

Original Article

Different priming effects of empathy on neural processing associated with firsthand pain and nonpain perceptionQiaoyue Ren,^{1,2,3} Ye Yang,⁴ Ye Wo,^{1,2} Xuejing Lu,^{1,2} and Li Hu^{1,2}¹CAS Key Laboratory of Mental Health, Institute of Psychology, Beijing, China. ²Department of Psychology, University of Chinese Academy of Sciences, Beijing, China. ³General and Experimental Psychology Unit, Department of Psychology, LMU Munich, Munich, Germany. ⁴Centre for Mental Health Research in School of Management, Zunyi Medical University, Zunyi, China

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The shared-representation model of empathy is still debated. One of the major questions is whether empathy-eliciting stimuli depicting others' pain selectively activate the representations of self-pain. To address this issue, we assessed the priming effects of empathy-eliciting pictures on firsthand pain and nonpain perception, as well as its associated neural processing. In Experiment 1, when compared with nonpainful pictures depicting individuals' body parts with no injury, participants primed by painful pictures showing individuals' body parts with injury reported higher ratings for perceived intensity, unpleasantness, and salience of nociceptive and auditory stimuli, but they only exhibited increased N2 amplitude in response to nociceptive stimuli. In Experiment 2, the results from another group of participants replicated the observations of Experiment 1 and validated the findings in the non-nociceptive somatosensory modality. Importantly, participants' concern ratings for priming pictures predicted their unpleasantness ratings for subsequent nociceptive stimuli, while participants' attention ratings predicted their unpleasantness ratings for subsequent auditory and tactile stimuli. This finding implies that empathy for pain might influence pain and nonpain perception via different psychological mechanisms. In summary, our findings highlight the existence of pain-selective representations in empathy for pain and contribute to a better understanding of the shared-representation model of empathy.

Keywords: empathy for pain; firsthand pain; nonpain perception; shared representation; electroencephalography

Introduction

Empathy is fundamental to human social ties.¹ It enables us to experience others' states in an isomorphic way, thereby sharing emotions, needs, and goals.^{2,3} Empathy for pain is the primary focus of most studies on empathy, because of its survival significance and its manipulability in the laboratory.⁴⁻⁶

Converging behavioral evidence has shown that empathy for others' pain could influence the firsthand experience of pain.⁷⁻¹⁰ For example, compared with the control group (e.g., watching videos of others telling nonpainful experiences or observing others' body parts in nonpainful situa-

tions), participants who saw others in pain reported higher pain intensity and unpleasantness ratings when receiving nociceptive heat stimuli⁷ or electric stimuli,⁹ and their pain ratings were positively correlated with their self-reported empathy scores.⁷ Relatedly, accumulating neuroimaging evidence has shown that viewing others' suffering activates the brain regions known to respond to firsthand pain.^{11,12} These brain regions included not only the anterior mid-cingulate cortex (aMCC) and bilateral anterior insular cortex (AI), which are associated with the affective-motivational component of firsthand pain,⁴ but also somatosensory cortices that are

related to the sensory-discriminative component of firsthand pain.¹³

These behavioral and neuroimaging connections between empathy for pain and firsthand pain have been interpreted as support for the influential shared-representation model of empathy.^{8,9,11} This model proposes that observing another individual in a given situation (e.g., painful situation) automatically leads the observer to match the neural states of the one being observed, and thereby to understand the psychophysiological states of the observee.^{14,15} In other words, individuals empathize with others by activating corresponding neural representations of the given motor, perceptual, or emotional states of others.

However, the shared-representation model of empathy has recently been questioned, given that shared functional activations do not necessarily imply shared neural representations.^{16–18} For instance, the overlapping activations in the aMCC and bilateral AI between empathy for pain and firsthand pain may reflect the basic neural processes related to arousal, salience, and attention,^{19–21} which are commonly associated with aversive and salient affective experiences.²² From this perspective, the shared activations observed in empathy for pain and firsthand pain may be consequences of the general processes in response to salient events rather than the processes exclusive to pain.^{23–25}

Here, we employed a priming paradigm to test whether empathy-eliciting stimuli selectively boost the processing of firsthand pain, while recording electroencephalograms (EEGs). The priming paradigm has been widely used in previous studies investigating the influence of empathy for pain on firsthand pain perception.^{7–10,26,27} Following the logic of priming, viewing empathy-eliciting materials is supposed to facilitate participants' responses to the subsequent nociceptive stimuli, if empathy for pain and firsthand pain perception share neural representations.^{8,9} Moreover, we compared the priming effects of empathy for pain on firsthand pain and nonpainful sensations (i.e., auditory and tactile sensations), which could help clarify whether there are pain-selective representations in empathy for pain. The existence of pain-selective representations in empathy for pain would be supported if the priming effect of empathy for pain on firsthand pain could not be applied to nonpainful sensory modalities. On the contrary, a lack of common

pain-selective representations between empathy for pain and firsthand pain could be inferred if empathy for pain affects firsthand pain and non-pain perception in a similar way. To ensure the reliability and generalizability of our experimental results, two experiments with slight differences in experimental settings were conducted on two independent groups of participants using different EEG acquisition equipment.

Materials and methods

Experiment 1

Participants. Forty-three right-handed healthy participants were recruited in this experiment. Five participants were excluded from data analysis due to either incomplete data collection or noise contamination in the EEG data, leaving a final sample of 38 participants (17 females; age range: 18–24 years; $M \pm SE$ age = 21.18 ± 0.34 years). The required sample size was determined using G*Power software (version 3.1)²⁸ with a significance level (α) at 0.05 by setting statistical power ($1-\beta$) at 0.80. Based on the effect size with respect to the main effect of priming on firsthand pain perception reported in a previous study⁸ ($\eta_p^2 = 0.248$), the minimum required sample size was 27. None of the participants reported any neurological diseases, psychiatric disorders, pain-related diseases, hearing loss, or current use of any medications. All participants gave their written informed consent and received monetary compensation for their participation. This experiment was approved by the local ethics committee.

Stimuli.

Priming pictures. Forty pictures from a published event-related potential (ERP) study on empathy⁸ were adopted to evoke participants' empathic responses to others' pain. Each picture shows a body part (i.e., hand, forearm, or foot) under a daily scenario in a painful (e.g., using a knife to cut vegetables improperly and the hand became injured) or a nonpainful situation (e.g., using a knife to cut vegetables properly, with no hand injuries). Painful and nonpainful picture pairs were well matched in terms of luminance, contrast, and color. All pictures were 7.08×5.32 inches (width $\times$ height), with a resolution of 100 pixels per inch.

Nociceptive stimuli. An infrared neodymium yttrium aluminum perovskite (Nd:YAP) laser (Electronical Engineering, Italy) with a wavelength of

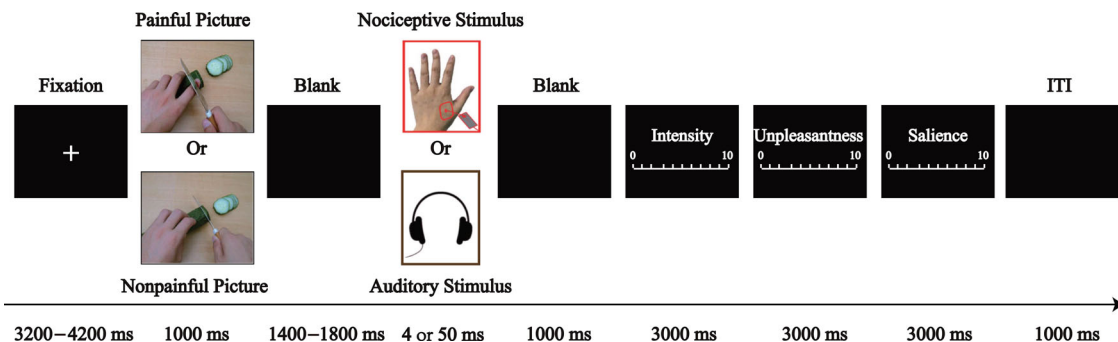


Figure 1. Experimental design of Experiment 1. Each trial started with a fixation cross (3200–4200 ms), followed by a painful or nonpainful picture (1000 ms). Then, a blank screen was presented for 2400–2800 ms, in which a brief nociceptive (4 ms) or auditory stimulus (50 ms) was administered 1000 ms before the disappearance of the blank screen. Subsequently, participants were instructed to orally rate the perceived intensity (3000 ms), unpleasantness (3000 ms), and salience (3000 ms) evoked by the nociceptive or auditory stimulus on 11-point numerical rating scales. The inter-trial interval (ITI) was 1000 milliseconds.

