Emotion

1528-3542/16/$12.00 http://dx.doi.org/10.1037/emo0000258

Neural Substrates and Social Consequences of Interpersonal Gratitude: Intention Matters

Hongbo Yu, Qiang Cai, Bo Shen, Xiaoxue Gao, and Xiaolin Zhou
Peking University

Voluntary help during a time of need fosters interpersonal gratitude, which has positive social and personal consequences such as improved social relationships, increased reciprocity, and decreased distress. In a behavioral and a functional magnetic resonance imaging (fMRI) experiment, participants played a multiround interactive game where they received pain stimulation. An anonymous partner interacted with the participants and either intentionally or unintentionally (i.e., determined by a computer program) bore part of the participants' pain. In each round, participants either evaluated their perceived pain intensity (behavioral experiment) or transferred an amount of money to the partner (fMRI experiment). Intentional (relative to unintentional) help led to lower experience of pain, higher reciprocity (money allocation), and increased interpersonal closeness toward the partner. fMRI revealed that for the most grateful condition (i.e., intentional help), value-related structures such as the ventromedial prefrontal cortex (vmPFC) showed the highest activation in response to the partner's decision, whereas the primary sensory area and the anterior insula exhibited the lowest activation at the pain delivery stage. Moreover, the vmPFC activation was predictive of the individual differences in reciprocal behavior, and the posterior cingulate cortex (PCC) activation was predictive of self-reported gratitude. Furthermore, using multivariate pattern analysis (MVPA), we showed that the neural activation pattern in the septum/hypothalamus, an area associated with affiliative affect and social bonding, and value-related structures specifically and sensitively dissociated intentional help from unintentional help conditions. These findings contribute to our understanding of the psychological and neural substrates of the experience of interpersonal gratitude and the social consequences of this emotion.

Keywords: gratitude, help, intention, interpersonal paradigm, multivariate pattern analysis

Supplemental materials: http://dx.doi.org/10.1037/emo0000258.supp

Being grateful for receiving intentional help is an important and almost universal feature of human sociality (McCullough, Kilpatrick, Emmons, & Larson, 2001). The literature has identified certain characteristic features of this emotion. Like many other positive emotions, gratitude may serve to build up individual's physical and social resources (Emmons & McCullough, 2003; Fredrickson, 2004), while also mitigating against aversive experiences such as pain and distress (Algoe & Stanton, 2012; Roberts, 2004). Moreover, as a social emotion, gratitude also has positive social consequences. For instance, gratitude helps improve social relationships (e.g., interpersonal closeness) by encouraging trust and reciprocal/prosocial behavior (Algoe, 2012; Algoe, Haidt, & Gable, 2008; Bartlett & DeSteno, 2006; McConnell, 2016; Tsang, 2006). Therefore, gratitude has been labeled "the parent of all other virtues" (Cicero, 1851, p. 139) and the "sentiment which most immediately and directly prompts us to reward" (A. Smith, 1795/2002, p. 79).

Given the significance of interpersonal gratitude, our understanding of the neurobiology of the experience of gratitude and its consequences is rather inadequate. Recently, Fox and colleagues (2015) made seminal progress along this line by combining a script-based imagination paradigm and functional magnetic resonance imaging (fMRI). In their study, the participants were asked to imagine themselves as the survivors of the Holocaust and to evaluate their gratitude in each situation. They found that gratitude ratings positively correlated with the neural activation in brain regions associated with valuation (e.g., the ventromedial prefrontal cortex, vmPFC), suggesting that the brain circuitry for value and positive emotion accompanies the experience of gratitude (see also Zahn et al., 2009). However, the script-based paradigm has limited ability to address questions regarding how receiving help and feeling grateful may influence an individual's social relationship

Hongbo Yu, Qiang Cai, Bo Shen, and Xiaoxue Gao, Center for Brain and Cognitive Sciences and Department of Psychology, Peking University; Xiaolin Zhou, Center for Brain and Cognitive Sciences and Department of Psychology, Key Laboratory of Machine Perception (Ministry of Education), Beijing Key Laboratory of Behavior and Mental Health, and PKU-IDG/McGovern Institute for Brain Research, Peking University.

The first two authors contributed equally to this study.

This work was supported by Natural Science Foundation of China (91232708, 31630034) and National Basic Research Program of China (973 Program: 2015CB856400). We thank Yang Hu, Lei Li, and Li Zhang and Li Hu for their help in carrying out the experiments. We are also very grateful to Jinting Liu for her help in data analysis and to the two anonymous reviewers, to Catherine Jan, Philip Blue, Tor Wager, Glenn Fox, and Ilona de Hooge for enlightening discussions and helpful comments on a previous version of the manuscript.

Correspondence concerning this article should be addressed to Xiaolin Zhou, Department of Psychology, Peking University, 5 Yiheyuan Road, Beijing 100871, China. E-mail: xz104@pku.edu.cn

and reciprocal behaviors toward the benefactor. There is also concern about the potential differences in the neural processing between third-person (vicarious) and first-person emotional experiences (Schilbach et al., 2013). Here, we developed a novel interpersonal task to elicit gratitude and measured its neural and behavioral consequences.

Social psychologists and philosophers have shown that the benevolent intention embedded in the help/gift is the essence of interpersonal gratitude, and it is such intention that distinguishes gratitude situations from other gift-giving situations, such as accepting bribery or winning a lottery (Berger, 1975; McConnell, 1993; Tesser, Gatewood, & Driver, 1968). These findings are in line with the words of the stoic philosopher Seneca, who points out, “what matters is not the deed or gift but the mentality behind them” (Seneca, 1995, p. 202). In the current study, we created different levels of gratitude by manipulating the intention of the benefactor. The participants received a pain stimulation on each trial, and an anonymous partner (confederate) could intentionally or unintentionally bear (i.e., take on) part of the stimulation for the participants. The participants either rated their perceived pain intensity (behavioral experiment) or allocated money to the partner (fMRI experiment). We predicted that intentional help would produce the highest feelings of gratitude, interpersonal closeness, and monetary reciprocity, while decreasing the subjective intensity of pain. Neurally, based on previous studies on gratitude (Fox, Kaplan, Damasio, & Damasio, 2015; van den Bos, McClure, Harris, Fiske, & Cohen, 2007; Zahn et al., 2009), we predicted that the brain regions associated with valuation (e.g., vmPFC or subgenual cingulate) should show the highest activation when intentional help is given, while the activation of pain and negative affect-related regions (e.g., insula) should be attenuated. We also hypothesized that, given gratitude’s role of creating and strengthening social bond both among kin and nonkin (Algoe, 2012), the brain structures associated with affiliative affect and social bonding (e.g., the septum/hypothalamus; see Moll et al., 2012; Rüsch et al., 2014) should encode information about gratitude.

Method

Participants

The behavioral experiment was composed of 15 participants (12 women, 19–22 years of age), and the fMRI experiment was composed of 31 participants. All were graduate and undergraduate students who were right-handed, with normal or corrected-to-normal vision, and no history of neurological problems. Four participants from the fMRI experiment were excluded from data analysis because of excessive head motion, leaving in the sample 27 participants (16 women, mean age 22 years, age range 19–25 years). Informed written consent was obtained from each participant before the test. This study was carried out in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Department of Psychology, Peking University.

Overview of the Experimental Design

In two experiments, the participants interacted with three anonymous partners, who were confederates of the experimenters and whose behaviors were predetermined. To ensure that the participants believed the experimental settings, we took pictures of the participants’ and the confederates’ faces before the start of the

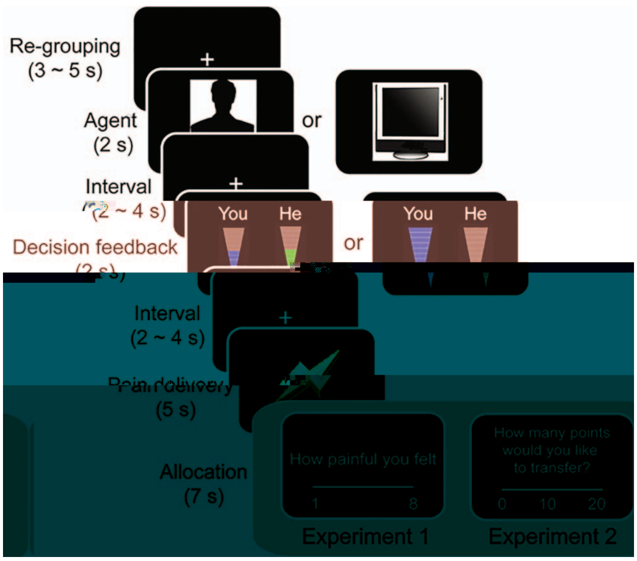

Figure 1. Experimental design and procedure. Stimuli presented in the behavioral and the functional magnetic resonance imaging (fMRI) experiments. Note that the timing presented was the parameters used in the fMRI experiment. See the online article for the color version of this figure.

bear in that trial. After another variable interval, pain stimulation was delivered to the participant (and the partner, ostensibly). After the pain stimulation, the participants were asked to rate stimulation on a discrete 1–8 scale.

