its role in understanding and resonating with others' emotional experiences, no matter positive or negative [53, 54]. However, distinct encoding schemes were observed for AES and MES between positive and negative stimuli, suggesting differences in their affective and motivational subprocesses. Second, shared stronger FC between positive and negative stimuli was observed for IES-encoding brain regions (between the right IFG and left MOTG), but none was observed for AES- and MES-encoding brain regions. Furthermore, the right mINS and bilateral SMG, encoding AES for negative stimuli, were all connected with the right SMA and supracallosal ACC. The supracallosal ACC, which is associated with various important cognitive functions, [55] has been proposed to integrate diverse information to create a rich representation and exert high-level, abstract control over decision and action. [56] It may play a similar role in the empathy process, acting as a hub to transfer integrated information into negative emotional reactions. The right SMA, which is involved in regulating emotional responses and modulating empathic reactions during empathy for pain [57], may be directly related to implicit or explicit reactions to distress, such as furrowing one's brows. Altogether, these findings provide both behavioral and neural

evidence—including encoding schemes and associated brain networks—demonstrating that positive and negative stimuli partly share the emotion recognition subprocess but substantially differ in the affective empathy and motivational empathy subprocesses.

In conclusion, this study employed real-life events with detailed contextual information to enhance the ecological validity and demonstrated that the three subprocesses of empathy are more tightly interconnected when responding to others' negative experiences than positive experiences. This is likely due to the similarity in the activation of participants' own negative emotions by others' suffering, which engaged a highly convergent affective neural network. In other words, in real-life contexts, people tend to respond more uniformly to others' negative experiences than positive experiences at both behavioral and neural levels. These findings contribute to a deeper understanding of the dynamics of empathy by highlighting its multifaceted nature and underscoring the importance of considering both positive and negative emotional contexts in empathy research. Specifically, the observed differences among empathy subprocesses—and between responses to positive *versus* negative valence—highlight the need for future studies to examine the distinct psychological and neural mechanisms underlying each subprocess in different emotional contexts. For example, for the bystander effect, is the lack of action due to reduced affective empathy or diminished motivational empathy? For people with a history of domestic violence, does the indifference toward victims' suffering originate from impaired emotion recognition or from weakened affective empathy? Identifying the specific stage at which empathy breaks down may help elucidate the psychological and neural mechanisms underlying empathy deficits and guide the development of targeted interventions and treatments.

Nonetheless, our study has several limitations. First, the experimental design may not have effectively elicited motivational empathy, as this subprocess tends to occur at a late stage, and our paradigm did not include a context in which participants could actively provide help. Future studies should consider optimizing experimental design to effectively activate motivational empathy, thereby improving our understanding of its neural underpinnings. Second, the color, brightness, and other visual characteristics may not be perfectly controlled in our experiment, since all stimuli were selected from online sources to keep high ecological validity. These possible confounding factors may have influenced participants' behavioral and neural responses. Third, given the high intercorrelation among empathy subprocesses, it is challenging to isolate any single subprocess with precision. In this study, we adopted a pragmatic, though suboptimal, approach by asking participants to rate three questions following each stimulus. To better dissociate the neural activations associated with

each specific subprocess, future studies could ideally employ task designs that incorporate clearly defined and temporally distinct stages for each subprocess. Addressing these limitations and expanding the scope of inquiry will help further elucidate the complexities of empathy and its vital role in social interactions.

Acknowledgements This work was supported by the National Natural Science Foundation of China (32441103) and the Beijing Natural Science Foundation (JQ22018).

Conflict of interest All authors declare no conflict of interests.