1.34 μm was used to generate nociceptive stimuli.²⁹ Each laser pulse with a duration of 4 ms was transmitted via an optic fiber and focused by a lens into a laser beam with a diameter of ~ 7 millimeters. The nociceptive laser stimuli were delivered to a predefined stimulation area ($3 \times 5 \text{ cm}^2$) on the dorsum of participants' left hands. To avoid nociceptor fatigue or sensitization, the target area of the laser beam was moved by about 1 cm in a random direction from trial to trial within the predefined stimulation area.³⁰ The energy of laser stimuli applied in the experiment was individually determined using an ascending method of limits. The energy was increased in steps of 0.25 from 1 J, until a rating of 3 or 6 out of 10 was obtained on an 11-point numerical rating scale (NRS; 0–10: *no pain—the strongest pain imaginable*), which represented a low-intensity and a high-intensity pain, respectively.

Auditory stimuli. The auditory stimuli were 800-Hz pure tones with a duration of 50 milliseconds. The intensity of auditory stimuli (i.e., loudness) applied in the experiment was also individually determined using the ascending method of limits. The loudness was increased in steps of 6 from 20 dB, until a rating of 3 or 6 out of 10 was obtained on an 11-point NRS (0–10: *no sound—the strongest sound imaginable*), which represented a low-intensity and a high-intensity sound, respectively. All auditory stimuli were presented binaurally via headphones.

Experimental procedures. This experiment adopted a 2 (priming: painful and nonpainful

pictures) $\times$ 2 (modality: nociceptive and auditory stimuli) $\times$ 2 (intensity: low and high intensities) within-subject design, and each condition consisted of 10 trials. As illustrated in Figure 1, each trial began with a white fixation cross presented for 3200–4200 ms randomly, followed by a painful or nonpainful picture presented for 1000 milliseconds. Each picture appeared twice in this experiment but not in two consecutive trials. The picture subtended a visual angle of $12.68^\circ \times 9.59^\circ$ at a viewing distance of about 80 centimeters. Then, there was a blank screen presented for 2400–2800 ms, in which a brief nociceptive or auditory stimulus was administered 1000 ms before the disappearance of the blank screen. Subsequently, participants were required to orally rate the perceived intensity (Question: *How strong was the perception induced by the sensory stimulus?* 0–10: *no sensation—the strongest sensation imaginable*), unpleasantness (Question: *How unpleasant did you feel when receiving the sensory stimulus?* 0–10: *not unpleasant—extremely unpleasant*), and salience (Question: *How salient was the sensory stimulus for you?* 0–10: *not salient—extremely salient*) of the nociceptive or auditory stimulus. Intensity and unpleasantness ratings focused on the sensory-discriminative and affective-motivational dimensions of perception, respectively,³¹ while salience rating reflected the extent to which the sensory stimulus transiently captures one's attention.^{32,33} The time window for each rating was 3000 milliseconds. The inter-trial interval (ITI) was 1000 milliseconds.

During the priming task, participants were required to pay attention to the fixation cross and the following priming picture, and to try to imagine witnessing another person in the situation presented in the picture. By this means, participants were explicitly encouraged to view the priming picture actively rather than anticipating the sensory stimulus before it was delivered. To be familiar with the experimental procedures, participants completed four practice trials before the formal experiment. The experiment consisted of two blocks, each of which included 40 trials pseudo-randomly presented. The sequence of the two blocks was counterbalanced across participants, and the break between the two blocks was 5 minutes.

EEG recording. EEG data were continuously recorded from 0.01 to 100 Hz with a 1000-Hz sampling rate via the Brain Products system (Brain Products GmbH). The 64 Ag-AgCl scalp electrodes were placed according to the international 10–20 system. The nose was used as the online reference. All impedances were kept below 10 k Ω . To monitor ocular movements and eye blinks, electrooculographic signals were simultaneously recorded using two surface electrodes, one placed over the lower eyelid and the other placed about 1 cm lateral to the outer corner of the orbit.

EEG data preprocessing. EEG data were preprocessed using EEGLAB,³⁴ an open-source toolbox running in the MATLAB environment (R2016a; Mathworks Inc., Natick, MA). To validate that the pictures used in the present experiment were capable of evoking empathic responses, we first analyzed the EEG data during the empathy phase. To examine the priming effects of empathy-eliciting stimuli, we then analyzed the EEG data during the firsthand perception phase. Following the suggested preprocessing pipeline,^{35,36} EEG data of the two phases were first band-pass filtered at 0.1–30 Hz and 1–30 Hz, respectively. Second, EEG epochs were extracted using a window analysis time of 1500 ms (for the empathy phase: 500 ms before and 1000 ms after the onset of the priming picture; for the firsthand perception phase: 500 ms before and 1000 ms after the onset of the nociceptive or auditory stimulus). Third, EEG epochs were visually inspected, trials contaminated by artifacts due to gross movements were removed, and bad electrodes were interpolated using a spherical spline

interpolation. Notably, no trials were removed due to gross artifacts, and one or two bad electrodes were interpolated for 13 participants. Fourth, the EEG epochs were baseline corrected using the prestimulus interval. Last, epochs contaminated by eye blinks and movements were corrected using an independent component analysis algorithm.³⁴ Specifically, 2.05 ± 0.23 and 1.63 ± 0.14 noisy components having a large frontal scalp distribution were removed for each participant from the empathy phase and the firsthand perception phase, respectively. The remaining independent components were used to reconstruct the denoised EEG data. After preprocessing, EEG data were rereferenced to the common average.

ERP analysis. Epochs belonging to the same condition were averaged, thus yielding two average waveforms for the empathy phase and eight average waveforms for the firsthand perception phase for each participant. Single-participant average waveforms were subsequently averaged across participants to obtain group-level waveforms.

Consistent with previous studies,^{37–39} four salient ERP components (i.e., N1, N2, P3, and LPP components) were identified for the empathy phase (Fig. S1, online only). Specifically, the N1 and N2 components were, respectively, defined as the most negative deflections within 100–200 ms and 200–300 ms after the stimulus onset, with a maximal distribution over the frontal-central region. The P3 component was defined as the most positive component within 300–500 ms over the central-parietal region. The LPP component was defined as the long-lasting positive component within 400–800 ms over the central-parietal region. Similar to previous studies,^{38,40} the mean amplitudes of N1 (measured at Fz, F1, F2, FCz, FC1, and FC2; within 120–150 ms), N2 (measured at Fz, F1, F2, FCz, FC1, and FC2; within 250–290 ms), P3 (measured at Pz, P1, P2, POz, PO3, and PO4; within 300–500 ms), and LPP (measured at Pz, P1, P2, POz, PO3, and PO4; within 500–700 ms) components were extracted from each participant. In addition, group-level scalp topographies at the latencies of these ERP components were computed by spline interpolation.

In line with previous studies,^{41,42} laser-evoked potentials (LEPs; i.e., N1, N2, and P2 components) and auditory-evoked potentials (AEPs; i.e., N2 and P2 components) were identified for the firsthand

perception phase (Fig. 2 and Fig. S2, online only). Specifically, the N1 component in LEPs was defined as the most negative deflection within 120–200 ms, which can be optimally detected at the central electrode contralateral to the stimulated side referenced to Fz (i.e., C4-Fz in our case).^{43,44} The N2 and P2 components in LEPs and AEPs were defined as the most negative and positive deflections between 100 and 500 ms after the stimulus onset at the vertex (i.e., Cz-avg), respectively.^{41,45,46} Please note that the same nomenclature (i.e., N2 and P2 components) was used for different sensory modalities to facilitate cross-modality comparison of these ERP responses.⁴⁶ Similar to previous studies,^{41,42} peak latencies and amplitudes of N1 (measured at C4-Fz; within 120–190 ms), N2 (measured at Cz; within 190–240 ms), and P2 (measured at Cz; within 325–375 ms) components in LEPs, as well as N2 (measured at Cz; within 100–140 ms) and P2 (measured at Cz; within 190–230 ms) components in AEPs were extracted from single-participant average waveforms for each condition. Group-level scalp topographies at the latencies of these ERP components were computed by spline interpolation.

Statistical analyses. Statistical analyses were performed using SPSS 22.0 (IBM Corp., New York, NY). Descriptive statistics ($M \pm SE$) were provided for subjective ratings (i.e., intensity, unpleasantness, and salience) and ERP responses (for the empathy phase: mean amplitudes of N1, N2, P3, and LPP components; for the firsthand perception phase: peak latencies and amplitudes of N1, N2, and P2 components).