The experiment had a 2 (decision agent: Human vs. Computer) × 2 (decision: Share vs. NoShare) factorial design, with the four conditions being partner deciding to share pain (Share_Hum), partner deciding not to share (NoShare_Hum), computer deciding to share (Share_Com), and computer deciding not to share (NoShare_Com). We acknowledge that the "decision" factor (Share vs. NoShare) is related to stimulation intensity and may be confounded with pain expectancy (Atlas & Wager, 2012), as Share decision was always associated with low-intensity stimulation. For this reason, we did not directly compare conditions across the two levels of decision (i.e., pain intensity level). Our inferences relied on the interaction between Agent (Human vs. Computer) and Decision (Share vs. NoShare) or the comparison between Human Share and Computer Share, both in Experiment 1 and Experiment 2, because pain intensity and expectancy were balanced in these comparisons. Note that in the Computer conditions, just as in the Human conditions, it was the partner who bore the pain stimulation if the decision was Share. The difference between Human and Computer conditions was that in the former it was the partner who voluntarily decided whether to share the pain for the participants (i.e., intentional), while in the latter the decision was made by a computer program (i.e., unintentional). Our hypothesis concerning subjective pain intensity was that on the one hand, intentional/voluntary help (i.e., Human Share) would decrease the perceived pain intensity, relative to unintentional sharing (i.e., Computer Share); on the other hand, intentionally/voluntarily refusing to help (i.e., Human NoShare) would increase the pain intensity perceived, relative to unintentional no help (i.e., Computer NoShare).

Each condition contained eight trials. Trials of different conditions were mixed pseudorandomly so that no more than three consecutive trials were from the same condition. Note that in the game, the role of the participant and the role of the partners were asymmetric: the participant was always the one who would receive help (or no help) from the partners, whereas the partners were always the ones who decided (or were forced) to help. After the behavioral task, the participants were also asked to rate, on a scale of 1 (*not at all*) to 9 (*very strong*), their feeling of gratitude, closeness, anger, guilt, shame, and unpleasantness for the four conditions in the pain rating task.

Experiment 2 (fMRI experiment). Upon arrival, the participant was introduced to three partners (confederates). To make sure that the participant believed the experimental settings, we asked three confederates to meet the participant before the start of the experiment. During this short "warm-up" period, we took pictures of the participants' and the confederates' faces. We told them that the pictures would be used in the subsequent interactive game, in which each player would be able to see his or her own face on the screen as a representative of him or herself. Then the confederates were led to another testing room, leaving the participant in the MRI room. An intraepidermal needle electrode was attached to the left wrist of the participant for cutaneous electrical stimulation (Inui et al., 2002). Participant-specific pain threshold was calibrated and two levels of pain stimulation were set as 3 and 7 repeated pulses (with 0.5 ms duration of each pulse and a 50 ms interval between consecutive pulses) of epidermal electrical stimulation. The participant was then asked to rate the intensity of the two levels of pain stimulation on a scale of 0 (*no sensation*) to 10 (*intolerably painful*). The mean intensity ratings were (mean ± *SD*) 5.3 ± 1.2 and 7.1 ± 1.2 for the low and high intensity, respectively. All participants reported that the two levels of pain stimulation were clearly distinguishable.

The task for the participants during the scanning session was identical to Experiment 1, except that at the end of each trial, the participants were asked to transfer a portion of their 20 money points to their partner (who would ostensibly receive pain), with the knowledge that the partner did not know this procedure. This was to ensure that, at least from the participants' perspective, the partner did not help the participants solely because of strategic considerations, which might be characterized by such thoughts as "by helping the participants I can get money from him or her." Such thoughts may hinder the generation of genuine feelings of gratitude and may trigger the feeling of indebtedness, which is distinct from gratitude in important ways (Doi, 1981; McConnell, 1993; Watkins, Scheer, Ovnicek, & Kolts, 2006). The participants were explicitly informed that they would get at most 50 yuan (~$8) as a bonus, determined by their monetary points collected during the fMRI task, in addition to the 100 yuan show-up fee. They were also informed that the cumulative money points would be exchanged as a bonus for both the participants and the partners at the end of the experiment. There were 16 trials in each condition. Trials of different conditions were mixed pseudorandomly such that no more than three consecutive trials were from the same condition. As a manipulation check, after scanning, the participants were asked to rate the intensity of the pain stimulation and their feelings of gratitude, anger, guilt, shame, and unpleasantness for each of the four conditions in the scanning session on a 1–9 scale (1 = *not at all*, 9 = *very strong*). We also asked the participants to recall the intensity of pain they experienced in each of the four conditions on a scale of 0 (no sensation) to 10 (intolerably painful).

Neuroimaging data acquisition. Images were acquired using a Siemens 3.0 Tesla Trio scanner with a standard head coil at the Key Laboratory of Cognition and Personality (Ministry of Education) of Southwest University, China. T2-weighted functional images were acquired in 36 axial slices parallel to the AC-PC line with no interslice gap, affording full-brain coverage. Images were acquired using an EPI pulse sequence (TR = 2,200 ms, TE = 30 ms, flip angle = 90°, FOV = 192 mm × 192 mm, slice thickness = 3 mm). A high-resolution, whole-brain structural scan (1 mm^3 isotropic voxel MPRAGE) was acquired after functional imaging. The whole scanning session was divided into two equal-length runs, each lasted about 15 min.

Preprocessing of neuroimaging data. fMRI data preprocessing was carried out using FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/) in the following steps: (a) motion correction using MCFLIRT (Jenkinson, Bannister, Brady, & Smith, 2002); (b) nonbrain removal using BET (S. M. Smith, 2002); (c) computing frame-wise displacement (FD) and temporal derivative of the root mean square variance over voxels (DVARS) using six motion correction parameters generated by motion correction; (d) spatial smoothing using a Gaussian kernel of FWHM 8 mm; and (e) normalizing the grand-mean intensity over the entire 4D dataset by a single multiplicative factor and a high-pass temporal filtering (Gaussian-weighted least-squares straight line fitting, with $\sigma = 64$ s, corresponding to a cutoff period of 1/128 Hz). This same high-pass filter was applied to the design matrix for analyzing the fMRI time-series. All functional images were segmented, normalized to Montreal Neurological Institute (MNI) space, and resampled to 3 × 3 × 3 isotropic voxel using SPM8 (the Statistical Parametric Mapping software; Wellcome Trust Department of Cognitive Neurology, London, United Kingdom). Four participants were excluded from further analysis because of excessive head motion (either FD > 0.5 or DVARS > 0.5; cf. Chen, Jimura, White, Maddox, & Poldrack, 2015).

Univariate analysis of neuroimaging data. Whole-brain analysis was conducted using a univariate GLM approach with FSL. Analyses were first conducted at the individual subject level. The event-related design was modeled using a canonical hemodynamic response function. Eight critical regressors were defined: four corresponded to decision feedback and the other four corresponded to pain delivery. In addition, the presentation of partner/computer cue, the response period, and stimulation delivery were also modeled with box-car regressors. Nuisance repressors included run indicators, all six motion correction parameters, FD, and DVARS. All the regressors except nuisance regressors in the individual-level model were convolved with a double-γ hemodynamic response function. At the group level, analyses were performed using the FLAME 1 mixed-effects model of FSL and corrected by cluster-based random field theory (Worsley, 2001). The statistical threshold was $z > 2.3$ at voxel-level and a family wise error corrected cluster significance threshold of $p = .05$ (whole-brain or within predefined ROIs using small-volume-correction; cf. Chen et al., 2015). For the decision feedback (outcome) stage, the interaction contrast was defined as "Hum_Share-Com_Share > Hum_NoShare-Com_NoShare". For the pain delivery stage the interaction contrast was defined as "Com_Share-Hum_Share > Com_NoShare-Hum_NoShare". Three regions-of-interest masks were defined. The ventromedial prefrontal cortex (vmPFC) was defined as a sphere (radius = 10 mm) around the coordinates reported in a meta-analysis of the valuation system (MNI system: [2, 46, −8]; Bartra, McGuire, and Kable, 2013). The ventral tegmental area (VTA) mask was defined as a sphere (radius = 10 mm) around the coordinates reported in a human fMRI study focusing on VTA's in reward processing (MNI system: [2, −12, 10]; Pecina et al., 2014). The septum mask was defined by an anatomical template reported in Moll et al. (2012; courtesy of Dr. Jorge Moll and colleagues). The aforementioned interaction contrasts were also carried out within these ROI masks with small-volume correction. To illustrate the activation patterns, parameter estimates were extracted from the activation foci (e.g., vmPFC, left insula, VTA, and the primary sensory area).

As we observed a number of interparticipant correlations between the brain (e.g., interaction in vmPFC and PCC activations) and behavioral responses (e.g., interaction in gratitude rating and money allocation) to intentional help (see Results), we went one step further to test whether the association between brain activations and monetary allocation (i.e., reciprocity) could be mediated by grateful feelings. To test this indirect pathway, we bootstrapped the indirect effect 20,000 times using the SPSS version of INDIRECT macro (http://www.afhayes.com/) developed by Preacher and Hayes (2008). In these tests, we set the interaction in the vmPFC or the PCC activations as the independent variable, the interaction in gratitude rating as mediating variable, and the interaction in money allocation as the dependent variable.

Multivariate pattern analysis of imaging data. We asked whether the brain uses specific pattern to represent social information (i.e.,Human vs. Computer). To this end, we trained multivariate brain patterns to dissociate Hum_Share versus Com_Share, and Hum_NoShare versus Com_NoShare, as social emotions like gratitude and resentment are only present in the Human conditions and not in the Computer conditions. These findings would supplement our univariate results. We used linear SVMs (Hastie, Tibshirani, & Friedman, 2001) to train multivariate pattern classifiers for Share trials (Hum_Share vs. Com_Share) and NoShare trials (Hum_NoShare vs. Com_NoShare). We trained the classifiers both on the whole-brain level and within a number of regions of interest that are particularly relevant for emotion processing, including the vmPFC, septum, VTA, middle cingulate cortex (MCC), and the periaqueductal gray (PAG). The VTA and vmPFC are core regions in the reward system responsible for computing and updating the value of an object or action, both social and nonsocial (Schultz, 2015). The MCC and PAG are critical nodes in the "pain-matrix" and also respond to physical and social stressors (Buhle et al., 2013). The septum/hypothalamus plays a crucial role in affiliative affect, interpersonal closeness, and attachment (Inagaki & Eisenberger, 2012; Moll et al., 2012; Strathearn, Fonagy, Amico, & Montague, 2009). We hypothesized that gratitude, as a way to improve interpersonal relationship, should be encoded in the septum/hypothalamus. For the ROI-based analysis, a priori voxels within a 10 mm-radius sphere centered at the coordinates reported in previous studies, were selected for training and testing. For the whole-brain analysis, we thresholded the weight-map using $q < 0.05$ (FDR) to reveal the voxels that contributed the most to the classification (cf. Wager et al., 2013). It should be noted that all the voxels in the training data contributed to the prediction. We thresholded the weight-map for illustration purposes.

