Title: I feel your pain: Higher empathy is associated with higher posterior default mode network activity

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Abstract

Empathy is characterized as the ability to share one's experience. Recent findings indicate that the anterior mid-cingulate cortex (aMCC) and insular cortices play a role in empathy. For example, insular lesions lead to less empathetic behaviors. Further, neuroimaging studies revealed that viewing and/or mentalizing one's romantic partner in pain produces higher aMCC and anterior insula activation. Said studies employed blood oxygen level dependent fMRI that may be less sensitive to comprehensively capture tonic empathetic responses to pain. Others have found that empathy for pain can elucidate self-other processing in pain-related brain regions (thalamus; somatosensory cortices). The present study investigated the differential neural empathetic responses elicited by viewing, in real-time, a female volunteer's romantic partner ($\geq$ 3 months) as compared to a stranger (laboratory technician) receive pain-evoking noxious heat during arterial spin labeling (ASL) fMRI acquisition. Based on prior work, we predicted that higher empathy would be associated with higher pain-related processing. Twenty-nine healthy females ($\bar{M}$ age = 29 years) were administered a noxious "heat series" (ten, 8s 48°C plateaus; 240 seconds; left forearm) during ASL fMRI (3T GE MR750). Female volunteers, during fMRI acquisition, then viewed, with an MRI-compatible mirror, a "stranger" (laboratory technician) and then her romantic partner receive the same "heat series" in the MRI room. Visual analog scale (VAS; 0 = "not unpleasant" to 10 = "extremely unpleasant") ratings for empathy (0 = "no pain" to 10 = "worst pain imaginable") were collected from all participants after each scan. As predicted, female volunteers reported 33% higher empathy while viewing their romantic partner receive noxious heat as compared to the stranger (p = 0.01). Higher empathy ratings for the romantic partner, as compared to the stranger, were associated with greater activation in the dorsoposterior precuneus and the visual cortex. The present findings are the first to demonstrate that perfusion fMRI can be used to reliably capture empathetic processes and revealed novel insights in the role of the precuneus, a central node of the default mode network, in empathy and suggest that self-embodiment of another's experience is associated with higher empathy.

Introduction

Empathy is characterized as a *sharing* of another person's emotion (Jackson et al., 2006) and is positively associated with higher compassion (e.g., sharing with one's experience *and* the desire to help), prosocial and altruistic behavior (Klimecki et al., 2013). Importantly, viewing and/or mentalizing another individual experiencing pain reliably increases empathy in non-psychopathological individuals (Finlay and Syal, 2014). It is then no surprise that experimental paradigms employing the visualization of another individual's pain (i.e., vicarious pain; pain empathy) are the most commonly employed methodologies to identify the behavioral and neural mechanisms supporting empathy (Jauniaux et al., 2019). Viewing another individual experiencing a pain-evoking stimulus reliably elicits behavioral and neural pain-related responses (Lamm et al., 2011). In particular, engagement of the anterior insula and anterior mid-cingulate cortex (aMCC) are the two most common empathetic pain neural mechanisms (Morrison et al., 2004; Singer et al., 2004; Danziger et al., 2009; Lamm et al., 2011; Decety et al., 2013; Preis et al., 2013; Zaki et al., 2016). Greater activation in these areas, in response to viewing others' pain, is directly associated with greater self-reports of empathy and the perception of "feeling someone else's pain" (Saarela et al., 2007; Corradi-Dell'Acqua et al., 2011; Kanske et al., 2015; Zhao et al., 2021). Collectively, these multisensory brain areas are associated with perspective-taking and understanding others' mental states, which are attentional mechanisms of empathy. However, the aMCC and anterior insula are also the central nodes of the so-called "salience network" and are activated during reflexive and bottom-attentional processes (Wiech et al., 2010; Chiong et al., 2013; Zhao et al., 2021). This has led some to argue that perceptual salience detection, as processed by the anterior insula and aMCC, are potential confounds of brain-brain empathy models because empathy is a salience driven experience (Lamm et al., 2011; Zaki et al., 2016; Zhao et al., 2021).

All prior functional magnetic resonance imaging (fMRI) studies have employed blood oxygen level dependent (BOLD) fMRI acquisition to capture empathetic states and traits. BOLD fMRI is well-suited to capture brain activity corresponding to the period when viewing a person receive painful stimulation to elucidate empathy. However, BOLD fMRI has some noteworthy limitations when applied to the complex and multifaceted processes of the empathetic experience and is also more susceptible to non-neuronal

signal fluctuations (Liu and Brown, 2007). There is also a potential for empathy-based psychological "carryover" effects that can influence BOLD-based ON-OFF block contrast designs. That is, the experience of empathy for one condition (e.g., viewing a baby in pain) may carryover to influence a subsequent condition (e.g., a cross-fixation) that would not otherwise elucidate an empathetic state. The perfusion-based Arterial Spin Labeling (ASL) fMRI technique addresses these caveats, as it is less temporally dependent and provides a direct quantification (ml/100g tissue/minute) of cerebral blood flow (CBF), making it much more suited for capturing stable representations supporting the neural mechanisms of empathy. ASL is also robust in controlling for low-frequency fluctuations that can help us better isolate and identify empathetic differences between viewing a romantic partner vs. stranger experience pain, since we can compare absolute levels of CBF across conditions that are separated by several minutes (Wang et al., 2003).