To assess and validate the empathic responses evoked by the priming pictures, paired-sample *t*-tests were conducted to analyze the ERP responses in the empathy phase between painful and non-painful picture conditions. Cohen's *d* was calculated to reflect the effect size of the *t*-tests. To compare the priming effects of empathy for pain on firsthand pain and auditory perception, three-way repeated measures analysis of variances (ANOVAs) with three within-subject factors (priming, modality, and intensity) were conducted on the subjective ratings and the ERP responses (i.e., latencies and amplitudes of N2 and P2 components) in the firsthand perception phase. Particularly, since the N1 component was evoked only by nociceptive stimuli in this experiment, two-way repeated measures ANOVAs

with two within-subject factors (i.e., priming and intensity) were conducted on the latencies and amplitudes of N1 component in LEPs. Greenhouse–Geisser correction was applied in case of violations of the sphericity assumption.⁴⁷ For the sake of brevity, the uncorrected degrees of freedom were reported. Partial eta-squared (η_p^2) was calculated to reflect the effect size of the *F*-tests. Post-hoc paired-sample *t*-tests were conducted and Bonferroni correction was applied for multiple comparisons when there was a significant interaction between factors.

Experiment 2

Participants. Another group of 32 right-handed healthy participants was recruited for this experiment. Four participants were excluded from data analysis because of either incomplete data collection or noise contamination in the EEG data, leaving a final sample of 28 participants (17 females; age range: 18–24 years; $M \pm SE$ age = 21.86 ± 0.40 years). Inclusion and exclusion criteria and experimental requirements were identical to Experiment 1.

Stimuli.

Priming pictures. The priming pictures were also from the image database used in Experiment 1. To ensure the body part shown in the priming picture was identical to the body part where participants received nociceptive and tactile stimuli, this experiment only adopted priming pictures showing the left hand or left forearm in painful (30 pictures) or nonpainful (30 pictures) situations.

Nociceptive stimuli. The apparatus and procedures regarding the nociceptive laser stimuli were identical to Experiment 1. Considering that low-intensity laser stimuli failed to evoke Aδ-LEPs²⁹ and the priming effects observed in Experiment 1 were mainly obtained from trials with high stimulus intensity, this experiment only adopted high-intensity laser stimuli with a rating of 7 out of 10.

Auditory stimuli. The apparatus and procedures regarding the auditory stimuli were identical to Experiment 1. Similar to nociceptive stimuli, this experiment only adopted high-intensity auditory stimuli with a rating of 7 out of 10. More importantly, to ensure the consistency of the laterality of sensory stimuli in different modalities, the auditory stimuli were presented only to the participant's left ear through an in-ear headphone, while the right ear was blocked by an earplug.

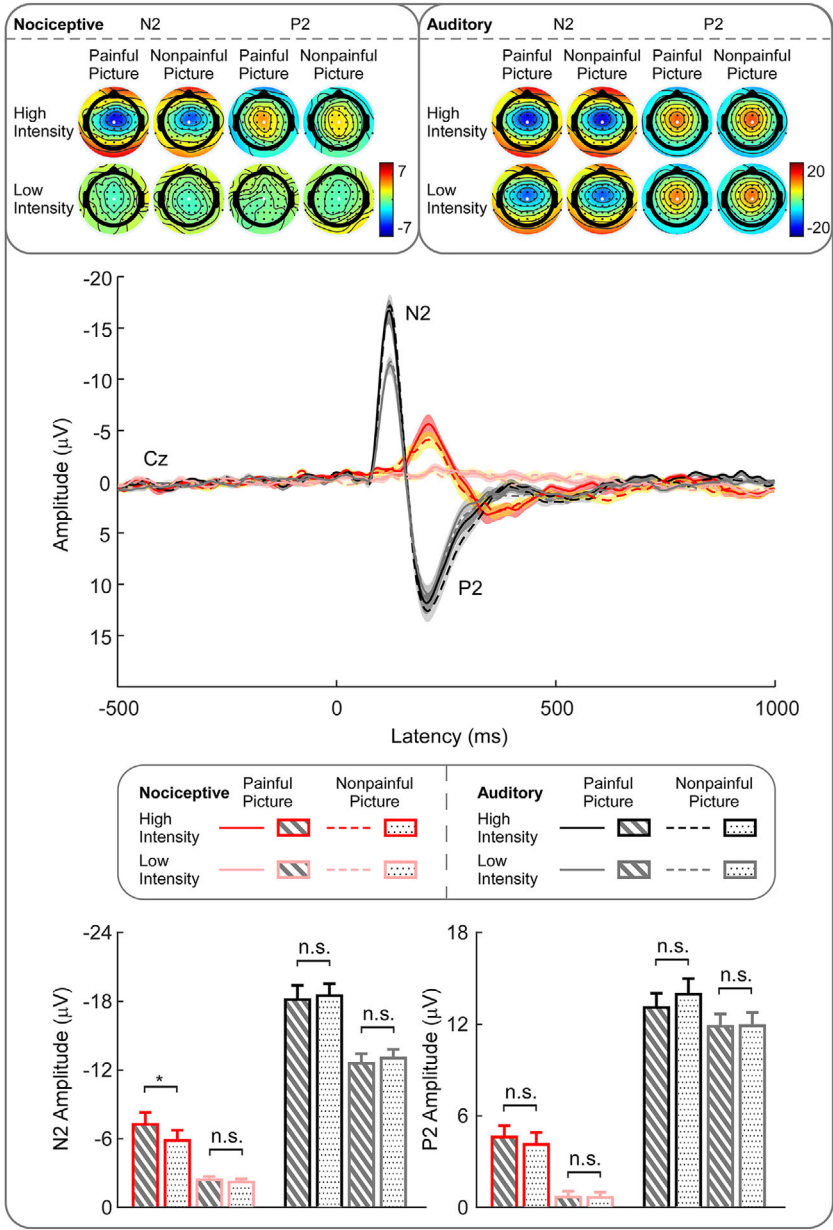


Figure 2. ERP responses evoked by nociceptive and auditory stimuli in Experiment 1. ERP waveforms and scalp topographies elicited by nociceptive stimuli with high intensity (red lines) or low intensity (pink lines) and by auditory stimuli with high intensity (black lines) or low intensity (gray lines) that were delivered after participants watched painful (solid lines) and nonpainful (dashed lines) pictures that are displayed. The Cz electrode that displayed the maximal responses is marked using an enlarged white dot. Low-intensity nociceptive stimuli did not evoke salient N2 and P2 components (i.e., Aδ-LEPs). Compared with viewing nonpainful pictures, the N2 amplitude evoked by high-intensity nociceptive stimuli was significantly larger after participants viewed painful pictures. Additionally, neither N2 nor P2 amplitudes evoked by high-intensity or low-intensity auditory stimuli were significantly different between the two priming conditions. Data are expressed as $M \pm SE$. n.s. indicates $P > 0.05$; $*P < 0.05$.

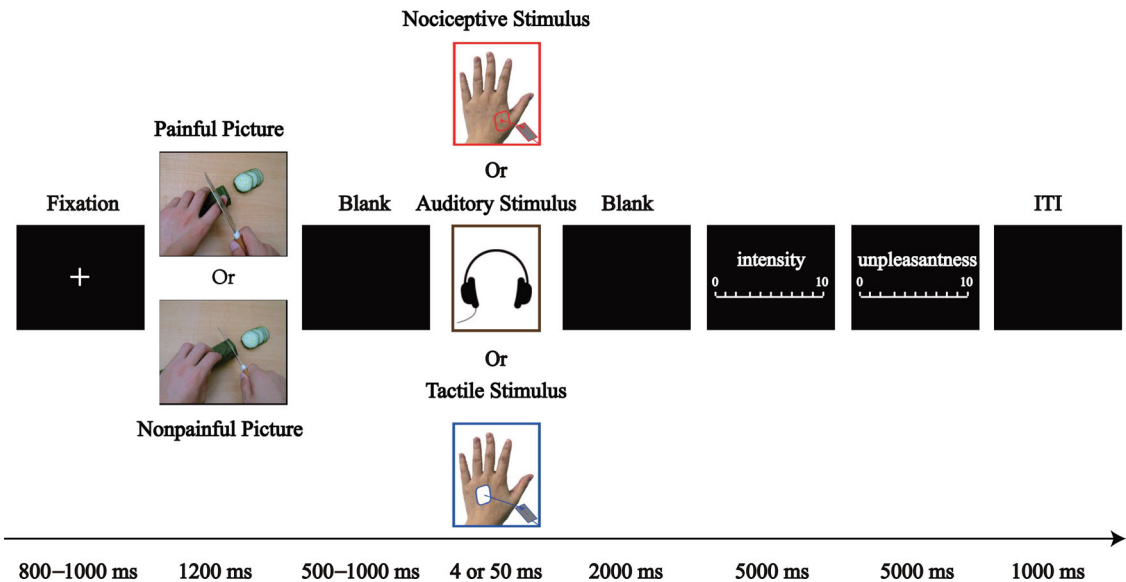


Figure 3. Experimental design of Experiment 2. Each trial started with a fixation cross (800–1000 ms), followed by a painful or nonpainful picture (1200 ms). Then, a blank screen was presented for 2500–3000 ms, in which a brief nociceptive (4 ms), auditory (50 ms), or tactile (50 ms) stimulus was administered 2000 ms before the disappearance of the blank screen. Subsequently, participants were instructed to rate the perceived intensity (5000 ms) and unpleasantness (5000 ms) evoked by the nociceptive, auditory, or tactile stimulus with a button press on 11-point numerical rating scales. The inter-trial interval (ITI) was 1000 milliseconds.