The SVMs were implemented using custom Matlab code based on the Spider toolbox (http://people.kyb.tuebingen.mpg.de/spider). The pattern classifiers were trained on first-level β images corresponding to the outcome stage for the two pairs of conditions (i.e., Hum_Share vs. Com_Share and Hum_NoShare vs. Com_NoShare) to separately discriminate "intentional help/genuine gratitude" and "intentional not-help/genuine resentment" from the respective two unintentional conditions. With a leave-one-participant-out cross-validation method, we calculated the classification accuracy of the SVM classifiers using the forced-choice test (cf. Chang, Gianaros, Manuck, Krishnan, & Wager, 2015; Wager et al., 2013; Woo et al., 2014). We calculated the accuracy for Hum_Share versus Com_Share and for Hum_NoShare versus Com_NoShare.

Results

Behavioral Results

Experiment 1 (behavioral). As a manipulation check, we first treated emotion type as a factor in a repeated measures analysis of variance (ANOVA) and found a significant three-way interaction (Type × Decision × Agent), $F(4, 56) = 7.42$, $p = 7.30 \times 10^{-5}$, suggesting that these emotions were not equally elicited by our manipulation. We then separately tested the effects for each type of emotion (Table 1). Specifically, the gratitude rating exhibited a significant Decision × Agent interaction, $F(1, 14) = 18.33$, $p = .001$. To interpret these interaction effects, planned comparisons were conducted, yielding a significant difference between human and computer only for the Share conditions (Figure 2A, left panel). Confirming our prediction, the perceived closeness (Figure 2A, right panel) also showed a Decision × Agent interaction, $F(1, 14) = 5.54$, $p = .034$. Participants felt closer, $t(14) = 3.31$, $p = .005$ and more grateful, $t(14) = 4.70$, $p < .001$ to the partner when the partner voluntarily shared the stimulation than when the computer determined the sharing decision. These findings demonstrated the validity of our paradigm to induce gratitude and suggested that receiving voluntary help can enhance interpersonal closeness and reduce pain. More important, the pain ratings also exhibited a significant Decision × Agent interaction, $F(1, 14) = 5.52$, $p = .034$ (Figure 2A, middle panel). Participants tended to feel less pain in the Share_Hum than in the Share_Com condition, and more pain in the NoShare_Hum than in the NoShare_Com condition, although post hoc tests of simple effects for these comparisons did not reach significance.

Experiment 2 (fMRI). A statistical procedure similar to that of Experiment 1 was carried out for the postscan manipulation check. We first treated emotion type as a factor in a repeated measures ANOVA and found a significant three-way interaction (Type × Decision × Agent), $F(4, 104) = 14.02$, $p = 1 \times 10^{-6}$. Given this interaction, we then tested the effects for each type of emotion separately (Table 2). The pattern of gratitude rating was similar to Experiment 1, indicating that our manipulation of gratitude was valid in the fMRI experiment (Figure 2B, left panel).

As for the money allocation (Figure 2B, right panel), the participants allocated significantly more to the partner in the Share than in the NoShare conditions, $F(1, 26) = 55.74$, $p < .001$. The participants also allocated more to the partner in the Human than in the Computer conditions, $F(1, 26) = 4.66$, $p = .04$. More important, the interaction between decision and agent was significant, $F(1, 26) = 22.83$, $p < .001$. Planned t tests showed that the participants allocated more to the partner when the partner voluntarily chose to share the pain stimulation than when the computer made the share decision, $t(26) = 4.59$, $p < .001$. In contrast, the participants allocated less to the partner when the partner voluntarily decided not to share the pain stimulation than when the computer forced the partner not to share, $t(26) = -3.17$, $p = .004$. Moreover, the effect of interaction in allocation ("Hum_Share—Com_Share − Hum_NoShare—Com_NoShare") positively correlated with the same interactive effect in the gratitude rating, $r = .40$, $p = .04$, indicating that the more the participants felt grateful, the more they "returned a favor" by allocating money. This correlation further confirmed that our online measure (i.e., money allocation) captured the affective responses elicited by our interactive task.

Consistent with Experiment 1, the postscan pain recall (Figure 2B, middle panel) also exhibited a decision-by-agent interaction, $F(1, 26) = 10.34$, $p = .003$. Planned t test showed that participants recalled less painful experience when the partner voluntarily shared the pain stimulation than when the computer forced the partner to share, $t(26) = -2.60$, $p = .015$). A reversed trend was observed when the decision was NoShare, $t(26) = 1.98$, $p = .059$).

Table 1
Behavioral Results for Experiment 1 (Behavioral)

Item	Share_Hum	Share_Com	NoShare_Hum	NoShare_Com	Interaction $F(1, 14)$
Online measure					
Pain intensity	3.1 (.2)	3.3 (.2)	5.8 (.3)	5.5 (.4)	5.52*
Posttask measures					
Closeness	5.1 (.5)	3.7 (.4)	2.3 (.5)	2.5 (.3)	5.54*
Gratitude	6.6 (.5)	4.6 (.5)	2.3 (.4)	2.4 (.5)	18.33***
Unpleasantness	1.5 (.2)	2.1 (.4)	5.1 (.5)	4.3 (.3)	5.91*
Anger	1.4 (.2)	1.9 (.3)	4.0 (.6)	3.3 (.5)	3.00
Shame	1.7 (.3)	1.7 (.3)	1.3 (.2)	1.7 (.4)	.79
Guilt	2.6 (.5)	1.8 (.3)	1.3 (.2)	1.3 (.2)	3.03

Note. *SE*s are shown in parentheses. Significant two-way interaction was denoted by * $p < .05$ and *** $p < .001$.

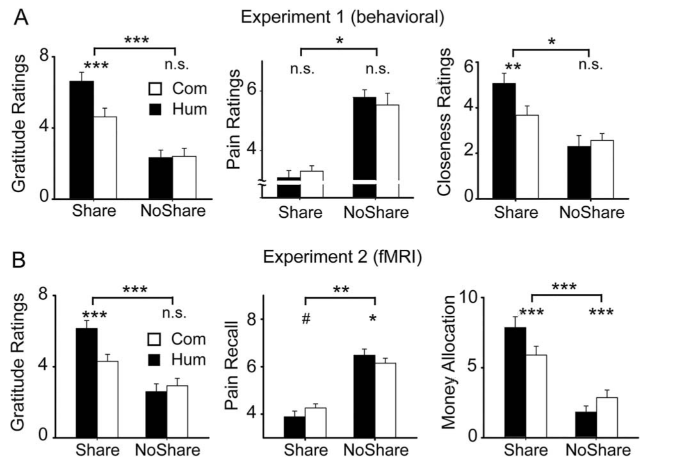

Figure 2. Behavioral results for the behavioral experiment (A) and for the functional magnetic resonance imaging (fMRI) experiment (B). Error bars indicate SEs. Asterisks on the top of the graph indicate significant Decision (Share vs. NoShare) by Agent (Human vs. Computer) interaction (* $p < .05$, ** $p < .01$, *** $p < .001$). Asterisks below indicate significance in a planned t test (# $p < .1$, * $p < .05$, ** $p < .01$, *** $p < .001$).

Neuroimaging Results

Univariate analysis of fMRI data. On the whole-brain level, the interaction contrast “Hum_Share—Com_Share > Hum_NoShare—Com_NoShare” corresponding to the decision outcome stage only revealed activations in the supplementary motor area (SMA) and the left precentral gyrus (see Table 3). Given that all the participants were asked to respond with their right hand, this activation may reflect motor preparation for the allocation stage. The same contrast revealed significant activation in the vmPFC mask (MNI coordinates: [0, 38, −8]; $k = 14$; $p_{FWE} = 0.015$, small-volume corrected; Figure 3A) and in the VTA mask (MNI coordinates: [3, −13, −5]; $k = 22$; $p_{FWE} = 0.021$, small-volume corrected; Figure 3A). Moreover, the effect size of the interaction in the vmPFC parameter estimates positively correlated with the effect size of the interaction in gratitude ratings, $r = .41$, $p = .034$. To further investigate the relationship between the brain and behavioral responses to intentional help, we tested the indirect pathway from vmPFC via gratitude to money allocation (i.e., reciprocity). Results supported the existence of the indirect pathway via gratitude: the indirect effect estimate = 0.19, $SE = 0.10$, 95% confidence interval was [0.01, 0.43] (Figure 3C).

We further carried out whole-brain exploratory parametric analyses. For the interaction contrast corresponding to the decision outcome stage, we added the participants’ gratitude trait (as measured by The Gratitude Questionnaire-6, GQ-6; McCullough et al., 2001) and the interaction effect in postscan gratitude rating as group-level covariates in two separate models, respectively. As can be seen from Figure 3D, the activation magnitude in the PCC and the precuneus positively correlated with the gratitude trait (red cluster), while the activation in the PCC positively correlated with the interaction effect of the gratitude rating (blue cluster). Conjunction analysis (Nichols, 2007) showed that these two contrasts commonly activated the PCC. This area has been showed to be responsible for attracting attention to valuable items (Grueschow, Polania, Hare, & Ruff, 2015). Using the aforementioned method (Preacher & Hayes, 2008), we found that the indirect pathway from trait gratitude to gratitude self-reports via PCC activation did exist, with indirect effect estimate = 0.08, $SE = 0.05$, 95% confidence interval was [0.01, 0.21].