The proposed study employed perfusion-fMRI to address the potential caveats of capturing empathy-related neural mechanisms as opposed to salience-based neural processing. Thus, the present study investigated the differential neural empathetic responses elicited by viewing, in real-time, a female volunteer's romantic partner (of $\geq$ 3 months) as compared to a stranger (laboratory technician) receive pain-evoking noxious heat during ASL fMRI acquisition. To increase ecological validity, female volunteers viewed their respective romantic partner (or a stranger) receive said noxious heat during ASL fMRI acquisition when they were positioned next to them in the in the scanner and after receiving the heat stimuli themselves. Based on prior research, we expected that female volunteers would report significantly higher empathy ratings for their romantic partners as compared to a stranger. Further, based on the relationship between self-other distinctions and empathy (Lamm et al., 2007; Minio-Paluello et al., 2009; Otti et al., 2010; Lamm et al., 2016; Krol and Bartz, 2022), we postulated that higher empathy ratings for the romantic partner as compared to the stranger would be associated with greater activation of pain-related brain processes (posterior insula; dorsal anterior cingulate cortex (dACC); thalamus).

METHODS

The proposed project was part a longitudinal study (unpublished) that examined the behavioral and neural effects of the eight-week Mindfulness-Based Stress Reduction (MBSR), Mindful Self-Compassion (MSC), and Compassion-Cultivation Training (CCT). The data included in the present study are from a pre-randomized MRI baseline session that included a total of 29 female volunteers and their respective romantic partners, and thus do not include any meditation interventions. After the baseline MRI session, seventeen participants were randomized to one of the three groups (i.e., n = 10 MBSR; n = 4 MSC; n =3 CCT) but these data are not presented in the present study. Only data from the first baseline MRI session is presented in this study.

Participants

The University of California San Diego (UCSD) Institutional Review Board approved (IRB#201729) all study procedures. Six hundred and eight individuals were screened from the local community using a Quick Response (CR) code to assess for study inclusion-exclusion criteria. Exclusion criteria included individuals with chronic pain, those taking psychoactive medication, and who were pregnant, claustrophobic, and presented with MRI contraindications. Females aged between 18 and 65 years that were in a 3-month or greater romantic relationship and had no prior meditation experience were part of the inclusion criteria. Twenty-nine, right-handed healthy female volunteers [mean age (SD) = 29 (6.67)] years and their respective romantic partners were enrolled in the study. All participants provided written, informed consent acknowledging that they would be administered noxious heat and that all methods were clearly explained. Participants were financially compensated for their involvement and were instructed that they were free to withdraw from the study at any point.

Participant conditions

Participants were characterized as 1) “female volunteers”, 2) their respective “romantic partner” and 3) a “stranger”. The female volunteers were considered the primary study participant because they underwent fMRI acquisition during noxious stimulation and when viewing their romantic partner of greater than 3-

months versus a stranger receive painful heat. Strangers were laboratory technicians that did not know nor interact with the female volunteer or romantic partner.

Stimuli

An MRI-compatible thermal sensory testing device (QST.Lab, Strasbourg, France) fitted with a 45mm surface area probe delivered all thermal stimuli. The thermal probe was positioned on the ventral aspect of the left forearm (C5/6 dermatome) and held in place with a Velcro strap. Participants were instructed to remove the strap if the thermal stimulus became too uncomfortable (none did so).

Psychophysical Pain and Empathy Assessment

Ratings of pain and empathy were assessed on an electronic 11 points visual analogue scale (VAS) coded with an in-house python script [PsychoPy, (Peirce, 2007)]. During the psychophysical training, participants viewed the VAS on a laptop screen and provided ratings using a two-button button box. In the MRI scanner, participants viewed the VAS on a projector screen through an MRI-compatible mirror and used an identical MRI-compatible button box to record responses. All VAS metrics had a minimum rating of “0” and was designated as “no pain sensation” whereas the maximum (10) was labeled as “most intense pain sensation imaginable”. For empathy ratings, female volunteers were asked: “How unpleasant did it feel for you when your partner (or the stranger) received the heat series?” The minimum rating (0) was designated as “not at all unpleasant” whereas the maximum (10) was labeled as “most unpleasant sensation imaginable”. All participants were asked: “How would you rate the pain intensity of the heat series you just received?” after each heat series (the same romantic partner and stranger data are not presented here). The female volunteer was also asked how much pain she felt that the stranger (or romantic partner) felt (data not presented here).

MRI Acquisition

All MRI scans were acquired on a GE Discovery MR750 3T scanner with a body transmit coil and a 32-channel receive-only head coil (Nova Medical, Wilmington, MA).

Anatomical MRI Acquisition

High-resolution structural scans were acquired using an MP-RAGE sequence [TI = 900 milliseconds (ms); TR = 2300ms; flip angle = 9°; TE = 2.95ms; 1mm isotropic spatial resolution; 263 slices, GRAPPA factor = 2; scan time = 180 seconds (s)].

Functional MRI Acquisition

Whole-brain CBF was acquired using ASL fMRI (Alsop et al., 2015). Four separate and temporally independent CBF volumes were collected in a single-shot spiral acquisition using 2D flow-sensitive alternating inversion recovery [FAIR, (Kim and Tsekos, 1997)] with QUIPSS II, using parameters: TI1= 800ms, TI2 = 1800ms, TR = 2550ms, TE = 3.3ms, matrix size = 64 x 64, FOV = 240mm x 240mm, 24 slices (Wong et al., 1998). The voxel size was 3.75mm x 3.75mm x 5mm, with the addition of a 1mm gap between slices. Each ASL scan was preceded by a proton density (PD) weighted scan for use in CBF quantification.

Experimental Design

Psychophysical Training

After providing written consent, female volunteers, their romantic partners, and strangers were familiarized with twenty, 5 second duration thermal stimuli (range of temperatures: 35 - 48°C) on the ventral aspect of the right forearm. VAS ratings of pain intensity were collected after each thermal stimulus (data not presented here) to familiarize and train all participants (i.e., female volunteer; romantic partner; stranger) to rate their pain.