Tactile stimuli. An electrical stimulator (Beijing Sanxia Technology Corp., China) was used to generate constant current with square-wave electrical pulses. Each tactile stimulus consisted of five successively distributed electrical pulses (250 μ s for each pulse) within 50 milliseconds. The electrical pulses were delivered to the dorsum of the participants' left hands through a pair of round surface electrodes (diameter: 1.2 cm). The distance between the two electrodes was 2 centimeters. The stimulation area was adjacent to but not overlapping with the laser stimulation area. Please note that the electrical pulses used in this experiment were non-nociceptive somatosensory stimuli, which induced tactile (e.g., numbness) but not painful sensation. Similar to nociceptive and auditory stimuli, the energy of electrical pulses applied in this experiment was individually determined using the ascending method of limits. The energy was increased in steps of 300 from 2500 μ A, until a rating of 7 out of 10 was obtained on an 11-point NRS (0–10: *no sensation—the strongest nonpainful somatic sensation/numbness imaginable*), which represented a high-intensity tactile perception.

Experimental procedures. This experiment included two tasks. The first task was an empathy-priming task similar to that of Experiment 1. The task adopted a 2 (priming: painful and nonpainful pictures) $\times$ 3 (modality: nociceptive, auditory, and tactile stimuli) within-subject experimental design, and each condition consisted of 30 trials. As illustrated in Figure 3, each trial began with a white fixation cross presented for 800–1000 ms randomly, followed by a painful or nonpainful picture presented for 1200 milliseconds. Each picture was only presented once in each block. Then, there was a blank screen presented for 2500–3000 ms, in which a brief nociceptive, auditory, or tactile stimulus was administered 2000 ms before the disappearance of the blank screen. Subsequently, participants were required to successively rate the perceived intensity and unpleasantness with a button press on an 11-point NRS. The time window for each rating was 5000 milliseconds. The ITI was 1000 milliseconds. To be familiar with the experimental procedures, participants completed six practice trials before the formal experiment. The experiment consisted of three blocks, each of which included 60 trials with identical sensory stimuli (nociceptive, auditory, or

tactile stimuli). Trials in each block were pseudo-randomly presented, and the sequence of blocks was counterbalanced across participants. The break between two consecutive blocks was 5 minutes. Compared with Experiment 1, several changes were made to obtain reliable and robust outcomes in this empathy-priming task, which could help reduce the potential influence of irrelevant factors and better capture the priming effects of empathy for pain on firsthand perception. Specifically, (1) more trials were included in each condition (30 versus 10 trials) for a higher signal-to-noise ratio; (2) each priming picture was presented for a longer time (1200 versus 1000 ms) to ensure that participants had a longer time to observe others' pain, thereby inducing stronger empathic responses; (3) the interval between the priming picture and the sensory stimulus was shortened (500–1000 versus 1400–1800 ms), in case their empathic responses evoked by pictures had attenuated greatly before the presentation of the subsequent sensory stimuli; (4) participants were required to indicate their subjective feelings with a button press rather than an oral report in order to avoid an observer effect; and (5) each block involved sensory stimuli of the same modality rather than sensory stimuli of different modalities, since some irrelevant factors, such as the uneven allocation of attention resources caused by the frequent shifts between different sensory modalities, might interact with the priming effect of empathy for pain.

To investigate which dimension of the empathy-eliciting pictures contributes the most to the priming effect, the second task was a behavioral rating task, in which participants were asked to rate the pictures they have seen in the empathy-priming task. This task consisted of 60 trials. Each trial began with a white fixation cross presented for 800–1000 ms, followed by one of the pictures shown previously. Each picture was presented once and for 1200 ms in this task. Participants were required to successively rate the pictures on the corresponding NRS (0–10: *lowest–highest*) in terms of attention (Question: *To what extent did the situation in the picture attract your attention?*), intensity (Question: *How strong was his/her pain?*), unpleasantness (Question: *How unpleasant did you feel viewing the situation in the picture?*), concern (Question: *To what extent did you feel concern about him/her?*), threat (Question: *To what extent did you feel threatened viewing the situation in the picture?*), and arousal (Question: *How*

great was your inner arousal viewing the situation in the picture?). The time window for each rating was 4000 milliseconds. The ITI was 1000 milliseconds. The break between the two tasks was self-paced.

EEG recording. EEG data were continuously recorded with a 1000-Hz sampling rate via a 32-electrode ANT-neuro system (Enschede, The Netherlands). The 32 Ag-AgCl scalp electrodes were placed according to the international 10–20 system. The AFz electrode served as the ground, and the FPz electrode served as the online reference. All impedances were kept below 10 k Ω .

EEG data preprocessing. In this experiment, we mainly focused on the firsthand perception phase (Fig. 4; Fig. S3, online only), since Experiment 1 has demonstrated well that the priming pictures we used could elicit empathic responses to others' pain. The preprocessing steps were similar to those in Experiment 1. Notably, no trials were removed due to the contamination of gross artifacts. For three participants, one or two bad electrodes were interpolated using the spherical spline interpolation. To correct epochs contaminated by eye blinks and movements, 2.64 ± 0.23 noisy components having a large frontal scalp distribution were removed for each participant.

ERP analysis. Peak latencies and amplitudes of N1 (measured at C4-Fz; within 120–190 ms), N2 (measured at Cz; within 180–240 ms), and P2 (measured at Cz; within 300–360 ms) components in LEPs, N2 (measured at Cz; within 80–140 ms) and P2 (measured at Cz; within 160–220 ms) components in AEPs, as well as N2 (measured at Cz; within 80–140 ms) and P2 (measured at Cz; within 200–260 ms) components in tactile-evoked potentials (TEPs), were extracted from single participant average waveforms for each condition.

Statistical analyses. Descriptive statistics ($M \pm SE$) were provided for subjective ratings (i.e., intensity and unpleasantness) and ERP responses (peak latencies and amplitudes of N1, N2, and P2 components) to sensory stimuli in the empathy-priming task, as well as subjective ratings (i.e., attention, intensity, unpleasantness, concern, threat, and arousal) to priming pictures in the behavioral rating task.