As for the pain delivery stage, we first checked the pain perception effect by carrying out the main effect contrast “NoShare > Share.” This contrast revealed the standard “pain matrix,” including the primary somatosensory cortex, the anterior cingulate cortex, thalamus, and bilateral insula (supplemental material Figure 1A). We also obtained the “Pain” feature map from the Neurosynth (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011) and calculated pattern expression[1] for each of the four pain-related maps in our study. High-pain conditions (i.e., Hum_NoShare, Com_NoShare) had significantly larger pattern expression, indicating that the brain states in those conditions were more similar to a pain state than the low-pain conditions (i.e., Hum_Share, Com_Share; supplemental material Figure 1B). These findings confirmed that our pain manipulation was effective and GLM settings were not flawed. Then we carried out the interaction contrast “Com_Share—Hum_Share > Com_NoShare—Hum_NoShare” and found activations in the bilateral anterior insula, the right postcentral gyrus (contralateral to the pain delivery site), and the SMA (Table 3; Figure 3B). As can be seen, the insula and postcentral gyrus activations elicited by pain stimulation were suppressed in the intentional help condition, consistent with a number of previous studies on how positive social interaction act to decrease the brain processing of pain (e.g., Coan, Schaefer, & Davidson, 2006; DeWall et al., 2010; Eisenberger et al., 2011).

Decoding Intentional Help From the Multivariate Activation Pattern

We first trained and tested multivariate patterns on the whole-brain level. The classifier trained to dissociate the Share conditions (Hum_Share vs. Com_Share) can classify these two conditions in a leave-one-participant-out cross-validation test with accuracy approaching 100%. When tested on the NoShare conditions, the accuracy dropped to chance level, indicating that the classifier was specific to positive social information (i.e., receiving voluntary help and feeling grateful). In a similar vein, the classifier trained to dissociate the NoShare conditions can classify the NoShare conditions with above-chance accuracy, but cannot dissociate the Share conditions (Figure 4B). As can be seen from Figure 4A, the caudate and posterior cingulate cortex, two regions of the valuation system, contributed significantly to dissociating intentional from unintentional help, suggesting that positive social interaction may have values over and above pain-reduction.

For the ROI-based analysis, we found that the pain- and stress-related regions (i.e., the MCC and PAG) could not dissociate the Share or NoShare conditions. The value- and affiliation-related regions (i.e., the vmPFC, VTA, and septum) could dissociate the Share conditions (Hum_Share vs. Com_Share), but not the NoShare condi-

[1] The pattern expression is a scalar value reflecting the extent to which a brain activation pattern is similar to a prototypical brain state as defined by a classifier or feature map (Wager et al., 2013). To calculate the strength of pattern expression, we used the dot-product of a vectorized activation map with the “Pain” feature map.

Table 2
Behavioral Results for Experiment 2 (fMRI)

Item	Share_Hum	Share_Com	NoShare_Hum	NoShare_Com	Interaction $F(1, 26)$
Online measure					
Money allocation	7.7 (.8)	5.7 (.6)	1.7 (.4)	2.8 (.5)	22.83***
Posttask measures					
Pain recall	3.9 (.2)	4.3 (.2)	6.5 (.3)	6.1 (.2)	10.34***
Gratitude	6.1 (.4)	4.3 (.4)	2.6 (.4)	2.9 (.3)	25.00***
Unpleasantness	1.5 (.2)	1.9 (.3)	5.0 (.5)	4.0 (.4)	10.74**
Anger	1.4 (.2)	1.6 (.2)	3.6 (.5)	2.8 (.4)	8.15**
Shame	1.5 (.2)	1.6 (.3)	1.4 (.2)	1.6 (.2)	1.00
Guilt	2.5 (.4)	1.9 (.3)	1.7 (.3)	1.6 (.2)	2.89

Note. *SE*s are shown in parentheses. Significant two-way interaction was denoted by ** $p < .01$ and *** $p < .001$.

tions (see Figure 5). We applied the Share classifiers (i.e., the multivariate pattern dissociating Hum_Share vs. Com_Share) to β the maps corresponding to the four conditions and obtained pattern expressions for these classifiers. As can be seen from Figure 5, the mode of the pattern expressions is consistent both with the behavioral measures (gratitude rating and money allocation) and the neural activation in the valuation system. These findings indicated that the value- and affiliation-related brain structures contained information specific and sensitive to intentional help and interpersonal gratitude.

Discussion

The feeling and expression of gratitude as a response to others' help/gift is a common feature of human sociality and a basic moral principle in many cultures (Mauss, 1950/2002; McConnell, 1993; McCullough et al., 2001). Although theoretical and psychological studies on the nature and antecedence of gratitude are abundant (for a collection of these work, see Emmons & McCullough, 2004), the investigation into the neurobiology of gratitude is just beginning (Decety & Porges, 2011; Fox et al., 2015; Zahn et al., 2009). A number of features of our study allow for novel contributions to the understanding of the psychological and neural substrates of the feeling and expression of gratitude beyond the scope of the previous studies. First, instead of using scenario-based imagination, we adopted an interpersonal interactive (or "reactive," in the terminology of Hari, Henriksson, Malinen, & Parkkonen, 2015) paradigm where the participants interacted with real human partners and received real help (or "gift"). Given the social nature of interpersonal gratitude, it is crucial to elicit and measure gratitude in a social context and to make sure that the participants experience such emotion from a first-person perspective (Schilbach et al., 2013). Compared with a scenario-based approach, "being a participant in an interaction may entail a commitment towards being responsive created by important difference in the motivational foundations of 'online' and 'offline' social cognition" (Pfeiffer, Timmermans, Vogeley, Frith, & Schilbach, 2013). Recent studies combining interpersonal paradigms and neuroimaging have greatly advanced our understanding of the neural and computational mechanisms of human social cognition and social emotions (e.g., Chang, Smith, Dufwenberg, & Sanfey, 2011; Crockett, Kurth-Nelson, Siegel, Dayan, & Dolan, 2014; Crockett et al., 2015; Koban, Corradi-Dell'Acqua, & Vuilleumier, 2013; Yu, Hu, Hu, & Zhou, 2014; Yu, Shen, Yin, Blue, & Chang, 2015). Second, because we elicited gratitude in an interactive context, we were able to quantify and examine the links between the experience of gratitude and the social consequences of this emotion, such as alleviated negative feelings in distressful and painful situations (Algoe & Stanton, 2012;

Table 3
Brain Activations Revealed by the Univariate Interaction Contrast

Regions	Hemisphere	Max *z*-value	Cluster size (voxels)	MNI coordinates		
Outcome stage						
vmPFC[a]	L/R	3.08	14	0	38	−8
SMA	L	2.73	28	12	5	55
Pre/postcentral	L	4.92	1228	−33	−13	55
Pain delivery stage						
Insula	R	2.95	56	33	23	1
Insula	L	3.32	75	−29	22	3
Pre/postcentral	R	4.07	738	45	8	31
Pre/postcentral	L	4.39	2268	−39	−7	52

Note. For the decision feedback (outcome) stage, the interaction contrast was defined as "Hum_Share-Com_Share > Hum_NoShare-Com_NoShare". For the pain delivery stage the interaction contrast was defined as "Com_Share-Hum_Share > Com_NoShare-Hum_NoShare". The statistical threshold was $z > 2.3$ at voxel-level and $p < .05$ cluster-corrected (whole-brain or within predefined ROIs).
[a] The vmPFC was revealed by an ROI-based contrast carried out within a 10 mm-radius sphere centered at the coordinates reported in Bartra et al. (2013). vmPFC = ventromedial prefrontal cortex; SMA = supplementary motor area; MNI = montreal neurological institute.