Functional MRI

Female volunteers were positioned in the MRI scanner with a respiratory transducer around the chest and a pulse oximeter on the left index finger. The respiratory transducer and pulse oximeter were included with the scanner from the MRI manufacturer. An anatomical scan was performed first. A resting state BOLD scan was then conducted (data not presented here). The thermal probe was then positioned

on the ventral aspect of their left forearm. ASL-fMRI acquisition then ensued, with a *neutral series* scan wherein female volunteers viewed a fixation cross icon cue on a projector screen throughout administration of a continuous 35°C stimulus (*female volunteer-35°C*). They were then administered the noxious *heat series* scan (*female volunteer-48°C*) while viewing a flame on the projector screen during 8-second periods of 48°C and a fixation cross during the interspersed 10-second periods of neutral 35°C. Ratings of pain intensity was collected after the *heat series.* The stranger was then escorted into the scanner room and seated on a stool next to the scanner bed where the female volunteer was lying. The stranger was next fitted with the thermal probe (ventral aspect of the left forearm), instructed to look away from the scanner (i.e., away from the female volunteer's face), and to extend their left arm on top of three MRI-compatible blocks to allow visualization of thermal stimulation by the female volunteer during fMRI acquisition through a mirror on the scanner (Figure 1). Importantly, the female volunteer could only clearly view the stranger's (and romantic partner's) arm, the attached thermal probe, and the projector screen. The same noxious *heat series* was then administered to the stranger's/romantic partner's arm during fMRI acquisition on the female volunteer (*stranger + 48°C*) while a flame icon again appeared on the projector screen during 48°C stimulation and a fixation cross was depicted during neutral 35°C stimuli (Figure 1). During this time, female volunteers in the scanner viewed the stranger's partner's arm and corresponding visual cues (i.e., flame/cross). After the *heat series*, the stranger left the MRI room, and empathy and pain intensity ratings, respectively, were collected from the female volunteer and stranger (latter data not included in this investigation). Thus, rating collection was not conducted in the presence of the female volunteer or romantic partner. The romantic partner then entered the scanner room, was positioned in front of the female volunteer, and the same procedures employed for the stranger were conducted for the romantic partner.

Analysis of Behavioral Data

All analyses of behavioral data were performed with SPSS software (SPSS v28, IBM, Armonk, New York). To test the primary hypothesis, a paired samples t-test examined if female volunteers' VAS pain empathy ratings were significantly higher for romantic partners as compared to the stranger.

Analysis of Neuroimaging Data

*Preprocessin*g. The Cerebral Blood Flow Biomedical Informatics Research Network (CBFBIRN) pipeline was used for CBF quantification (Shin et al., 2013). For each ASL series, fieldmap unwarping was applied to correct for B0 non-uniformity. Alternating tag and control ASL images were subtracted and then averaged over time to generate a mean perfusion-weighted image. The PD-weighted image was then used for voxelwise calibration to convert the mean perfusion-weighted image into physiological CBF units [ml/100gr tissue/min]. In healthy adults, CBF is approximately 50 mL/100g-min (Lassen, 1985). Thus, all CBF maps were filtered with a lower threshold of 0 and a liberal upper threshold of 200 to eliminate obvious artifacts. Final CBF volumes were visually inspected for significant dropouts by multiple researchers. No subject was excluded because of extensive artifacts.

All the following preprocessing and data analytical steps were performed using FSL version 6.0 [FMRIB Software Library (Center for FMRIB, University of Oxford, Oxford, UK (Jenkinson et al., 2012))]. Individual 3D CBF volumes from each ASL series (1) *female volunteer-35°C, 2) female volunteer-48°C, 3) stranger + 48°C, 4) romantic partner + 48°C*) were concatenated into one 4D image to perform first-level analyses. A 9mm FWHM 3D isotopic Gaussian smoothing kernel and intensity normalization (mean global intensity scaling) was applied to the 4D fMRI data. After motion correction (MCFLIRT) was applied, functional images were co-registered to their corresponding anatomical reference using FLIRT boundary-based registration, and subsequently to the standard MNI template through 12-parameter linear, and 10mm warp resolution nonlinear transformations. This nonlinear transform then was applied to CBF data. Temporal filtering was not applied because each CBF volume is temporally independent from adjacent volumes.

Statistical analysis of cerebral blood flow signal changes. First-level analyses were performed on the 4D concatenated CBF data for every subject using a fixed-effect modeling approach (Woolrich et al., 2001). Importantly, significant clusters of activation across were Gaussianized and thresholded using clusters determined by a threshold of $Z > 3.1$. Corrected cluster significance threshold was set at $p < 0.05$ to

ensure that the probability of false-positive findings is corrected for multiple comparisons across all brain voxels (Woo et al., 2014; Eklund et al., 2016). All higher-level Individual contrast of parameter estimate (COPE) images were imputed into a random effects model (FSL FLAME) to determine higher level group effects.

Neural processes evoked by noxious (48°C) vs. innocuous (35°C) heat. A first-level ANOVA examined for significant CBF changes corresponding to noxious heat (*female volunteer-48°C*) as compared to the 35°C ASL fMRI scan (*female volunteer-35°C*). A second-level paired samples t-test was performed across individuals was employed to identify significant mean effects associated with stimulation level (48°C vs. 35°C).