To compare the priming effects of empathy-eliciting pictures on firsthand pain and auditory

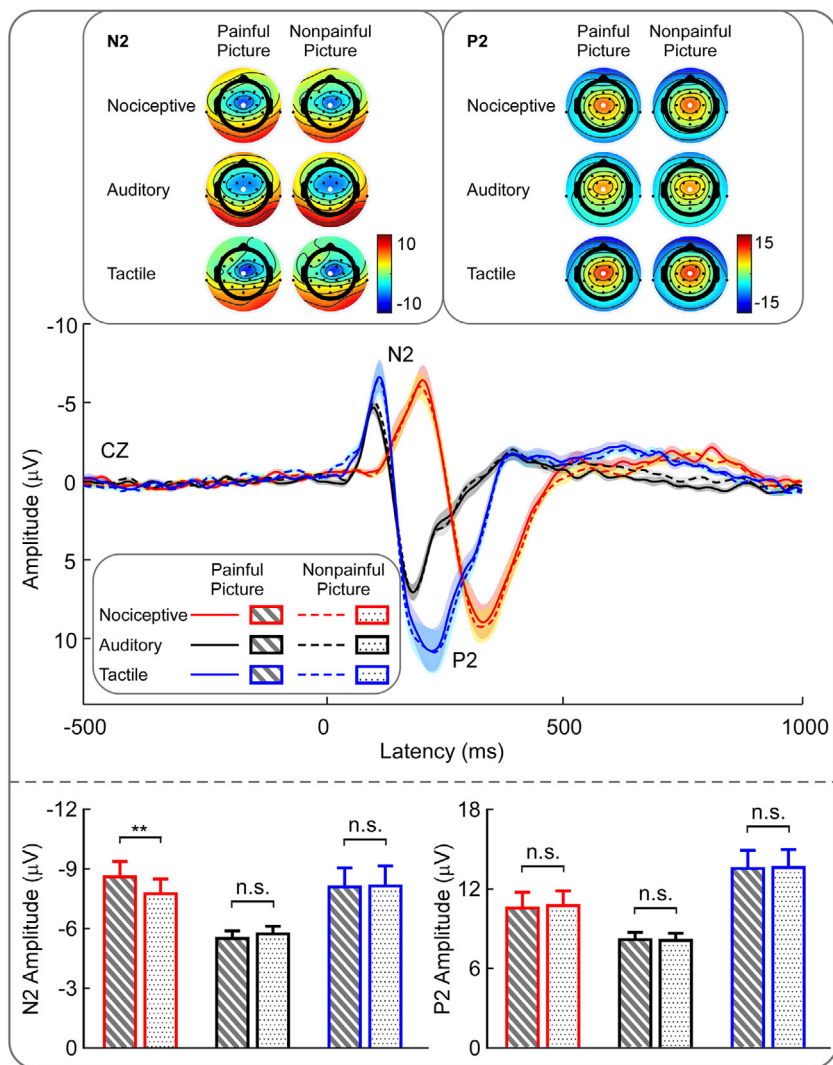


Figure 4. ERP responses evoked by nociceptive, auditory, and tactile stimuli in Experiment 2. ERP waveforms and scalp topographies elicited by nociceptive (red lines), auditory (black lines), and tactile (blue lines) stimuli that were delivered after participants watching painful (solid lines) and nonpainful (dashed lines) pictures are displayed. The Cz electrode that displayed the maximal responses is marked using an enlarged white dot. Compared with viewing nonpainful pictures, the N2 amplitude evoked by nociceptive stimuli was significantly larger after participants viewed painful pictures, whereas N2 amplitudes evoked by auditory and tactile stimuli as well as P2 amplitudes evoked by all sensory stimuli were not significantly different between the two priming conditions. Data are expressed as $M \pm SE$. n.s. indicates $P > 0.05$; $**P < 0.01$.

and tactile perception, two-way repeated measures ANOVAs with two within-subject factors (priming and modality) were conducted on the subjective ratings and the ERP responses (i.e., latencies and amplitudes of N2 and P2 components) of the firsthand perception phase in the empathy-priming task. Particularly, similar to Experiment 1, paired-sample *t*-tests were conducted to analyze

latencies and amplitudes of N1 component in LEPs.

To explore the psychological mechanisms underlying the priming effects of empathy-eliciting pictures on firsthand perception, linear stepwise regression analyses were conducted between the subjective ratings of priming pictures and the subjective ratings of firsthand perception. The

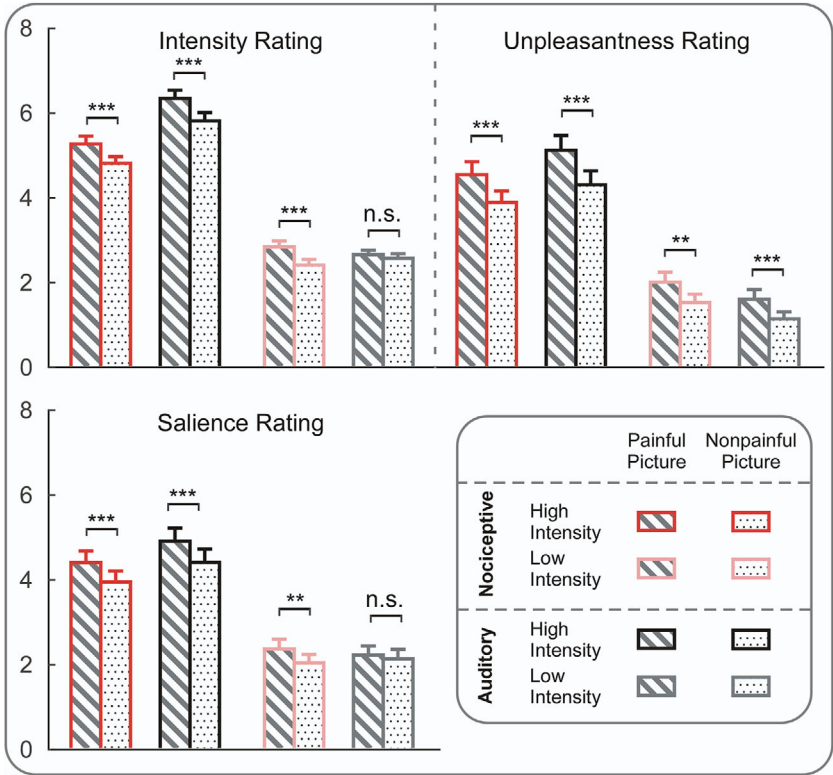


Figure 5. Subjective ratings for nociceptive and auditory stimuli in Experiment 1. Participants reported higher intensity, unpleasantness, and salience ratings for the high-intensity nociceptive stimuli, low-intensity nociceptive stimuli, and high-intensity auditory stimuli after viewing painful pictures, compared with viewing nonpainful pictures. Participants also reported higher unpleasantness ratings for low-intensity auditory stimuli after viewing painful pictures, compared with viewing nonpainful pictures, whereas the intensity and salience ratings for the low-intensity auditory stimuli were not significantly different between the two priming conditions. Data are expressed as $M \pm SE$. n.s. indicates $P > 0.05$; $**P < 0.01$; $***P < 0.001$.

regression model was established separately for each modality. In each regression analysis, we used the six subjective ratings for priming pictures (i.e., the difference between painful and nonpainful pictures in terms of attention, intensity, unpleasantness, concern, threat, and arousal ratings) as the independent variables, and one of the ratings for the firsthand perception (i.e., the difference of intensity or unpleasantness ratings for nociceptive, auditory, or tactile stimuli between painful and nonpainful picture conditions) as the dependent variable. In total, there were six regression models. Other statistical procedures were identical to Experiment 1.

Results

Experiment 1

Priming effects of empathy on subjective ratings. Subjective ratings of perceived intensity,

unpleasantness, and salience in eight conditions are shown in Figure 5 and summarized in Table S1 (online only).

For intensity ratings, three-way repeated measures ANOVA showed significant main effects of priming ($F(1,37) = 58.63, P < 0.001, \eta_p^2 = 0.613$), modality ($F(1,37) = 15.30, P < 0.001, \eta_p^2 = 0.292$), and intensity ($F(1,37) = 424.93, P < 0.001, \eta_p^2 = 0.920$). There were also significant interactions between priming and intensity ($F(1,37) = 12.89, P = 0.001, \eta_p^2 = 0.258$), and between modality and intensity ($F(1,37) = 25.52, P < 0.001, \eta_p^2 = 0.408$). Moreover, the three-way interaction was significant ($F(1,37) = 9.35, P = 0.004, \eta_p^2 = 0.202$). To interpret the three-way interaction, we performed three two-way repeated measures ANOVAs with two factors by fixing the other factor. Four significant two-way interactions were found: (1) for low-

intensity stimuli, there was a significant interaction between priming and modality, ($F(1,37) = 9.83$, $P = 0.003$, $\eta_p^2 = 0.210$); (2) for auditory stimuli, there was a significant interaction between priming and intensity ($F(1,37) = 35.70$, $P < 0.001$, $\eta_p^2 = 0.491$); (3) for both painful and nonpainful priming, the two interactions between modality and intensity were significant ($F(1,37) = 30.91$, $P < 0.001$, $\eta_p^2 = 0.455$ and $F(1,37) = 16.05$, $P < 0.001$, $\eta_p^2 = 0.303$, respectively). Among these significant two-way interactions, we were interested in the priming effect in two modalities. Therefore, we further broke down the interaction between modality and priming. The results showed that, for low-intensity stimuli, participants reported higher intensity ratings for nociceptive stimuli after viewing painful pictures, compared with viewing nonpainful pictures ($P < 0.001$), whereas such significant difference in intensity ratings was not observed for auditory stimuli ($P = 0.189$). In contrast, for high-intensity stimuli, participants reported higher intensity ratings for both nociceptive stimuli ($P < 0.001$) and auditory stimuli ($P < 0.001$) after viewing painful pictures, compared with viewing nonpainful pictures.