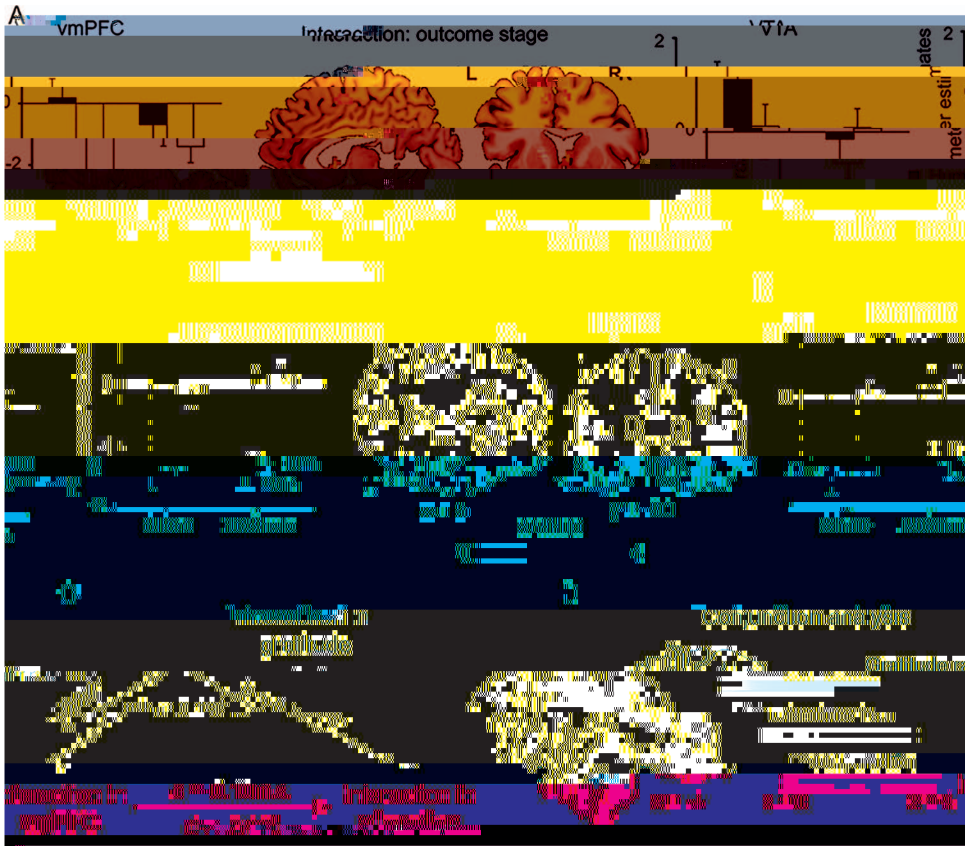

Figure 3. Results of the univariate analysis of functional magnetic resonance imaging (fMRI) data. (A) The statistical parametric map of the interaction contrast (“Hum_Share—Com_Share > Hum_NoShare—Com_NoShare”) corresponding to the decision outcome stage. (B) The statistical parametric map of the interaction contrast (“Com_Share—Hum_Share > Com_NoShare—Hum_NoShare”) corresponding to the pain delivery stage. (C) The indirect pathway from the neural processes related to receiving intentional help, via self-reported gratitude, to reciprocal behavior. (D) The statistical parametric map of the conjunction analysis. Activations in the red clusters positively correlated with individual gratitude trait while activations in the blue clusters positively correlated with the interaction effect of postscan gratitude self-report. Yellow-to-red clusters are the area commonly activated by the above two covariate analyses. Threshold for display was $z > 2.3$ uncorrected. Bar charts represent across-participant mean parameter estimates for all conditions for selected peak voxels. These charts served illustrative purpose only. Error bars represent SE. vmPFC = ventromedial prefrontal cortex; VTA = ventral tegmental area; Ins = insula; SI = primary sensory cortex. ** $p < .01$, * $p < 0.05$.

Huffman et al., 2014), improved social relationships (Algoe, 2012; Bartlett, Condon, Cruz, Baumann, & Desteno, 2012) and enhanced prosocial/reciprocal behaviors (McCullough & Tsang, 2004; Tsang, 2006), which are difficult to test with the scenario-based approach.

Gratitude, Reciprocity, and Reward System

A grateful beneficiary has positive evaluations about the benefactor’s helping behavior and benevolent intention (Fredrickson, 2004; McConnell, 2016). Here we found that the reward-related brain structures (e.g., vmPFC, VTA, and caudate) exhibited the highest activation in the most grateful condition (Figure 3A), had predictive power to sensitively and specifically dissociate intentional versus unintentional help (Figure 5D and 5G), and showed positive association with gratitude ratings across participants (Figure 3C). Thus, the positive feeling/evaluation interpretation is in line with the role of the reward system in computing abstract subjective value (Bartra et al., 2013; Rangel, Camerer, & Montague, 2008) and representing praiseworthy social intention (Cooper, Kreps, Wiebe, Pirkl, & Knutson, 2010; Izuma, Saito, & Sadato, 2008; Ruff & Fehr, 2014), including gratitude (Fox et al., 2015). It should be noted, however, that the subregion of MPFC that is associated with gratitude ratings in Fox et al. (2015) is more dorsal relative to the typical value representation area (see Bartra et al., 2013) and also to the vmPFC identified in our study (Figure 3A). In contrast, another study that compares social versus nonsocial feedback using an interpersonal paradigm did identify the ventral part of MPFC (or the subgenual anterior cingulate cortex) as being more sensitive to the valence of feedback in social (participants’ being praised vs. punished by an interactive partner) than in nonsocial (participants’ being praised vs. punished by a

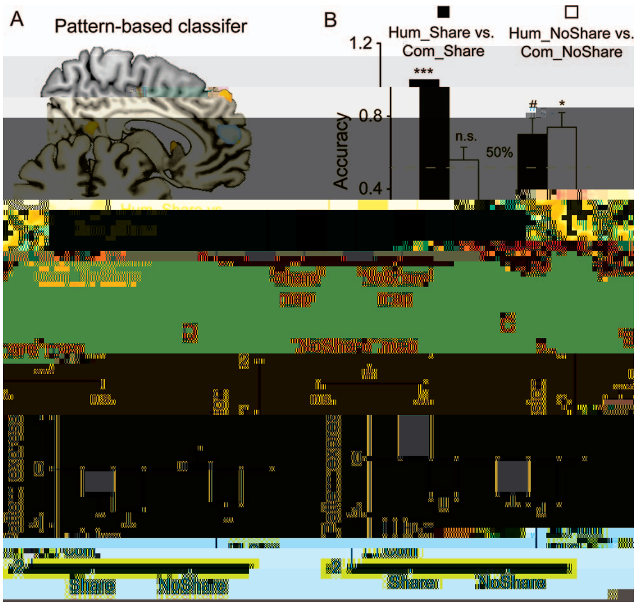

Figure 4. Results of the multivariate analysis at the whole-brain level. Panel (A) shows the whole-brain classifier maps, consisting of voxels whose activity reliably classify Share conditions (i.e., "Share" map; Orange) or NoShare (i.e., "NoShare" map; Blue) conditions. The maps show weights that exceed a threshold (a false discovery rate of $q < 0.05$) for display only; all weights were used in prediction. Panel (B) shows the accuracy of the Share map classifying Share and NoShare conditions (left two bars) and of the NoShare map classifying Share and NoShare conditions (right two bars). Panel (C) and (D) show the pattern expression of the two maps. Error bars represent SE. # $p < .01$, * $p < 0.05$.

computer program) context (van den Bos et al., 2007; compare their Figure 5A and 5C with our Figure 3A; see also Lin et al., 2012). This dissociation may be inherent in the design: in both van den Bos et al.'s (2007) study and in ours, the gift is delivered to the participants themselves (self-regarding value), while in Fox et al.'s (2015) study, the participants were asked to imagine situations in which other people received help (other-regarding value). Recently, it has been shown that the representation of self-regarding value and other-regarding value exhibit a ventral-dorsal gradient with self-regarding value being represented in a more ventral part and other-regarding value being represented in a more dorsal part of the MPFC (Nicolle et al., 2012; Sul et al., 2015). The discrepancy of the neural findings derived from scenario-based and interaction-based studies may also arise from the fact that the brain processes related to social cognition are modulated by the extent to which human participants perceive themselves as being involved in an ongoing interaction (Schilbach, 2010).

Feeling grateful and expressing it in some appropriate manner is a virtue of the beneficiary. Although people do not usually use money to express their gratitude to their friends and families (Ariely, 2010), it is not uncommon to use money between strangers, especially when money is the only way to do so (as in our experimental set-up). Our postscan gratitude ratings confirmed that money allocation is indeed associated with feelings of gratitude. Moreover, our data support the notion that gratitude is an intermediate step between the external reciprocal behaviors and the hidden brain processes of the benefactor's praiseworthy intention (Figure 3D). This finding bridged two otherwise separate views of gratitude: on the one hand, it is a positive emotion the makes people feel good (Fredrickson, 2004), on the other hand, it is also a moral emotion that motivates people to do good (Bartlett & DeSteno, 2006; Chang, Lin, & Chen, 2012; McCullough & Tsang, 2004; Tsang, 2006). Given that the vmPFC does not only represent good-based value, but also uses such a value signal to guide appropriate and adaptive actions (Padoa-Schioppa, 2011), it is conceivable that this brain structure may link the experiential and the motivational facets of gratitude.

Another possible interpretation of the vmPFC activation is the regulation of affective responses to adverse situations (i.e., receiving pain stimulation). A wealth of recent research have demonstrated the crucial role of vmPFC in regulating physical and social threat, such as viewing aversive pictures, facing social-evaluative threats, and minimizing conditioned fear (for review, see Etkin,

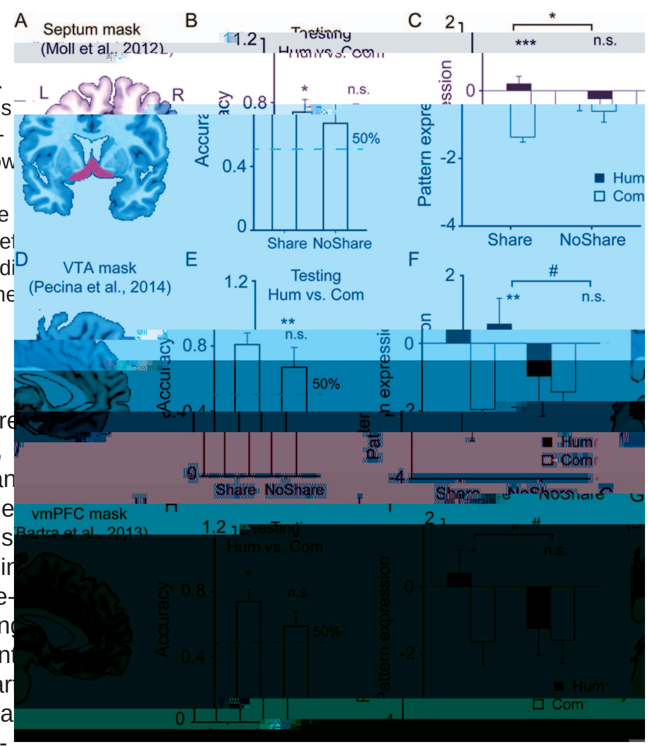

Figure 5. Results of the multivariate analysis within the ROIs. Panels (A), (D), and (G) show the anatomical position of the predefined ROIs. Panels (B), (E), and (H) show the prediction accuracy of the "Share" map classifying Share and NoShare conditions. (Because the classifiers within these ROIs cannot dissociate NoShare conditions, we did not further examine the performance of the NoShare maps.) For these panels, statistical significance refers to the comparison between classification accuracy in each situation and chance level (i.e., 50%; * $p < .05$, ** $p < .01$). Panels (C), (F), and (I) show the pattern expressions of the Share map. Asterisks on the top of the graph indicate significant Decision (Share vs. NoShare) by Agent (Human vs. Computer) interaction. For these panels, statistical significance refers to the comparison between pattern expressions across conditions (# $.05 < p < .1$, * $p < .05$). Asterisks below indicate significance in post hoc test (* $p < .05$, ** $p < .01$, *** $p < .001$). See the online article for the color version of this figure.