The relationship between whole-brain CBF and empathy. A first-level analyses compared CBF changes when viewing the stranger and romantic partner receive noxious heat, respectively (*stranger + 48°C, romantic partner + 48°C*). The difference in empathy ratings between the romantic partner and stranger was then calculated, demeaned, and entered into a simple regression analysis to examine the relationship between empathy ratings and corresponding brain activation. To appreciate any significant correlations, the thresholded z-statistic image was binarized, CBF values were extracted (FSL FeatQuery) and entered into a bivariate correlation with empathy ratings (romantic partner – stranger).

Results

Behavioral

As predicted, female volunteers reported 33% higher empathy while viewing their romantic partner receive noxious heat as compared to the stranger (p = 0.01, CI_{95} = 0.23; 1.67; Figure 2). Noxious heat was associated with an average pain intensity rating of 3.50 (2.76) in the female volunteer.

Whole-brain CBF responses to noxious as compared to innocuous heat.

Neural processes evoked by noxious (48°C) vs. innocuous (35°C) heat, in the female volunteer, were associated with greater activation in the contralateral (to stimulation site) anterior – extending into posterior – insula, secondary somatosensory cortex (SII), inferior frontal gyrus, frontal operculum, bilateral cerebellum, and posterior pons of the brainstem (Figure 3). Noxious heat also produced greater deactivation of the ventral precuneus and the primary motor cortex (MI).

The relationship between whole-brain CBF and empathy.

Viewing the romantic partner receive noxious heat produced greater deactivation in the dorsal aspect of the precuneus and the right-lateralized inferior parietal lobe including the supramarginal and angular gyrus when compared to viewing the heat paradigm in the stranger (Figure 4; left panel). We found that higher empathy ratings for the romantic partner, as compared to the stranger, were associated with greater activation in the dorsoposterior precuneus and the visual cortex (R^2 = 30%, p = .002, Figure 4; right panel).

DISCUSSION

The present study is innovative because it is the first to use perfusion fMRI acquisition (ASL) to identify neural mechanisms supporting higher empathy. Noxious heat was administered to the female volunteer to enhance ecological validity by providing a first-person perspective of what the romantic partner and stranger would *feel* during the heat-empathy paradigm. Female volunteers, in a 3 month or greater romantic relationship, reported significantly higher empathy ratings for viewing their respective romantic partner receive noxious heat when compared to observing a stranger receive the same painful stimulus (Figure 2). To help the female volunteer appreciate the pain experience of the romantic partner and stranger, noxious heat was applied to female volunteers and produced greater activation in a contralateral distributed network of pain-related activity including the anterior insula, posterior insula, SII, central – frontal operculum, cerebellum and inferior frontal gyrus coupled with deactivation of the precuneus, and MI (Figure 3). As seen in other studies, the aMCC and anterior insula were not associated with empathetic responses. This was likely due to a lack of differential bottom-up salience processing between viewing the romantic partner and stranger receive painful heat. This may also have been, in part, due to the inability for the female volunteer to see the romantic partner and stranger's face, a procedure that was intentional to reduce processing corresponding to viewing affective facial expressions. During fMRI acquisition, viewing the application of noxious heat on the romantic partner's arm produced significantly greater deactivation of the aspects of the inferior parietal lobe including the supramarginal and angular gyrus, amygdala, and the precuneus when compared to the stranger (Figure 4; left panel). Lower amygdalar activation was likely associated with less negative affective processing and greater empathetic responses when viewing the romantic partner receive painful heat as compared to the stranger (Leigh et al., 2013; Kim et al., 2023). Although speculative, greater inferior parietal lobe deactivation when viewing the romantic partner as compared to the stranger may be associated attenuated allocation of attentional to processes to viewing the familiar romantic partner as compared to the stranger (Zeidan et al., 2015). The right supramarginal gyrus is critically involved in processing bottom-up attentional processing supporting self-other affective distinctions and (Silani et al., 2013; Steinbeis et al., 2015; Bukowski et al., 2020; Zhao et al., 2021). Thus, in the present case, there may

have been less self-other distinction when viewing the romantic partner in contrast to viewing the stranger.

Importantly, higher empathy ratings for the romantic partner (as compared to the stranger) were significantly correlated with greater deactivation in a distinct and more medial and posterior aspect of the precuneus than the precuneus activity exhibited in the mean effect of the regression model (Figure 4; left panel). We provide novel evidence that the precuneus is directly involved in processing greater empathy for one's romantic partner as compared to a stranger. This is in line with previous working indicating more lateral aspects of the precuneus engaged in visual guidance and attentional processing and dorsomedial aspects supporting self-referential processing (Cavanna and Trimble, 2006). The precuneus exhibits the highest metabolic consumption in the brain (Gusnard and Raichle, 2001) and is anatomically situated to integrate somatosensory representations with the sense of self (Penfield and Boldrey, 1937; Zeharia et al., 2019). It is also highly involved in task-based and self-referential processes (Cavanna and Trimble, 2006). Recent work, employing intracranial recordings in human patients, revealed that aspects of the precuneus explicitly process somatic self-association and self-embodied reference (Lyu et al., 2023). We postulate that the precuneus is an important neural mechanism supporting self-other distinction in the context of empathetic processes. Thus, higher empathy ratings may reflect an embodiment of another that facilitates the experience of pain in the perceiver. Higher visual cortex activity also predicted higher empathy for the romantic partner when compared to the stranger (Figure 4). Due to the role of the visual cortex and the posterior default mode network in facilitating task- and salience-based visual attention, we postulate that greater allocation of attentional resources were recruited when viewing the romantic partner as compared to the stranger (Figure 4; right panel).