For unpleasantness ratings, three-way repeated measures ANOVA showed significant main effects of priming ($F(1,37) = 38.77$, $P < 0.001$, $\eta_p^2 = 0.512$) and intensity ($F(1,37) = 170.66$, $P < 0.001$, $\eta_p^2 = 0.822$). There were also significant interactions between priming and intensity ($F(1,37) = 7.33$, $P = 0.010$, $\eta_p^2 = 0.165$), and between modality and intensity ($F(1,37) = 9.66$, $P = 0.004$, $\eta_p^2 = 0.207$). Further analyses showed that participants reported higher unpleasantness ratings for both high-intensity stimuli (painful pictures: 4.83 ± 0.30 ; nonpainful pictures: 4.10 ± 0.26 ; $P < 0.001$) and low-intensity stimuli (painful pictures: 1.79 ± 0.22 ; nonpainful pictures: 1.31 ± 0.17 ; $P < 0.001$) after viewing painful pictures, compared with viewing nonpainful pictures.

For salience ratings, three-way repeated measures ANOVA showed significant main effects of priming ($F(1,37) = 28.94$, $P < 0.001$, $\eta_p^2 = 0.439$) and intensity ($F(1,37) = 119.52$, $P < 0.001$, $\eta_p^2 = 0.764$). There were also significant interactions between priming and intensity ($F(1,37) = 13.39$, $P = 0.001$, $\eta_p^2 = 0.266$), and between modality and intensity ($F(1,37) = 6.85$, $P = 0.013$, $\eta_p^2 = 0.156$). Further analyses showed that participants reported higher salience ratings for both high-intensity stimuli

(painful pictures: 4.66 ± 0.28 ; nonpainful pictures: 4.17 ± 0.26 ; $P < 0.001$) and low-intensity stimuli (painful pictures: 2.29 ± 0.22 ; nonpainful pictures: 2.07 ± 0.20 ; $P = 0.003$) after viewing painful pictures, compared with viewing nonpainful pictures.

ERP responses during the empathy phase.

Group-level ERP waveforms and scalp topographies of N1, N2, P3, and LPP components are shown in Figure S1 (online only). The N1 and N2 components were maximal at the frontal region, and the P3 and LPP components were maximal at the parietal region. Mean amplitudes of these components and the results of the paired-sample *t*-tests are summarized in Table S2 (online only). The LPP amplitude was significantly higher in the painful-picture condition than in the nonpainful-picture condition ($t(37) = 2.47$, $P = 0.018$, Cohen's $d = 0.406$). No significant differences in N1 ($P = 0.785$), N2 ($P = 0.830$), and P3 ($P = 0.199$) amplitudes between the two conditions were observed.

Priming effects of empathy on ERP responses during the firsthand perception phase.

Group-level ERP waveforms and scalp topographies of N1, N2, and P2 components for sensory stimuli are shown in Figure 2 and Figure S2 (online only). The N1 component in LEPs was maximal at central electrodes contralateral to the stimulated side, and the N2 and P2 components in LEPs and AEPs were maximal at the central region. Peak latencies and amplitudes of these components are summarized in Table S1 (online only).

For N1 latencies, two-way repeated measures ANOVA showed that none of the main effect of priming ($P = 0.677$), the main effect of intensity ($P = 0.969$), and their interaction ($P = 0.779$) were significant. For N2 latencies, three-way repeated measures ANOVA showed a significant main effect of modality ($F(1,37) = 2849.94$, $P < 0.001$, $\eta_p^2 = 0.987$). For P2 latencies, three-way repeated measures ANOVA showed a significant main effect of modality ($F(1,37) = 3685.66$, $P < 0.001$, $\eta_p^2 = 0.990$).

For N1 amplitudes, two-way repeated measures ANOVA showed a significant main effect of intensity ($F(1,37) = 20.67$, $P < 0.001$, $\eta_p^2 = 0.358$). For N2 amplitudes, three-way repeated measures ANOVA showed significant main effects of modality ($F(1,37) = 142.01$, $P < 0.001$, $\eta_p^2 = 0.793$) and intensity ($F(1,37) = 65.62$, $P < 0.001$, $\eta_p^2 =$

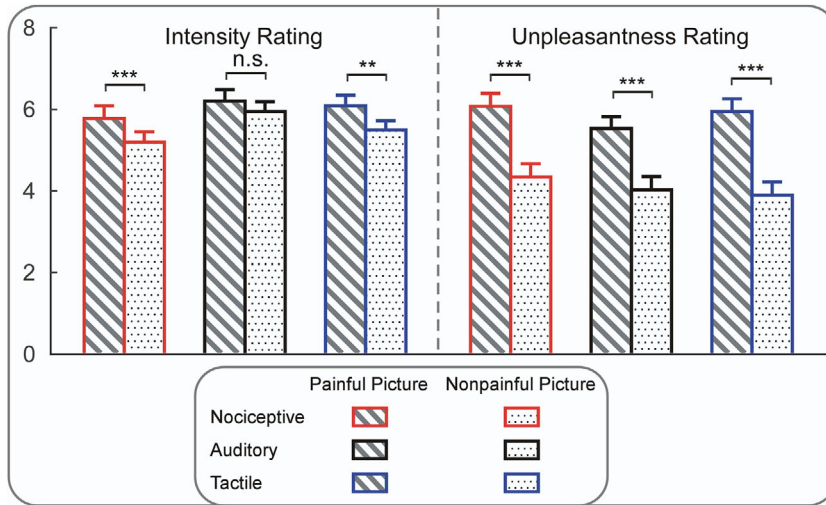


Figure 6. Subjective ratings for nociceptive, auditory, and tactile stimuli in Experiment 2. Participants reported higher intensity and unpleasantness ratings for the nociceptive stimuli and tactile stimuli after viewing painful pictures, compared with viewing nonpainful pictures. Participants also reported higher unpleasantness ratings for auditory stimuli after viewing painful pictures, compared with viewing nonpainful pictures. However, the intensity ratings for the auditory stimuli were not significantly different between the two priming conditions. Data are expressed as $M \pm SE$. n.s. indicates $P > 0.05$; $**P < 0.01$; $***P < 0.001$.

0.639). There was also a significant interaction between priming and modality ($F(1,37) = 9.21$, $P = 0.004$, $\eta_p^2 = 0.199$). Further analyses showed that compared with viewing nonpainful pictures, the N2 component in LEPs had a higher amplitude after participants viewing painful pictures (painful pictures: $-4.80 \pm 3.24 \mu V$; nonpainful pictures: $-3.98 \pm 3.16 \mu V$; $P = 0.020$). However, such a priming effect on the N2 component was not found in AEPs (painful pictures: $-15.39 \pm 0.99 \mu V$; nonpainful pictures: $-15.78 \pm 0.88 \mu V$; $P = 0.184$). For P2 amplitudes, three-way repeated measures ANOVA showed significant main effects of modality ($F(1,37) = 103.10$, $P < 0.001$, $\eta_p^2 = 0.736$) and intensity ($F(1,37) = 54.63$, $P < 0.001$, $\eta_p^2 = 0.596$). There was also a significant interaction between modality and intensity ($F(1,37) = 5.31$, $P = 0.027$, $\eta_p^2 = 0.125$). Further analyses showed that compared with low-intensity nociceptive stimuli, the P2 component evoked by high-intensity nociceptive stimuli had a larger amplitude (low-intensity: $0.62 \pm 0.31 \mu V$; high-intensity: $4.34 \pm 0.73 \mu V$; $P < 0.001$). Similarly, the amplitude of the P2 component evoked by high-intensity auditory stimuli was larger than that evoked by low-intensity auditory stimuli (low-intensity: $11.90 \pm 0.81 \mu V$; high-intensity: $13.55 \pm 0.96 \mu V$; $P < 0.001$).

Experiment 2

Priming effects of empathy on subjective ratings. Subjective ratings of perceived intensity and unpleasantness in six conditions are shown in Figure 6 and summarized in Table S3 (online only).

For intensity ratings, two-way repeated measures ANOVA showed a significant main effect of priming ($F(1,27) = 20.96$, $P < 0.001$, $\eta_p^2 = 0.437$). There was also a significant interaction between priming and modality ($F(2,54) = 3.61$, $P = 0.049$, $\eta_p^2 = 0.118$). Further analyses showed that participants reported higher intensity ratings for nociceptive ($P < 0.001$), auditory ($P = 0.007$), and tactile stimuli ($P = 0.001$) after viewing painful pictures, compared with viewing nonpainful pictures.