Egner, & Kalisch, 2011). This evidence has led some researchers to postulate that "the vmPFC is not necessary for affective responses per se, but is critical when affective responses are shaped by conceptual information about specific outcomes" (Roy, Shohamy, & Wager, 2012). The emotion regulation view is not in contradiction with the value representation view, which we outlined above. In fact, emotion regulation has been reconceptualized as a value-based decision-making process, "as a set of decisions about actions that are aimed at achieving a desired emotional state" (Etkin, Büchel, & Gross, 2015). In this frame, the vmPFC functions to compute the value of a "desired emotional state" and determine whether to engage in emotion regulation to achieve such a state (Etkin et al., 2015). In light of this, our vmPFC activation in the Human Share condition may reflect the social value of receiving voluntary help (McConnell, 2016) and the value of regulating negative affective states when social support is available (Eisenberger et al., 2011).

Interpersonal Closeness and Septum

Gratitude is beneficial to the formation and maintenance of close social relationships (Algoe, Haidt, & Gable, 2008). According to an influential account on the relationship between gratitude and social relationships (Algoe, 2012), gratitude may help one detect the social relationships that are conducive to his or her survival in a social environment. Plainly, someone who intentionally helps this time is likely to offer help in similar situations in the future. Feeling grateful and expressing it may keep and strengthen such a social tie (Algoe, 2012; Grant & Gino, 2010). This process is analogous to the development of affiliative affects between children and their caregivers: receiving love and care from caregivers triggers affiliative affect such as attachment. This affect not only helps children to identify valuable social partners, but also keeps them close to these social partners. The affiliative affects and attachment has been reported to be associated with the neural activity in septum and hypothalamus in both animals and humans (Moll et al., 2012; Noriuchi et al., 2008; Strathearn et al., 2009). A scenario-based study on gratitude also reported that reading gratitude-related scripts can activate this area (Zahn et al., 2009). Here, in a lab-based, controlled manner, we demonstrated that receiving intentional help made the beneficiary feel closer to the benefactor. Moreover, we showed that the neural activity in septum contained information that specifically and sensitively distinguished the gratitude situation (i.e., receiving intentional help) from the physically identical nonsocial situation (i.e., receiving unintentional help). The converging evidence from our behavioral and neuroimaging results and the previous evidence concerning the functions of the septum suggest that receiving intentional help may trigger affiliative affect in the recipient of the benefit and enhance the perceived interpersonal closeness to the benefactor. Future research is needed to systematically examine the link between gratitude and affiliative affect and attachment style.

Subjective Pain Intensity and Insula

"Two in distress makes the sorrow less"—we usually feel better when social support is present in adverse situations (Berscheid, 2003). Holding the hand of one's spouse (Coan et al., 2006) or viewing the picture of one's romantic partner (Eisenberger et al., 2011) can reduce the experience and neural responses to physical pain. The intention of the partner in delivering a pain stimulation could also modify the participants' subjective experience of pain (Gray, 2012; Gray & Wegner, 2008). Here we found that participants' experience of pain was reduced by the benefactor's intentional help (relative to unintentional help). Lending support to this behavioral finding, our neuroimaging results showed that the response of the primary sensory area and the bilateral anterior insula to pain stimulation was reduced in the intentional help condition. The anterior insula has been implicated in a wide range of cognitive, social, and affective processes, including the affective component of pain (Bushnell, Ceko, & Low, 2013), empathy (Gu et al., 2012; Lamm & Singer, 2010; Singer et al., 2004), and the computation of salience (Uddin, 2015). In interpersonal contexts, the anterior insula has been consistently implicated in assessing (un-)fairness (Gabay, Radua, Kempton, & Mehta, 2014; Sanfey, Rilling, Aronson, Nystrom, & Cohen, 2003), reactive aggression (Krämer, Jansma, Tempelmann, & Münte, 2007), and social isolation (Eisenberger, 2015). Together, these studies suggest that the anterior insula may serve as an interface between the processing of social context (e.g., intention) and the representation of affective states. In light of these findings and the current finding concerning the anterior insula, it is possible to infer that the affective aspect of pain perception is modulated by interpersonal context.

In addition to the affective processing of pain, we also found that intentional help could attenuate the sensory processing of pain. The exact mechanism through which social and affective contexts modulates the sensory aspects of pain is still under debate (Iannetti & Mouraux, 2011; Zaki, Wager, Singer, Keysers, & Gazzola, 2016). Some researchers view social information as a source of pain. However, in their studies, no physical pain stimulation is actually delivered to the participants and thus the term "pain" is used in a metaphoric or analogous sense, referring to an unpleasant affective state. Some of these studies show that social rejection information (e.g., viewing the picture of an ex-partner; Kross et al., 2011) can activate the sensory areas, including the primary and secondary sensory area. However, recent advances in multivariate pattern analysis of neuroimaging data offer novel evidence against the "shared representation" view of the relation between social pain and physical pain: the brain pattern diagnostic of the levels of physical pain cannot predict the levels of social 'pain,' nor vice versa (Woo et al., 2014). A possible approach to offer decisive evidence concerning how social information influences the sensory aspect of pain processing is to directly measure (e.g., using PET; cf. Wager, Scott, & Zubieta, 2007) or manipulate (e.g., using opioid receptor blockade; cf. Casey, Svensson, Morrow, Raz, Jone, & Minoshima, 2000) the binding of neurotransmitters in the brain pain system.

Note that in the current study we attempted to prevent any learning during the game by pairing the participant with three confederates and making each round of interaction anonymous. By using such a setting, we intended to ensure that each encounter was new and independent, to avoid potential confounding processes such as strategic thinking, reputation and impression formation. This being said, we acknowledge that learning about others' character and forming impression is an interesting and theoretically significant issue. In fact, this question has been addressed in a number of recent neuroimaging studies (Hackel, Doll, & Amodio, 2015; Hein, Engelmann, Vollberg, & Tobler, 2016). These studies showed that in the settings where learning of the interactive partner's character is possible, individuals' emotional and behavioral responses are not solely determined by the benefits and suffering that resulted from the partner's current action; who performs that action also counts. Participants can gradually learn the characters of different interactive partners and treat their behaviors differently, despite the fact that at a given encounter the objective benefits or suffering induced by those partners are identical. This feature of social learning is also highly relevant to social emotions like gratitude, as previous empirical and theoretical studies have shown that the same gift/benefit may induce either gratitude or indebtedness contingent on who provides that gift/benefit (McConnell, 1993; Watkins et al., 2006). Future studies could incorporate learning procedures and mathematical modeling to address this question.

Conclusion

By combining an interpersonal paradigm with fMRI, we documented the neural substrates of experiencing interpersonal gratitude in real social interaction. Compared with previous studies on the neurobiology of gratitude using scenario-based approach, our study made novel contributions in that we not only measured the neural correlates of the grateful experience, but also showed how such neural processes may give rise to important social consequences of receiving help, namely, alleviated negative experience of pain, improved interpersonal relationships, and increased reciprocal/prosocial behavior. In a broader sense, these contributions underlie the benefits of using interpersonal paradigms in the investigation of the psychological and neurobiological mechanisms of complex social cognition and emotion.

References

Algoe, S. B. (2012). Find, remind, and bind: The functions of gratitude in everyday relationships. *Social and Personality Psychology Compass, 6,* 455–469. http://dx.doi.org/10.1111/j.1751-9004.2012.00439.x

Algoe, S. B., Haidt, J., & Gable, S. L. (2008). Beyond reciprocity: Gratitude and relationships in everyday life. *Emotion, 8,* 425–429. http://dx.doi.org/10.1037/1528-3542.8.3.425

Algoe, S. B., & Stanton, A. L. (2012). Gratitude when it is needed most: Social functions of gratitude in women with metastatic breast cancer. *Emotion, 12,* 163–168.

Ariely, D. (2010). *Predictably irrational: The hidden forces that shape our decisions.* New York, NY: HarperCollins Publishers.

Atlas, L. Y., & Wager, T. D. (2012). How expectations shape pain. *Neuroscience Letters, 520,* 140–148. http://dx.doi.org/10.1016/j.neulet.2012.03.039

Bartlett, M. Y., & DeSteno, D. (2006). Gratitude and prosocial behavior helping when it costs you. *Psychological science, 17,* 319–325.

Bartlett, M. Y., Condon, P., Cruz, J., Baumann, J., & Desteno, D. (2012). Gratitude: Prompting behaviours that build relationships. *Cognition & emotion, 26,* 2–13.

Bartra, O., McGuire, J. T., & Kable, J. W. (2013). The valuation system: A coordinate-based meta-analysis of BOLD fMRI experiments examining neural correlates of subjective value. *NeuroImage, 76,* 412–427. http://dx.doi.org/10.1016/j.neuroimage.2013.02.063

Berger, F. R. (1975). Gratitude. *Ethics, 85,* 298–309.