The present findings are the first to demonstrate that perfusion fMRI can be used to reliably capture empathetic processes and revealed novel insights in the role of the precuneus, a central node of the default mode network, in empathy. We found that higher activation in brain mechanisms supporting the embodiment of another's experience is associated with higher empathy. Inclusion of the romantic partner and stranger also, likely, increased the ecological validity of empathetic manipulation as

compared to the use of static images and/or videos (Krishnan et al., 2016; Lopez-Sola et al., 2017). These data suggest that therapies/interventions that target the precuneus may be uniquely efficacious in the cultivation of empathetic response. To this extent, therapies like mindfulness-based mental training and/or psychedelics increase empathy-compassion (Laneri et al., 2017; Ashar et al., 2021; Domínguez-Clavé et al., 2022; Zheng et al., 2023) and also modulate posterior aspects of the default mode network (precuneus) (Brewer et al., 2011; Palhano-Fontes et al., 2015; Doss et al., 2022; Riegner et al., 2023).

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Figure Legends

Figure 1. Functional MRI experimental procedures. After positioned in the MRI scanner, 1) resting state blood oxygen level dependent (BOLD) fMRI scan was performed in the female volunteer (data not presented here). 2) The female volunteer then underwent an arterial spin labeling (ASL) fMRI scan with the thermal probe fixated on the arm and innocuous heat (35°C) was administered with a fixation cross projected onto the screen (visible using an MRI compatible mirror). 3). The thermal probe was moved to a new location on the forearm and another ASL scan was performed during 8-second plateaus of 48°C and 10-second 35°C interstimulus intervals. Visual analog scale (VAS) pain intensity ratings were collected. 4) The stranger (depicted with a "?"; laboratory technician) was then escorted into the scanner room and positioned in front of the female volunteer. The thermal probe was placed on the stranger's arm and positioned in a fashion that allowed the female volunteer to view the arm (and not the face) and the projection screen. The female volunteer was aware when the noxious heat was presented when a flame-icon was projected and a fixation point when the innocuous 35°C interstimulus was applied. After this scan, female volunteers were asked: "How unpleasant did it feel for you when your partner (or the stranger) received the heat series?" using the VAS. The stranger was asked "How would you rate the pain intensity of the heat series you just received?" after each heat series (data are not presented here). The female volunteer was also asked how much pain she felt that the stranger felt (data not presented here). 5) The romantic partner (depicted with a heart icon) was then escorted into the scanner room and positioned in front of the female volunteer. The thermal probe was placed on the romantic partner's arm and positioned in a fashion that allowed the female volunteer to view her romantic partner's arm (and not the face) and the projection screen. The female volunteer was aware when the 48°C was presented when a flame-icon was projected and a fixation point when the innocuous 35°C was applied. After this scan, female volunteers were asked: "How unpleasant did it feel for you when your romantic partner received the heat series?" using the VAS. The stranger was asked "How would you rate the pain intensity of the heat series you just received?" after each heat series (data are not presented here). The female volunteer was also asked how much pain she felt that the romantic partner felt (data not

presented here).

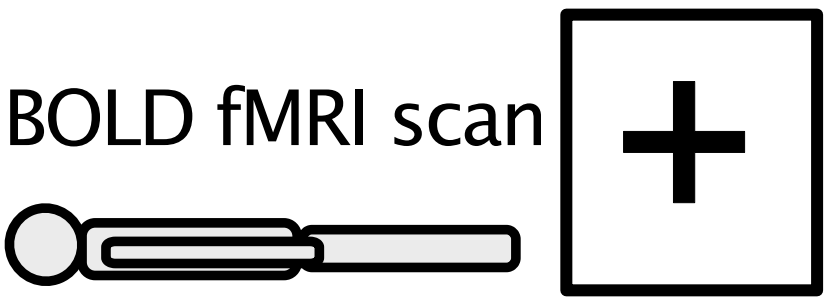
Figure 2. Empathy ratings for the romantic partner was significantly, $p = 0.01$, $CI_{95} = 0.23; 1.67$, higher than the stranger. Error bars = standard error of the mean.

Figure 3. In female volunteers, noxious heat (48°C) produced greater activation in the contralateral (to the left arm) anterior insula, posterior insula, secondary somatosensory cortex (SII), inferior gyrus, frontal operculum and bilateral cerebellum. Brain areas are delineated as depicted from left to right each image. Slice locations correspond to standard stereotaxic space.

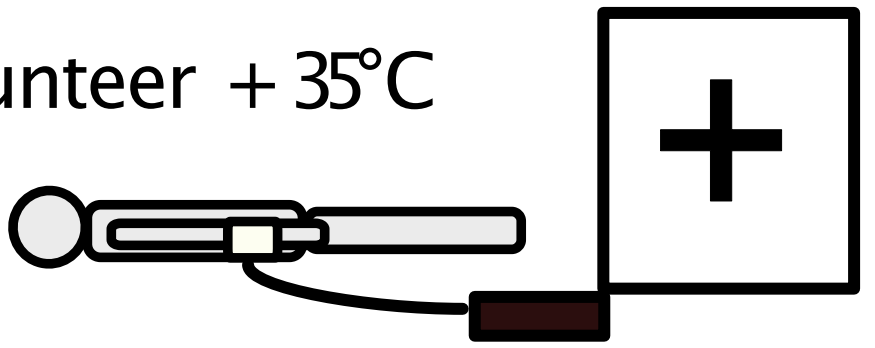
Figure 4. A regression was performed to determine the neural correlates of empathy for the romantic partner as compared to the stranger. Left panel: ASL scans corresponding to viewing the romantic partner as compared to the stranger was first contrasted and revealed greater deactivation in the ventral precuneus, aspects of the inferior (I.) parietal lobe (supramarginal gyrus; angular gyrus), superior (S.) temporal lobe and the amygdala when viewing the romantic partner as compared to the stranger. Right panel: The difference in empathy ratings between the romantic partner and stranger (romantic partner – stranger) was calculated, demeaned and regressed onto the mean effect (left panel). Higher empathy ratings for the romantic partner were associated with greater activation of the dorsomedial precuneus ($R^2 = 30\%$, $p = .002$). There were no significant brain correlations between empathy for strangers (as compared to romantic partner). Brain areas are delineated as depicted from left to right each image. Slice locations correspond to standard stereotaxic space.