For unpleasantness ratings, two-way repeated measures ANOVA showed a significant main effect of priming ($F(1,27) = 37.19$, $P < 0.001$, $\eta_p^2 = 0.579$). There was also a significant interaction between priming and modality ($F(2,54) = 3.27$, $P = 0.046$, $\eta_p^2 = 0.108$). Further analyses showed that participants reported higher unpleasantness ratings for nociceptive ($P < 0.001$), auditory ($P < 0.001$), and tactile stimuli ($P < 0.001$) after viewing painful pictures, compared with viewing nonpainful pictures.

Priming effects of empathy on ERP responses during the firsthand perception phase. Group-level ERP waveforms and scalp topographies of N1, N2, and P2 components to sensory stimuli are shown in Figure 4 and Figure S3 (online only). Peak latencies and amplitudes of these components are summarized in Table S3 (online only).

For N1 latencies, a paired-sample *t*-test showed that there was no significant difference between painful and nonpainful picture conditions ($t(27) = 1.25, P = 0.221$). For N2 latencies, two-way repeated measures ANOVA showed a significant main effect of modality ($F(2,27) = 591.59, P < 0.001, \eta_p^2 = 0.956$). For P2 latencies, two-way repeated measures ANOVA showed a significant main effect of modality ($F(2,27) = 483.70, P < 0.001, \eta_p^2 = 0.947$).

For N1 amplitudes, a paired-sample *t*-test showed that there was no significant difference between painful and nonpainful picture conditions ($t(27) = -1.03, P = 0.314$). For N2 amplitudes, two-way repeated measures ANOVA showed a significant main effect of modality ($F(2,27) = 5.07, P = 0.010, \eta_p^2 = 0.158$). There was also a significant interaction between priming and modality ($F(2,54) = 3.52, P = 0.036, \eta_p^2 = 0.115$). Further analyses showed that the N2 component in LEPs had a higher amplitude after participants viewed painful pictures, compared with after viewing nonpainful pictures ($P = 0.004$). However, such priming effect on the N2 component was found neither in AEPs ($P = 0.478$) nor in TEPs ($P = 0.867$). For P2 amplitudes, two-way repeated measures ANOVA showed a significant main effect of modality ($F(2,27) = 8.45, P = 0.001, \eta_p^2 = 0.238$).

Different empathy ratings for priming pictures predicted perception ratings for sensory stimuli in different modalities. Subjective ratings (i.e., attention, intensity, unpleasantness, concern, threat, and arousal) of priming pictures and the results of the paired-sample *t*-tests are summarized in Table S4 (online only). For all ratings, the scores of painful pictures were significantly higher than those of nonpainful pictures (all $P < 0.05$).

Linear stepwise regression analyses indicated that no predictor (i.e., subjective ratings of priming pictures) was entered in the prediction model when intensity ratings for nociceptive, auditory, or tactile stimuli were used as the dependent variable. However, when unpleasantness ratings

for nociceptive, auditory, or tactile stimuli were used as the dependent variable, several significant findings were observed. The prediction model of unpleasantness ratings for nociceptive stimuli included concern ratings as the only predictor ($\beta = 0.37$) at a marginally significant level and was reached in one step, accounting for 13.9% of the variance of the pain unpleasantness ratings ($F(1,27) = 4.19, P = 0.051, R^2 = 0.139$). Moreover, the prediction model of unpleasantness ratings for auditory stimuli included attention ratings as the only predictor ($\beta = 0.53$) and was reached in one step, accounting for 28.2% of the variance of the auditory unpleasantness ratings ($F(1,27) = 10.22, P = 0.004, R^2 = 0.282$). The prediction model of unpleasantness ratings for tactile stimuli also included attention ratings as the only predictor ($\beta = 0.47$) and was reached in one step, accounting for 21.9% of the variance of the tactile unpleasantness ratings ($F(1,27) = 7.31, P = 0.012, R^2 = 0.219$).

Discussion

The present study aimed to investigate whether empathy for pain selectively facilitates the processing of firsthand pain perception. By performing two complementary sets of experiments using the priming paradigm, we compared the priming effect of viewing pictures depicting others' pain on healthy participants' subjective feelings and electrophysiological responses to nociceptive, auditory, and tactile stimuli. The present study yields three main findings. First, participants reported higher intensity, unpleasantness, and salience ratings for nociceptive, auditory, and tactile stimuli when they were primed by painful pictures in comparison with nonpainful pictures, indicating a similar priming effect of empathy for pain on firsthand perception across different sensory modalities at the behavioral level. Second, participants exhibited exaggerated N2 amplitude in response to nociceptive stimuli when they were primed by painful pictures rather than by nonpainful pictures, while ERP responses to auditory and tactile stimuli did not differ in the two priming conditions. This finding suggests a selective priming effect on firsthand pain at the neurophysiological level. Third, participants' concern ratings for the priming pictures predicted their unpleasantness ratings for the subsequent nociceptive stimuli, while participants' attention ratings for the priming pictures predicted their unpleasantness

ratings for the subsequent auditory and tactile stimuli. This finding implies that the psychological mechanisms underlying the priming effect of empathy for pain on firsthand pain are different from those on firsthand nonpain perception. Altogether, these results demonstrate that empathy for pain influences firsthand pain and nonpain perception in different ways, thus providing evidence of pain-selective representations in empathy for pain.

The facilitation effect of empathy for pain on the firsthand experience of pain has been repeatedly reported in previous studies.^{7–10,26,27,48} For example, participants reported higher intensity ratings for nociceptive electrical stimuli while observing images of people undergoing painful somatic sensation, compared with observing images showing enjoyable somatic sensation,⁴⁸ indicating an enhancing effect of pain-related contexts on the subjective experience of physical pain. Similarly, observing body parts in pain or facial expressions of pain exaggerated the amplitude of the nociceptive flexion reflex and the pain intensity and unpleasantness induced by nociceptive electrical stimuli,^{9,10} suggesting that empathy for pain modulates both spinal and supraspinal processes related to pain. Consistent with these previous studies, in Experiment 1, we found that the observation of others' pain increased participants' intensity, unpleasantness, and salience ratings for both high- and low-intensity nociceptive laser stimuli, suggesting that empathy-eliciting stimuli depicting others' pain affect sensory-discriminative, affective-motivational, and attention-attracting aspects of sensory stimuli.^{31–33} However, such priming effect on subjective ratings existed not only for pain but also for auditory perception. In Experiment 2, we validated the priming effects of empathy for pain on pain and auditory perception on another group of participants, and further found that empathy for pain increased participants' subjective ratings for tactile stimuli. In other words, both nociceptive and non-nociceptive stimuli primed by empathy for pain could induce more intense perception and stronger emotional response. This finding is reliable and robust, as the two experiments yielded similar results, which reflects a general priming effect of empathy for pain on firsthand perception at the behavioral level.

This finding converges with the view that the so-called “shared activations” between empathy for

pain and firsthand pain are at least partly related to domain-general mental processes, such as salience detection and automatic emotion processing.^{49,50} Indeed, previous studies have revealed the various functional significances of the activations in the aMCC and AI.^{19–21} Specifically, apart from being consistently engaged in empathy for pain and firsthand pain,⁴ these brain regions are also involved in many other processes, such as interoceptive,⁵¹ affective,⁵² and salience processing.³² Put more explicitly, the overlapping activations in the aMCC and AI between empathy for pain and firsthand pain reported in prior studies^{4,5} can be partly attributed to the processes of perceptually salient events, no matter through which modality they were presented. In good agreement with this explanation, we found that empathy for pain could influence not only the subjective experience of pain but also the subjective ratings for auditory and tactile stimuli in the present study.

However, such observed cross-modality similarity in behaviors might be the consequences of different psychological and neural processes.^{41,53} Indeed, when assessing the predictive ability of participants' subjective ratings for the priming pictures on their subjective ratings for the subsequent sensory stimuli, we observed different patterns of the prediction between pain and other sensory modalities. We demonstrated that the more people were concerned about others' pain, the more they felt unpleasant when receiving high-intensity nociceptive stimuli; the more people paid attention to others' pain, the more they felt unpleasant when receiving high-intensity auditory and tactile stimuli. Since the empathic concern for others' pain represents a mental activity specifically related to pain,⁵⁴ there is no doubt that the concern ratings of the priming pictures selectively predict the unpleasantness of the subsequent firsthand pain. By contrast, one's attention to others' pain is likely to be modulated by the high-arousal, aversive properties of the materials used to evoke empathic responses,²² thus the empathy-eliciting pictures facilitate the processing of subsequent auditory and tactile stimuli.