Berscheid, E. (2003). The human's greatest strength: Other humans. In L. G. Aspinwall & U. M. Staudinger (Eds.), *A psychology of human strengths: Fundamental questions and future directions for a positive psychology* (pp. 37–47). Washington, DC: American Psychological Association. http://dx.doi.org/10.1037/10566-003

Buhle, J. T., Kober, H., Ochsner, K. N., Mende-Siedlecki, P., Weber, J., Hughes, B. L., . . . Wager, T. D. (2013). Common representation of pain and negative emotion in the midbrain periaqueductal gray. *Social cognitive and affective neuroscience, 8,* 609–616.

Bushnell, M. C., Čeko, M., & Low, L. A. (2013). Cognitive and emotional control of pain and its disruption in chronic pain. *Nature Reviews Neuroscience, 14,* 502–511. http://dx.doi.org/10.1038/nrn3516

Casey, K. L., Svensson, P., Morrow, T. J., Raz, J., Jone, C., & Minoshima, S. (2000). Selective opiate modulation of nociceptive processing in the human brain. *Journal of Neurophysiology, 84,* 525–533.

Chang, L. J., Smith, A., Dufwenberg, M., & Sanfey, A. G. (2011). Triangulating the neural, psychological, and economic bases of guilt aversion. *Neuron, 70,* 560–572.

Chang, L. J., Gianaros, P. J., Manuck, S. B., Krishnan, A., & Wager, T. D. (2015). A sensitive and specific neural signature for picture-induced negative affect. *PLoS Biology, 13,* e1002180. http://dx.doi.org/10.1371/journal.pbio.1002180

Chang, Y. P., Lin, Y. C., & Chen, L. H. (2012). Pay it forward: Gratitude in social networks. *Journal of Happiness Studies, 13,* 761–781. http://dx.doi.org/10.1007/s10902-011-9289-z

Chen, M. Y., Jimura, K., White, C. N., Maddox, W. T., & Poldrack, R. A. (2015). Multiple brain networks contribute to the acquisition of bias in perceptual decision-making. *Frontiers in Neuroscience, 9,* 63. http://dx.doi.org/10.3389/fnins.2015.00063

Cicero, M. T. (1851). *The orations of Marcus Tullius Cicero* (Vol. III). (C. D. Younge, Trans.). London, England: George Bell & Son.

Coan, J. A., Schaefer, H. S., & Davidson, R. J. (2006). Lending a hand: Social regulation of the neural response to threat. *Psychological Science, 17,* 1032–1039. http://dx.doi.org/10.1111/j.1467-9280.2006.01832.x

Cooper, J. C., Kreps, T. A., Wiebe, T., Pirkl, T., & Knutson, B. (2010). When giving is good: Ventromedial prefrontal cortex activation for others' intentions. *Neuron, 67,* 511–521.

Crockett, M. J., Kurth-Nelson, Z., Siegel, J. Z., Dayan, P., & Dolan, R. J. (2014). Harm to others outweighs harm to self in moral decision making. *Proceedings of the National Academy of Sciences,* **111**, 17320–17325.

Crockett, M. J., Siegel, J. Z., Kurth-Nelson, Z., Ousdal, O. T., Story, G., Frieband, C., . . . Dolan, R. J. (2015). Dissociable effects of serotonin and dopamine on the valuation of harm in moral decision making. *Current Biology, 25,* 1852–1859.

Decety, J., & Porges, E. (2011). Imagining being the agent of actions that carry different moral consequences: An fmri study. *Neuropsychologia, 49,* 2994–3001.

DeWall, C. N., Macdonald, G., Webster, G. D., Masten, C. L., Baumeister, R. F., Powell, C., . . . Eisenberger, N. I. (2010). Acetaminophen reduces social pain: Behavioral and neural evidence. *Psychological Science, 21,* 931–937. http://dx.doi.org/10.1177/0956797610374741

Doi, T. (1981). *The anatomy of dependence.* Tokyo: Kodansha International.

Eisenberger, N. I. (2015). Social pain and the brain: Controversies, questions, and where to go from here. *Annual Review of Psychology, 66,* 601–629. http://dx.doi.org/10.1146/annurev-psych-010213-115146

Eisenberger, N. I., Master, S. L., Inagaki, T. K., Taylor, S. E., Shirinyan, D., Lieberman, M. D., & Naliboff, B. D. (2011). Attachment figures activate a safety signal-related neural region and reduce pain experience. *Proceedings of the National Academy of Sciences of the United States of America, 108,* 11721–11726. http://dx.doi.org/10.1073/pnas.1108239108

Emmons, R. A., & McCullough, M. E. (2003). Counting blessings versus burdens: An experimental investigation of gratitude and subjective well-being in daily life. *Journal of personality and social psychology, 84,* 377.

Emmons, R. A., & McCullough, M. E. (2004). *The psychology of gratitude*. New York, NY: Oxford University Press.

Etkin, A., Egner, T., & Kalisch, R. (2011). Emotional processing in anterior cingulate and medial prefrontal cortex. *Trends in cognitive sciences, 15,* 85–93.

Etkin, A., Büchel, C., & Gross, J. J. (2015). The neural bases of emotion regulation. *Nature Reviews Neuroscience, 16,* 693–700.

Fox, G. R., Kaplan, J., Damasio, H., & Damasio, A. (2015). Neural correlates of gratitude. *Frontiers in psychology*. Advance online publication. http://dx.doi.org/10.3389/fpsyg.2015.01491

Fredrickson, B. L. (2004). Gratitude, like other positive emotions, broadens and builds. In R. A. Emmons & M. E. McCullough (Eds.), *The Psychology of Gratitude* (pp. 145–166). New York, NY: Oxford University Press.

Grant, A. M., & Gino, F. (2010). A little thanks goes a long way: Explaining why gratitude expressions motivate prosocial behavior. *Journal of personality and social psychology, 98,* 946.

Gabay, A. S., Radua, J., Kempton, M. J., & Mehta, M. A. (2014). The Ultimatum Game and the brain: A meta-analysis of neuroimaging studies. *Neuroscience and Biobehavioral Reviews, 47,* 549–558. http://dx.doi.org/10.1016/j.neubiorev.2014.10.014

Gray, K. (2012). The power of good intentions perceived benevolence soothes pain, increases pleasure, and improves taste. *Social Psychological & Personality Science, 3,* 639–645. http://dx.doi.org/10.1177/1948550611433470

Gray, K., & Wegner, D. M. (2008). The sting of intentional pain. *Psychological Science, 19,* 1260–1262. http://dx.doi.org/10.1111/j.1467-9280.2008.02208.x

Grueschow, M., Polania, R., Hare, T. A., & Ruff, C. C. (2015). Automatic versus choice-dependent value representations in the human brain. *Neuron, 85,* 874–885.

Gu, X., Gao, Z., Wang, X., Liu, X., Knight, R. T., Hof, P. R., & Fan, J. (2012). Anterior insular cortex is necessary for empathetic pain perception. *Brain: A Journal of Neurology, 135,* 2726–2735. http://dx.doi.org/10.1093/brain/aws199

Hackel, L. M., Doll, B. B., & Amodio, D. M. (2015). Instrumental learning of traits versus rewards: Dissociable neural correlates and effects on choice. *Nature neuroscience*.

Hari, R., Henriksson, L., Malinen, S., & Parkkonen, L. (2015). Centrality of social interaction in human brain function. *Neuron, 88,* 181–193. http://dx.doi.org/10.1016/j.neuron.2015.09.022

Hastie, T., Tibshirani, R., & Friedman, J. (2001). *The elements of statistical learning*. New York, NY: Springer.

Hein, G., Engelmann, J. B., Vollberg, M. C., & Tobler, P. N. (2016). How learning shapes the empathic brain. *Proceedings of the National Academy of Sciences, 113,* 80–85.

Huffman, J. C., DuBois, C. M., Healy, B. C., Boehm, J. K., Kashdan, T. B., Celano, C. M., . . . Lyubomirsky, S. (2014). Feasibility and utility of positive psychology exercises for suicidal inpatients. *General Hospital Psychiatry, 36,* 88–94. http://dx.doi.org/10.1016/j.genhosppsych.2013.10.006

Iannetti, G. D., & Mouraux, A. (2011). Can the functional MRI responses to physical pain really tell us why social rejection "hurts"? *Proceedings of the National Academy of Sciences of the United States of America, 108,* E343. http://dx.doi.org/10.1073/pnas.1105451108

Inagaki, T. K., & Eisenberger, N. I. (2012). Neural correlates of giving support to a loved one. *Psychosomatic Medicine, 74,* 3–7.

Inui, K., Tran, T. D., Hoshiyama, M., Kakigi, R. (2002). Preferential stimulation of Ad fibers by intra-epidermal needle electrode in humans. *Pain, 96,* 247–252.

Izuma, K., Saito, D. N., & Sadato, N. (2008). Processing of social and monetary rewards in the human striatum. *Neuron, 58,* 284–294.

Jenkinson, M., Bannister, P., Brady, M., & Smith, S. (2002). Improved optimization for the robust and accurate linear registration and motion correction of brain images. *NeuroImage, 17,* 825–841. http://dx.doi.org/10.1006/nimg.2002.1132

Koban, L., Corradi-Dell'Acqua, C., & Vuilleumier, P. (2013). Integration of error agency and representation of others' pain in the anterior insula. *Journal of Cognitive Neuroscience, 25,* 258–272.

Krämer, U. M., Jansma, H., Tempelmann, C., & Münte, T. F. (2007). Tit-for-tat: The neural basis of reactive aggression. *NeuroImage, 38,* 203–211. http://dx.doi.org/10.1016/j.neuroimage.2007.07.029

Kross, E., Berman, M. G., Mischel, W., Smith, E. E., & Wager, T. D. (2011). Social rejection shares somatosensory representations with physical pain. *Proceedings of the National Academy of Sciences of the United States of America, 108,* 6270–6275. http://dx.doi.org/10.1073/pnas.1102693108

Lamm, C., & Singer, T. (2010). The role of anterior insular cortex in social emotions. *Brain Structure & Function, 214,* 579–591. http://dx.doi.org/10.1007/s00429-010-0251-3

Lin, A., Adolphs, R., & Rangel, A. (2012). Social and monetary reward learning engage overlapping neural substrates. *Social cognitive and affective neuroscience, 7,* 274–281.