Functional MRI Session

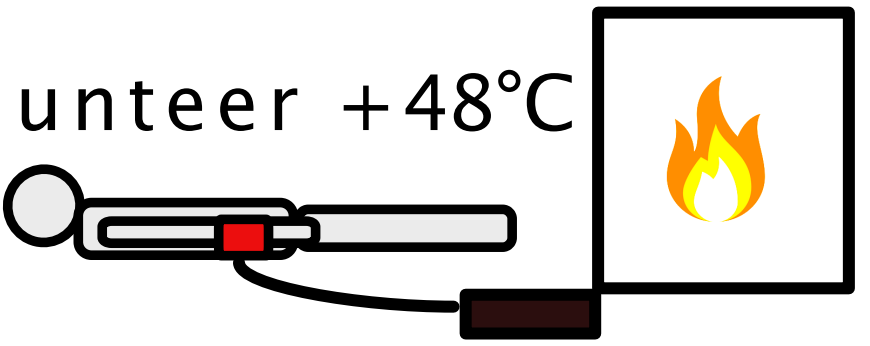
1. Resting state BOLD fMRI scan



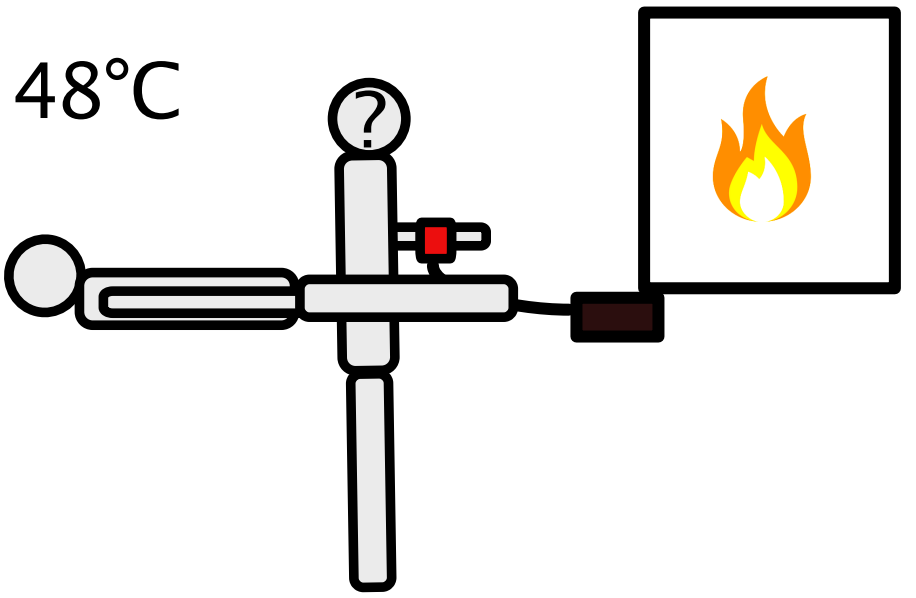
2. Female Volunteer +35°C



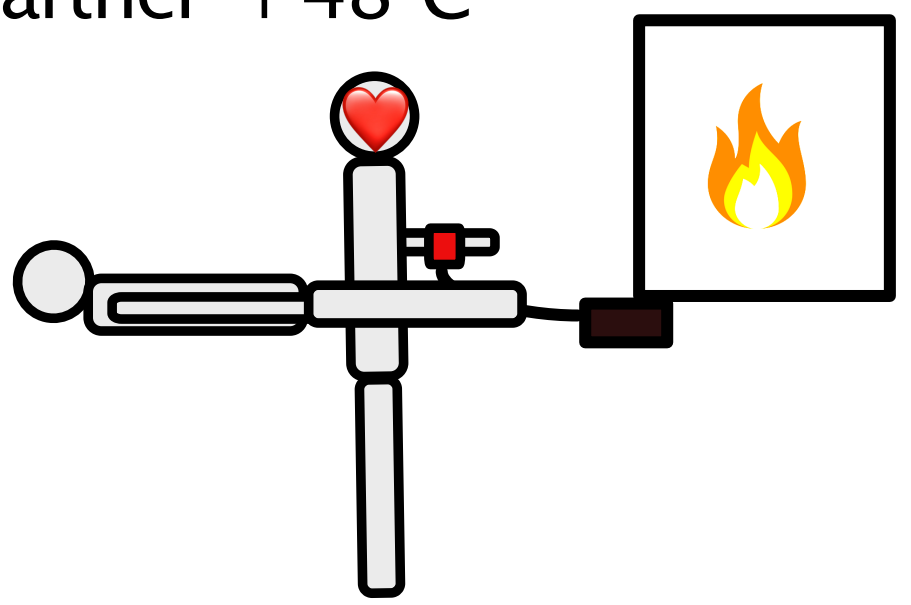
3. Female Volunteer +48°C

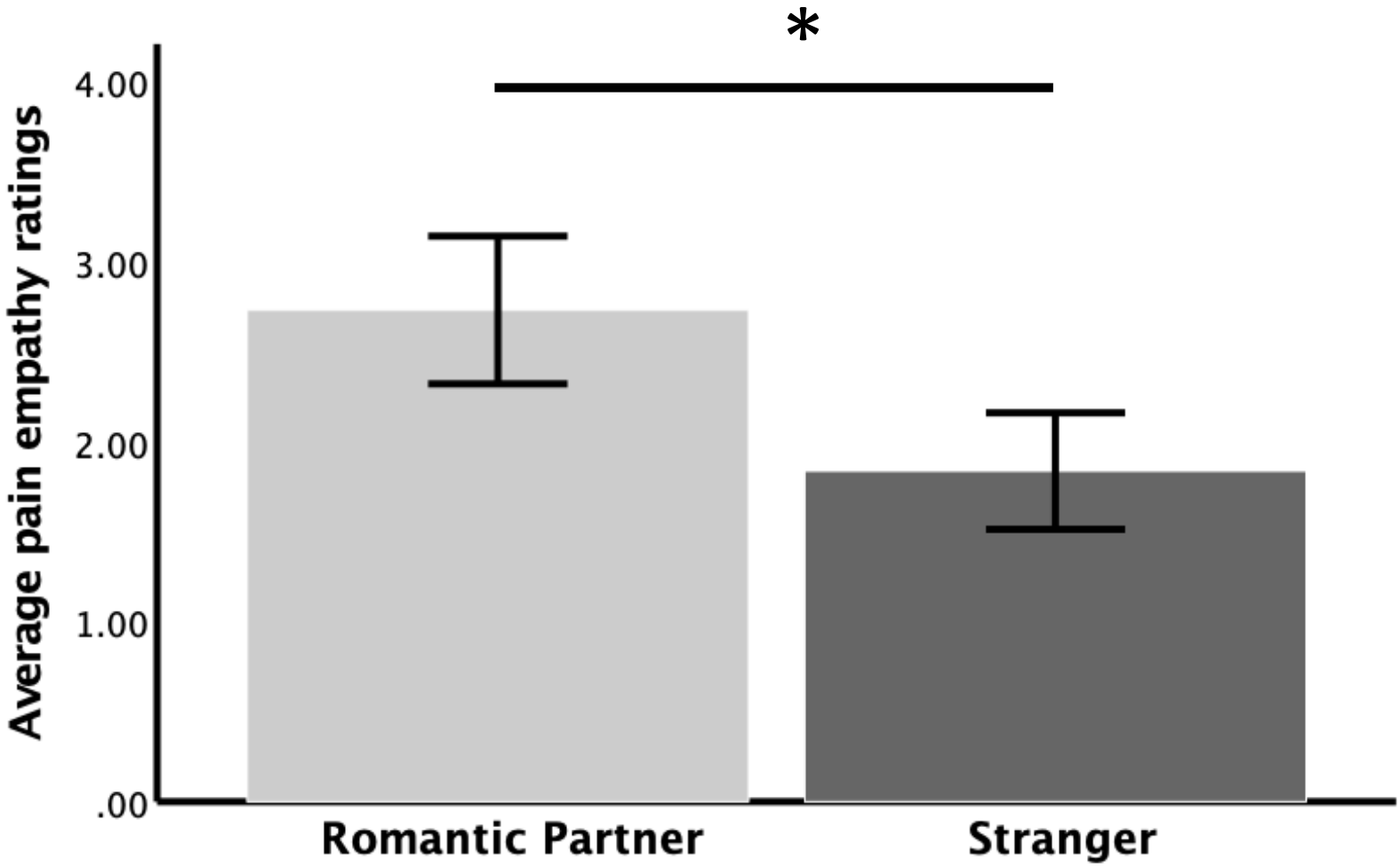


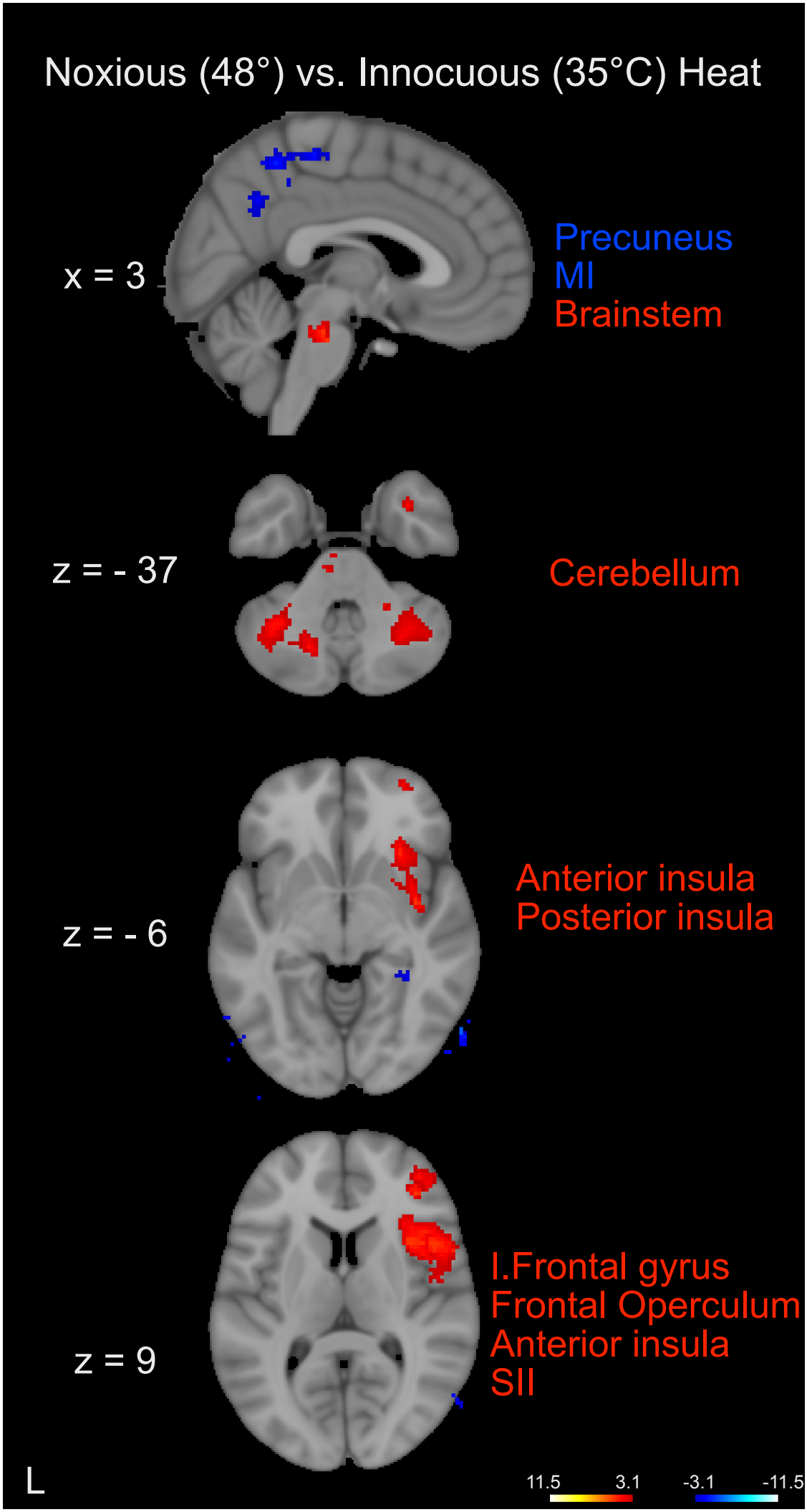
4. Stranger +48°C