References

- Decety J, Jackson PL. A social-neuroscience perspective on empathy. *Curr Dir Psychol Sci* 2006, 15: 54–58.
- Melis Yavuz H, Colasante T, Galarneau E, Malti T. Empathy, sympathy, and emotion regulation: A meta-analytic review. *Psychol Bull* 2024, 150: 27–44.
- Wu X, Lu XJ, Zhang HJ, Bi YZ, Gu RL, Kong YZ. Sex difference in trait empathy is encoded in the human anterior insula. *Cerebral Cortex* 2023, 33: 5055–5065.
- Morelli SA, Lieberman MD, Zaki J. The emerging study of positive empathy. *Social Personality Psych* 2015, 9: 57–68.
- Zaki J, Ochsner KN. The neuroscience of empathy: Progress, pitfalls and promise. *Nat Neurosci* 2012, 15: 675–680.
- Kogler L, Müller VI, Werminghausen E, Eickhoff SB, Derntl B. Do I feel or do I know? Neuroimaging meta-analyses on the multiple facets of empathy. *Cortex* 2020, 129: 341–355.
- Weisz E, Zaki J. Motivated empathy: A social neuroscience perspective. *Curr Opin Psychol* 2018, 24: 67–71.
- Mercer SW, Reynolds WJ. Empathy and quality of care. *Br J Gen Pract* 2002, 52: S9–12.
- Wu X, Yao SC, Lu XJ, Zhou YQ, Kong YZ, Hu L. Categories of training to improve empathy: A systematic review and meta-analysis. *Psychol Bull* 2024, 150: 1237–1260.
- Decety J, Jackson PL. The functional architecture of human empathy. *Behav Cogn Neurosci Rev* 2004, 3: 71–100.
- Perry D, Hender T, Shamay-Tsoory SG. Can we share the joy of others? Empathic neural responses to distress vs joy. *Soc Cogn Affect Neurosci* 2012, 7: 909–916.
- Morelli SA, Rameson LT, Lieberman MD. The neural components of empathy: Predicting daily prosocial behavior. *Soc Cogn Affect Neurosci* 2014, 9: 39–47.
- Pang C, Zhou N, Deng Y, Pu Y, Han S. Neural tracking of race-related information during face perception. *Neurosci Bull* 2025, <https://doi.org/10.1007/s12264-025-01419-y>
- Tao MX, Hu JP, Zhang ZQ, Chen YQ. The effects of implicit emotion on the use of theory of mind among college students in China. *Cogn Process* 2024, 25: 267–279.
- Andreychik MR, Migliaccio N. Empathizing with others' pain versus empathizing with others' joy: Examining the separability of positive and negative empathy and their relation to different types of social behaviors and social emotions. *Basic Appl Soc Psychol* 2015, 37: 274–291.
- Ramachandran VS, Jalal B. The evolutionary psychology of envy and jealousy. *Front Psychol* 2017, 8: 1619.
- Ganegoda DB, Bordia P. I can be happy for you, but not all the time: A contingency model of envy and positive empathy in the workplace. *J Appl Psychol* 2019, 104: 776–795.