Mauss, M. (2002). *The Gift: The form and reason for exchange in archaic societies*. London, United Kingdom: Routledge. (Original work published 1950)

McConnell, T. (1993). *Gratitude*. Philadelphia, PA: Temple University Press.

McConnell, T. (2016). Gratitude's value. In D. Carr (Ed.), *Perspectives on Gratitude: An interdisciplinary approach*. New York, NY: Routledge.

McCullough, M. E., Kilpatrick, S. D., Emmons, R. A., & Larson, D. B. (2001). Is gratitude a moral affect? *Psychological Bulletin, 127,* 249–266. http://dx.doi.org/10.1037/0033-2909.127.2.249

McCullough, M. E., & Tsang, J. A. (2004). Parent of the Virtues: The Prosocial Contours of Gratitude. In R. A. Emmons & M. E. McCullough (Eds.), *The Psychology of Gratitude* (pp. 145–166). New York, NY: Oxford University Press.

Moll, J., Bado, P., de Oliveira-Souza, R., Bramati, I. E., Lima, D. O., Paiva, F. F., . . . Zahn, R. (2012). A neural signature of affiliative emotion in the human septohypothalamic area. *The Journal of Neuroscience, 32,* 12499–12505. http://dx.doi.org/10.1523/JNEUROSCI.6508-11.2012

Nichols, T. (2007). *Easythresh_conj quick method of getting conjunction stats outside of Feat* [web p.]. Retrieved from http://www2.warwick.ac.uk/fac/sci/statistics/staff/academic-research/nichols/scripts/fsl/easythresh_conj.sh

Nicolle, A., Klein-Flügge, M. C., Hunt, L. T., Vlaev, I., Dolan, R. J., & Behrens, T. E. (2012). An agent independent axis for executed and modeled choice in medial prefrontal cortex. *Neuron, 75,* 1114–1121.

Noriuchi, M., Kikuchi, Y., & Senoo, A. (2008). The functional neuroanatomy of maternal love: Mother's response to infant's attachment behaviors. *Biological Psychiatry, 63,* 415–423.

Padoa-Schioppa, C. (2011). Neurobiology of economic choice: A good-based model. *Annual Review of Neuroscience, 34,* 333–359. http://dx.doi.org/10.1146/annurev-neuro-061010-113648

Peciña, M., Martínez-Jauand, M., Love, T., Heffernan, J., Montoya, P., Hodgkinson, C., . . . Zubieta, J. K. (2014). Valence-specific effects of BDNF Val66Met polymorphism on dopaminergic stress and reward processing in humans. *The Journal of Neuroscience, 34,* 5874–5881. http://dx.doi.org/10.1523/JNEUROSCI.2152-13.2014

Pfeiffer, U. J., Timmermans, B., Vogeley, K., Frith, C. D., & Schilbach, L. (2013). Towards a neuroscience of social interaction. *Frontiers in Human Neuroscience, 7,* 22.

Preacher, K. J., & Hayes, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. *Behavior research methods, 40,* 879–891.

Rangel, A., Camerer, C., & Montague, P. R. (2008). A framework for studying the neurobiology of value-based decision making. *Nature Reviews Neuroscience, 9,* 545–556.

Roberts, R. C. (2004). The blessings of gratitude. In R. A. Emmons & M. E. McCullough (Eds.), The Psychology of Gratitude (pp. 58–78). New York, NY: Oxford University Press.

Roy, M., Shohamy, D., & Wager, T. D. (2012). Ventromedial prefrontal-subcortical systems and the generation of affective meaning. Trends in cognitive sciences, 16, 147–156.

Ruff, C. C., & Fehr, E. (2014). The neurobiology of rewards and values in social decision making. Nature Reviews Neuroscience, 15, 549–562.

Rüsch, N., Bado, P., Zahn, R., Bramati, I. E., de Oliveira-Souza, R., & Moll, J. (2014). You and your kin: Neural signatures of family-based group perception in the subgenual cortex. Social Neuroscience, 9, 326–331. http://dx.doi.org/10.1080/17470919.2014.912676

Sanfey, A. G., Rilling, J. K., Aronson, J. A., Nystrom, L. E., & Cohen, J. D. (2003). The neural basis of economic decision-making in the Ultimatum Game. Science, 300, 1755–1758. http://dx.doi.org/10.1126/science.1082976

Schilbach, L. (2010). A second-person approach to other minds. Nature Reviews Neuroscience, 11, 449.

Schilbach, L., Timmermans, B., Reddy, V., Costall, A., Bente, G., Schlicht, T., & Vogeley, K. (2013). Toward a second-person neuroscience. Behavioral and Brain Sciences, 36, 393–414.

Schultz, W. (2015). Neuronal reward and decision signals: from theories to data. Physiological Reviews, 95, 853–951.

Seneca, L. A. (1995). Moral and Political Essays. Cambridge, UK: Cambridge University Press.

Singer, T., Seymour, B., O'Doherty, J., Kaube, H., Dolan, R. J., & Frith, C. D. (2004). Empathy for pain involves the affective but not sensory components of pain. Science, 303, 1157–1162. http://dx.doi.org/10.1126/science.1093535

Smith, A. (2002). The theory of moral sentiments. Cambridge, United Kingdom: Cambridge University Press. (Original work published 1795). http://dx.doi.org/10.1017/CBO9780511800153.005

Smith, S. M. (2002). Fast robust automated brain extraction. Human Brain Mapping, 17, 143–155. http://dx.doi.org/10.1002/hbm.10062

Strathearn, L., Fonagy, P., Amico, J., & Montague, P. R. (2009). Adult attachment predicts maternal brain and oxytocin response to infant cues. Neuropsychopharmacology, 34, 2655–2666.

Sul, S., Tobler, P. N., Hein, G., Leiberg, S., Jung, D., Fehr, E., & Kim, H. (2015). Spatial gradient in value representation along the medial prefrontal cortex reflects individual differences in prosociality. Proceedings of the National Academy of Sciences, 112, 7851–7856.

Tesser, A., Gatewood, R., & Driver, M. (1968). Some determinants of gratitude. Journal of Personality and Social Psychology, 9, 233–236. http://dx.doi.org/10.1037/h0025905

Tsang, J. A. (2006). Gratitude and prosocial behaviour: An experimental test of gratitude. Cognition and Emotion, 20, 138–148. http://dx.doi.org/10.1080/02699930500172341

Uddin, L. Q. (2015). Salience processing and insular cortical function and dysfunction. Nature Reviews Neuroscience, 16, 55–61. http://dx.doi.org/10.1038/nrn3857

van den Bos, W., McClure, S. M., Harris, L. T., Fiske, S. T., & Cohen, J. D. (2007). Dissociating affective evaluation and social cognitive processes in the ventral medial prefrontal cortex. Cognitive, Affective & Behavioral Neuroscience, 7, 337–346. http://dx.doi.org/10.3758/CABN.7.4.337

Wager, T. D., Atlas, L. Y., Lindquist, M. A., Roy, M., Woo, C. W., & Kross, E. (2013). An fMRI-based neurologic signature of physical pain. The New England Journal of Medicine, 368, 1388–1397. http://dx.doi.org/10.1056/NEJMoa1204471

Wager, T. D., Scott, D. J., & Zubieta, J. K. (2007). Placebo effects on human μ-opioid activity during pain. Proceedings of the National Academy of Sciences of the United States of America, 104, 11056–11061. http://dx.doi.org/10.1073/pnas.0702413104

Watkins, P., Scheer, J., Ovnicek, M., & Kolts, R. (2006). The debt of gratitude: Dissociating gratitude and indebtedness. Cognition and Emotion, 20, 217–241. http://dx.doi.org/10.1080/02699930500172291

Woo, C. W., Koban, L., Kross, E., Lindquist, M. A., Banich, M. T., Ruzic, L., . . . Wager, T. D. (2014). Separate neural representations for physical pain and social rejection. Nature Communications, 5, 5380. http://dx.doi.org/10.1038/ncomms6380

Worsley, K. J. (2001). Statistical analysis of activation images. In P. Jezzard, P. M. Matthews, & S. M. Smith (Eds.), Functional MRI: An introduction to methods (pp. 251–270). New York, NY: Oxford University Press.

Yarkoni, T., Poldrack, R. A., Nichols, T. E., Van Essen, D. C., & Wager, T. D. (2011). Large-scale automated synthesis of human functional neuroimaging data. Nature methods, 8, 665–670.

Yu, H., Hu, J., Hu, L., & Zhou, X. (2014). The voice of conscience: Neural bases of interpersonal guilt and compensation. Social cognitive and affective neuroscience, 9, 1150–1158.

Yu, H., Shen, B., Yin, Y., Blue, P. R., & Chang, L. J. (2015). Dissociating Guilt- and Inequity-Aversion in Cooperation and Norm Compliance. The Journal of Neuroscience, 35, 8973–8975.

Zahn, R., Moll, J., Paiva, M., Garrido, G., Krueger, F., Huey, E. D., & Grafman, J. (2009). The neural basis of human social values: Evidence from functional MRI. Cerebral Cortex, 19, 276–283. http://dx.doi.org/10.1093/cercor/bhn080

Zaki, J., Wager, T. D., Singer, T., Keysers, C., & Gazzola, V. (2016). The anatomy of suffering: Understanding the relationship between nociceptive and empathic pain. Trends in cognitive sciences, 20, 249–259.

Received November 12, 2015
Revision received May 12, 2016
Accepted October 24, 2016 ■