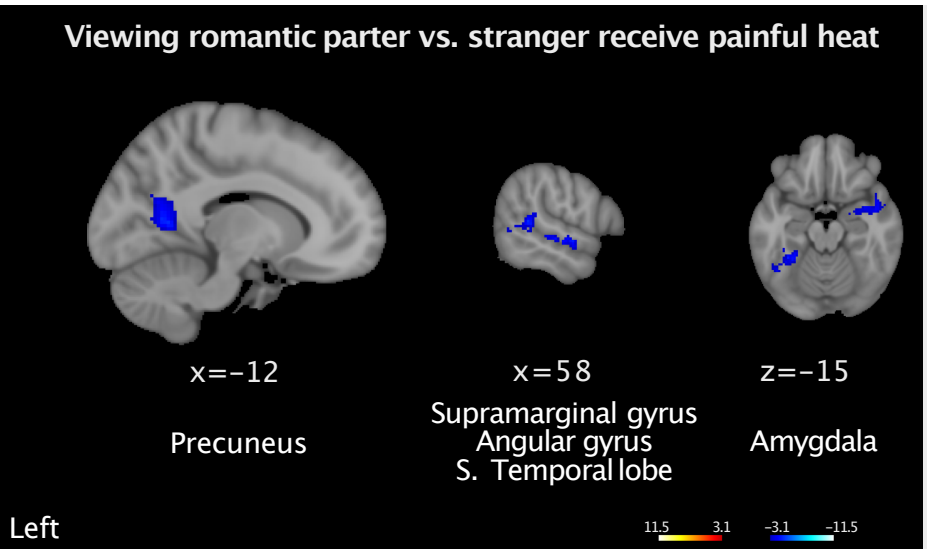


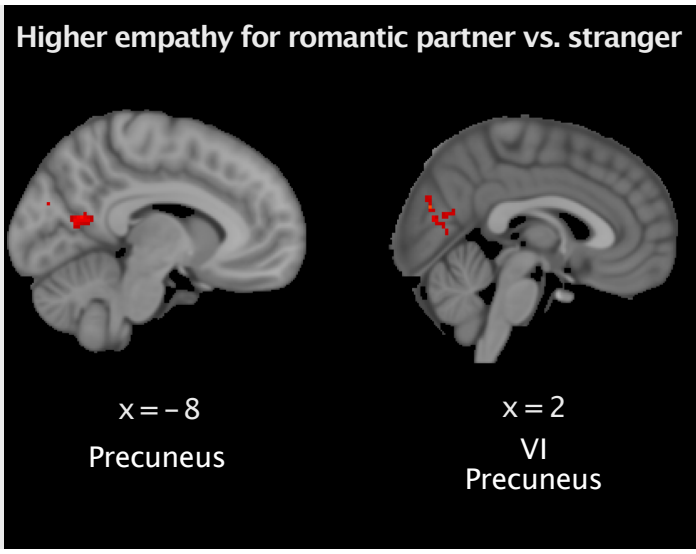
5. Romantic Partner +48°C




*
4.00
3.00
2.00
1.00
.00
Average pain empathy ratings
Romantic Partner
Stranger


Noxious (48°) vs. Innocuous (35°C) Heat
x = 3
Precuneus
MI
Brainstem
z = - 37
Cerebellum
z = - 6
Anterior insula
Posterior insula
z = 9
I.Frontal gyrus
Frontal Operculum
Anterior insula
SII
L
11.5
3.1
-3.1
-11.5


Viewing romantic parter vs. stranger receive painful heat
x=-12
Precuneus
x=58
Supramarginal gyrus
Angular gyrus
S. Temporal lobe
z=-15
Amygdala
Left
11.5
3.1
-3.1
-11.5


Higher empathy for romantic partner vs. stranger
x=-8
Precuneus
x=2
VI
Precuneus