18. Salles BM, Fadel JV, Mograbi DC. Moderate similarity leads to empathic concern, but high similarity can also induce personal distress towards others' pain. *Psych J* 2024, 13: 322–334.
19. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods* 2007, 39: 175–191.
20. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behav Res Methods* 2009, 41: 1149–1160.
21. Thompson SK, Engel SA, Olman CA. Larger neural responses produce BOLD signals that begin earlier in time. *Front Neurosci* 2014, 8: 159.
22. Ziaei M, Oestreich L, Reutens DC, Ebner NC. Age-related differences in negative cognitive empathy but similarities in positive affective empathy. *Brain Struct Funct* 2021, 226: 1823–1840.
23. Depow GJ, Francis Z, Inzlicht M. The experience of empathy in everyday life. *Psychol Sci* 2021, 32: 1198–1213.
24. Tustison NJ, Avants BB, Cook PA, Zheng Y, Egan A, Yushkevich PA, *et al.* N4ITK: Improved N₃ bias correction. *IEEE Trans Med Imaging* 2010, 29: 1310–1320.
25. Ullman JB. Structural equation modeling. Using Multivariate Statistics In: Using Multivariate Statistics. 1st ed. Boston: Pearson Education. 2001: 653–771.
26. Hu LT, Bentler PM. Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Struct Equ Model A Multidiscip J* 1999, 6: 1–55.
27. Makowski D, Ben-Shachar M, Patil I, Lüdtke D. Methods and algorithms for correlation analysis in R. *J Open Source Softw* 2020, 5: 2306–2309.
28. Makowski D, Wiernik BM, Patil I, Lüdtke D, Ben-Shachar MS. correlation: Methods for correlation analysis [R package]. 2022. <https://CRAN.R-project.org/package=correlation>.
29. Vallat R. Pingouin: Statistics in Python. *J Open Source Softw* 2018, 3: 1026.
30. Nummenmaa L, Lahnakoski JM, Glerean E. Sharing the social world *via* intersubject neural synchronisation. *Curr Opin Psychol* 2018, 24: 7–14.
31. Wu X, Wang X, Lu XJ, Kong YZ, Hu L. Enhanced neural synchrony associated with long-term ballroom dance training. *Neuroimage* 2023, 278: 120301.
32. Hasson U, Nir Y, Levy I, Fuhrmann G, Malach R. Intersubject synchronization of cortical activity during natural vision. *Science* 2004, 303: 1634–1640.
33. Kauppi JP, Jääskeläinen IP, Sams M, Tohka J. Inter-subject correlation of brain hemodynamic responses during watching a movie: Localization in space and frequency. *Front Neuroinform* 2010, 4: 5.
34. Nastase SA, Gazzola V, Hasson U, Keysers C. Measuring shared responses across subjects using intersubject correlation. *Soc Cogn Affect Neurosci* 2019, 14: 667–685.
35. Chen G, Shin YW, Taylor PA, Glen DR, Reynolds RC, Israel RB, *et al.* Untangling the relatedness among correlations, part I: Nonparametric approaches to inter-subject correlation analysis at the group level. *Neuroimage* 2016, 142: 248–259.
36. Schacht A, Sommer W. Emotions in word and face processing: Early and late cortical responses. *Brain Cogn* 2009, 69: 538–550.
37. Cisler JM, Bush K, Scott Steele J. A comparison of statistical methods for detecting context-modulated functional connectivity in fMRI. *Neuroimage* 2014, 84: 1042–1052.
38. Brett M, Anton JL, Valabrègue R, Poline JB. Region of interest analysis using an SPM toolbox. The 8th International Conference on Functional Mapping of the Human Brain 2002, 16: 497.
39. Jahn A, Nee D. Beta Series Analysis in SPM. 2014. <https://www.andysbrainblog.com/andysbrainblog/2014/06/beta-series-analysis-in-spm.html>.
40. Davis MH. Empathy: A social psychological approach. Routledge, London, 2018.
41. Decety J, Ickes W. The social neuroscience of empathy. MIT Press, Cambridge, MA, 2009.
42. Troncoso A, Soto V, Gomila A, Martínez-Pernía D. Moving beyond the lab: Investigating empathy through the Empirical 5E approach. *Front Psychol* 2023, 14: 1119469.
43. Nelson DW, Klein CTF, Irvin JE. Motivational antecedents of empathy: Inhibiting effects of fatigue. *Basic Appl Soc Psychol* 2003, 25: 37–50.
44. Batson CD, Duncan BD, Ackerman P, Buckley T, Birch K. Is empathic emotion a source of altruistic motivation? *J Pers Soc Psychol* 1981, 40: 290–302.
45. Decety J, Barta IB, Uzefovsky F, Knafo-Noam A. Empathy as a driver of prosocial behaviour: Highly conserved neurobehavioural mechanisms across species. *Philos Trans R Soc Lond B Biol Sci* 2016, 371: 20150077.
46. Gamble RS, Henry JD, Decety J, Vanman EJ. The role of external factors in affect-sharing and their neural bases. *Neurosci Biobehav Rev* 2024, 157: 105540.
47. Motomura Y, Takeshita A, Egashira Y, Nishimura T, Kim YK, Watanuki S. Interaction between valence of empathy and familiarity: Is it difficult to empathize with the positive events of a stranger? *J Physiol Anthropol* 2015, 34: 13.
48. Schurz M, Radua J, Aichhorn M, Richlan F, Perner J. Fractionating theory of mind: A meta-analysis of functional brain imaging studies. *Neurosci Biobehav Rev* 2014, 42: 9–34.
49. Saxe R, Kanwisher N. People thinking about thinking people. The role of the temporo-parietal junction in “theory of mind”. *Neuroimage* 2003, 19: 1835–1842.
50. Seminowicz DA, Moayed M. The dorsolateral prefrontal cortex in acute and chronic pain. *J Pain* 2017, 18: 1027–1035.
51. Chen M, Wu X, Zhang L, Zhang F, Li L, Zhang Y, *et al.* Neural mechanisms underlying placebo and nocebo effects in tonic muscle pain. *Neuroimage* 2024, 300: 120877.
52. Zhang M, Li C, Xue Q, Lu CB, Zhao H, Meng FC, *et al.* Activation of cannabinoid receptor 1 in GABAergic neurons in the rostral anterior insular cortex contributes to the analgesia following common peroneal nerve ligation. *Neurosci Bull* 2023, 39: 1348–1362.
53. Riess H. The science of empathy. *J Patient Exp* 2017, 4: 74–77.
54. Prochazkova E, Kret ME. Connecting minds and sharing emotions through mimicry: A neurocognitive model of emotional contagion. *Neurosci Biobehav Rev* 2017, 80: 99–114.
55. Wu X, Lu X, Zhang H, Wang X, Kong Y, Hu L. The association between ballroom dance training and empathic concern: Behavioral and brain evidence. *Hum Brain Mapp* 2023, 44: 315–326.
56. Heilbronner SR, Hayden BY. Dorsal anterior cingulate cortex: A bottom-up view. *Annu Rev Neurosci* 2016, 39: 149–170.
57. Avenanti A, Buetti D, Galati G, Aglioti SM. Transcranial magnetic stimulation highlights the sensorimotor side of empathy for pain. *Nat Neurosci* 2005, 8: 955–960.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.