Interestingly, the subjective ratings for the priming pictures could only predict the unpleasantness ratings but not the intensity ratings of the subsequent sensory stimuli. Intensity ratings are generally linked to the sensory-discriminative aspect of perception, whereas unpleasantness ratings are

typically associated with the affective-motivational aspect of perception.³¹ Therefore, our result indicates that affect sharing plays a prominent role in empathy for pain, which coincides with recent functional magnetic resonance imaging (fMRI) studies investigating the shared representations between empathy for pain and firsthand pain.^{55–57} For example, the activations in the AI and aMCC were stronger while participants observed others' facial expressions of genuine pain versus pretended pain; more importantly, the increased activation in the AI was selectively correlated with unpleasantness ratings for others' pain.⁵⁵ These results suggest that, in addition to the responses triggered by perceptual salience, the empathy-related brain responses also reflect the sharing of others' actual affective states triggered by pain. More directly, by investigating the effect of causal manipulation of firsthand pain on empathy for pain, researchers observed that the firsthand placebo analgesia in the participant's right hand resulted in a comparable reduction of unpleasantness ratings for others' pain in both hands instead of a localized reduction for the right hand only.⁵⁶ This further suggests that shared affective representations play more of a role during empathy for pain compared with shared somatosensory representations.

Such cross-modality difference in psychological mechanisms underlying the priming effect was also supported by findings obtained from ERP responses. Specifically, we found in both experiments that strong nociceptive laser stimuli primed by painful pictures evoked a larger N2 amplitude than those primed by nonpainful pictures. Previous studies have corroborated a strong correlation between the N2 amplitude in LEPs and the intensity of pain perception.^{41,58} Therefore, the elevated N2 amplitude in LEPs in the painful picture condition reflected increased pain perception, which is consistent with the behavioral result, that is, higher subjective ratings for the nociceptive stimuli. However, we did not find any difference in ERP responses to auditory and tactile stimuli between the two priming conditions, providing indirect evidence that empathy for pain involves pain-selective processes.

Notably, we only observed the priming effect of empathy for pain on the amplitude of N2, but not on that of other LEPs. This is mainly because these components originate from different sources and are associated with different neural processes.

Specifically, the N1 LEP component is largely generated from the primary somatosensory cortex contralateral to the stimulated side, reflecting early nociceptive processing related to stimulus properties (e.g., stimulus intensity and location).^{43,59} The result that empathy for pain had no priming effect on N1 amplitude suggests that empathy for pain does not modulate the early stage of neural processing of stimulus properties. The N2 LEP component is mainly generated from the secondary somatosensory cortex and insula, while the P2 LEP component is largely generated from the anterior cingulate cortex.^{60–62} Such different neural generators lead to the distinctly functional significances of N2 and P2 components to some extent,^{61,63,64} thus the two components are believed to be differentially modulated by cognitive tasks.⁶⁵ From this perspective, it could be possible that the priming effects of empathy for pain are more evident for one component than the other. The detailed psychological mechanisms underlying this discrepancy should be investigated in the future.

Nevertheless, given that we observed similar priming effects of empathy for pain on pain and nonpain perception at the behavioral level, we cannot exclude the possibility that the brain responses reflecting the priming effects could not be appropriately captured by EEG or were difficult to be disentangled from other neural signals in the ERP responses. This seems a remote possibility, though, considering that the two experiments in the present study varied in experimental design and EEG acquisition equipment but yielded similar results, and a previous study also failed to identify a difference in ERP responses corresponding to the priming effect of empathy for pain on non-nociceptive heat stimuli at the behavioral level.⁸ In addition, empathy for pain did not influence the ERP responses evoked by low-intensity laser stimuli in the present study, and this negative finding was caused by the fact that the low-intensity laser stimuli failed to evoke Aδ-LEPs,²⁹ which hampered the assessment of the priming effect of empathy for pain on the brain responses.

Our observation that empathy for pain involves pain-selective processes coincides with the findings from recent animal and human studies.^{18,66–68} For example, compared with healthy individuals with low sensitivity to firsthand pain, those with high sensitivity to firsthand pain exhibited

greater empathic responses when viewing pictures depicting others' pain, manifested as greater estimated pain intensity experienced by others, greater unpleasantness reported when viewing others in pain, and better performance in discriminating others' pain.⁶⁸ This revealed a shared sensitivity to firsthand pain and empathy for pain. More directly, a previous study found that a multivariate decoder of electrophysiological signals trained on observations of a painful conspecific could predict firsthand pain in rats, and this was specifically related to single-neuron activities in the cingulate cortex.⁶⁶ Moreover, a transient lesion of this region could affect pain perception but not negative affect such as fear. The researchers interpreted these results as evidence for the shared pain-specific neural responses between firsthand and empathy for pain in rats. Similarly, in a human fMRI study, the shared brain activation patterns between empathy for pain and firsthand pain identified using multivariate pattern analyses were predictive of firsthand thermal pain, while these patterns were not sensitive to the processing of nonpainful high-arousal negative stimuli.¹⁸ This suggested that the shared neural signature might capture pain-selective brain responses rather than domain-general processes to aversive events. Based on these findings, we argue that observing pictures of others' pain may trigger representations exclusive to pain that could facilitate the processing of congruent nociceptive stimuli relative to less congruent auditory or tactile stimuli. This explains why empathy for pain influenced the ERP responses to nociceptive stimuli and the ERP responses to nonpain sensory stimuli in different ways in the present study.

Some limitations of the present study should be considered for future research. First, although up to six dimensions of subjective feelings to priming pictures were reported by the participants, these ratings may still not fully describe the psychological states during empathy for pain. Because of this, the regression results between the subjective ratings for the empathy-eliciting pictures and the subjective ratings for the firsthand perception may not fully reveal the psychological mechanisms underlying the priming effect of empathy for pain on firsthand perception. Second, this study only assessed the priming effects of empathy for pain on firsthand pain and nonpain perception, but not the other way round. The priming effect between empathy and

firsthand experience is supposed to be bidirectional under the shared-representation model of empathy. To our best knowledge, only one published study investigated the interaction between firsthand pain/nonpain perception and empathy for pain using the priming paradigm.⁸ However, the sensory stimuli used to induce pain (i.e., high-intensity heat stimuli) and nonpain perception (i.e., low-intensity heat stimuli) in that study were not well-matched, which made it impossible to determine whether the difference in priming effects of firsthand pain and nonpain perception was due to the activation of pain-selective representations or a difference in some stimulus properties, for example, stimulus intensity. Therefore, the priming effect of firsthand experience on one's empathy needs further exploration.

In conclusion, our results demonstrate that empathy for pain influences firsthand pain and nonpain perception in different ways, which suggests the existence of pain-selective representations in empathy for pain, thus contributing to a better understanding of the shared-representation model of empathy.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant Nos. 31822025, 32071061, and 32171077).

Author contributions

Q.R. contributed to experimental design, data collection, data analysis, and writing. Y.Y. assisted in experimental design and data collection. Y.W. assisted in data collection. X.L. and L.H. contributed to the experimental design, data analysis, and writing.

Supporting information

Additional supporting information may be found in the online version of this article.

Figure S1. ERP responses evoked by priming pictures in Experiment 1.

Figure S2. N1 components evoked by nociceptive stimuli in Experiment 1.

Figure S3. N1 components evoked by nociceptive stimuli in Experiment 2.

Table S1. Descriptive statistics ($M \pm SE$) of subjective ratings (intensity, unpleasantness, and salience) and ERP responses (N1, N2, and P2 latencies and amplitudes) evoked by nociceptive and auditory stimuli in Experiment 1.

Table S2. Descriptive statistics ($M \pm SE$) of ERP responses evoked by priming pictures and the *t*-test results of the comparisons between painful and nonpainful picture conditions in Experiment 1.

Table S3. Descriptive statistics ($M \pm SE$) of subjective ratings (intensity and unpleasantness) and ERP responses (N1, N2, and P2 latencies and amplitudes) evoked by nociceptive, auditory, and tactile stimuli in Experiment 2.

Table S4. Descriptive statistics ($M \pm SE$) of subjective ratings for priming pictures and the *t*-test results of the comparisons between painful and nonpainful picture conditions in Experiment 2.

Competing interests

The authors declare no competing interests.

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