Cognitive, Affective, & Behavioral Neuroscience (2020) 20:481–492
https://doi.org/10.3758/s13415-020-00779-4

Your losses are mine: The influence of empathic concern on evaluative processing of others' outcomes

Xin Liu[1,2] · Xinmu Hu[1] · Kan Shi[1] · Xiaoqin Mai[1]

Abstract

Neural responses to others' decision-making outcomes can be modulated by many social factors. Using the event-related potential (ERP) technique, we explored the neural mechanisms of empathic concern modulating evaluative processing of others' outcomes. Participants were asked to perform a gambling task for three beneficiaries: themselves and two strangers. One stranger was an economically underprivileged student requiring help (high-empathy condition); the other stranger was a student with no upsetting information to induce empathic concern (low-empathy condition). ERP results showed that the valence effect of the feedback-related negativity (FRN) was larger when participants exhibited high empathic concern than when they did not. The FRN responses to strangers' outcomes in the high-empathy condition were as strong as those to their own outcomes. The P300 showed no differences between the low- and high-empathy conditions. These findings indicate that empathic concern could modulate the early stage of outcome processing, implying empathic emotional/altruistic motivational impacts of others' outcomes.

Keywords Empathic concern · Outcome evaluation · Event-related potential · Feedback-related negativity · P300

Introduction

In everyday life, individuals must often make decisions for themselves and others. Rapid evaluation of decision outcomes for oneself and others is an important function of the cognitive system, which is helpful to guide and improve future decision behavior. In the past 20 years, many studies have focused on neural mechanisms underlying the evaluation of decision outcomes (Gehring & Willoughby, 2002; Gold & Shadlen, 2007; Hajcak, Holroyd, Moser, & Simons., 2005; Holroyd & Coles, 2002; Kahnt, Heinzle, Park, & Romo, 2010; Knutson, Adams, Fong, & Hommer, 2001; Knutson, Westdorp, Kaiser, & Hommer, 2000). Many fMRI studies have shown that several brain areas are associated with reward processing during outcome evaluation, such as the striatum, nucleus accumbens, anterior cingulate cortex, and orbitofrountal cortex (Kahnt, Heinzle, Park, & Romo, 2010; Kirsch, Schienle, Stark, Blecker, & Walter., 2003; Knutson, Adams, Fong, & Hommer, 2001; Knutson, Westdorp, Kaiser, & Hommer, 2000; Preuschoff, Bossaerts, & Quartz, 2006). In particular, the technique of event-related potentials (ERPs) has provided important information for the temporal properties of the processing of outcome evaluation in humans. Researchers have identified two ERP components, the feedback-related negativity (FRN) and the P300, reflecting early and later outcome evaluative processing, respectively (Gehring & Willoughby, 2002; Hu, Xu, Li, & Mai, 2018; Miltner, Braun, & Coles, 1997; Schupp et al., 2000).

The FRN, a negative deflection in the frontocentral region of the scalp, peaks between 200–300 ms following the onset of feedback-related stimuli and is typically larger for negative outcomes (e.g., monetary losses or incorrect responses) than positive outcomes (Gehring & Willoughby, 2002; Hajcak, Holroyd, Moser, & Simons, 2005; Hauser et al., 2014; Holroyd & Coles, 2002; Nieuwenhuis, Holroyd, Mol, & Coles, 2004; Paul & Pourtois, 2017). According to the motivation/affective theory, the FRN reflects the early, rapid evaluation of the affective or motivational impact of outcomes (Gehring & Willoughby, 2002; Yu, Luo, Ye, & Zhou, 2007). However, because FRN amplitude decreases after unpredicted reward and increases after unpredicted nonreward, and dopaminergic neuron firing is related to reward (Hollerman &

✉ Xiaoqin Mai
maixq@ruc.edu.cn

[1] Department of Psychology, Renmin University of China, 59 Zhongguancun Street, Beijing 100872, China

[2] University Counseling Service, Beijing International Studies University, Beijing 100024, China

Schultz, 1998; Schultz, Dayan, & Montague, 1997), the reinforcement learning theory of the FRN proposes that the FRN reflects dopaminergic reward prediction errors (Holroyd & Coles, 2002; Nieuwenhuis, Holroyd, Mol, & Coles, 2004). Some studies also suggest that the FRN is associated with the salience prediction error (Talmi, Atkinson, & El-Deredy, 2013) or expectation (Cao, Gu, Bi, Zhu, & Wu, 2015). Moreover, other recent evidence has suggested that the FRN might reflect a reward positivity that is more positive following a reward compared with a nonreward outcome (Proudfit, & Hajcak, 2015; Wang, Jing, Zhang, Lin, & Valadez, 2017).

The P300 is a centroparietal positive component with a peak in the period of 300–600 ms after stimulus onset, which is larger for reward outcomes or feedback with high arousal levels. Some studies have found that the P300 is sensitive to the valence of the reward, with larger amplitudes for positive outcomes than for negative outcomes (Bellebaum & Daum, 2008; Hajcak, Holroyd, Moser, & Simons, 2005; Hajcak, Moser, Holroyd, & Simons, 2007; Kreussel et al., 2012). However, other studies reported that feedback valence had no impact upon the P300 (Sato et al., 2005; Yeung & Sanfey, 2004). The P300 also is more pronounced for self-related positive feedback than other-related positive feedback (Gray, Ambady, Lowenthal, & Deldin, 2004; Kiat & Cheadle, 2017). Moreover, P300 amplitude can be modulated by some social factors, such as personal responsibility for outcomes and interpersonal relationship (Leng & Zhou, 2010; Li, Han, Lei, Holroyd, & Li, 2011; Ma et al., 2011). Some researchers have posited that the P300 is related to allocation of attentional resources and high-level affective evaluation of outcomes, such as regret or disappointment (Gray, Ambady, Lowenthal, & Deldin, 2004; Hajcak, Moser, Holroyd, & Simons, 2007; Linden, 2005; Yeung & Sanfey, 2004).

A growing number of ERP studies have begun to explore how the brain responds to outcomes related to others and found that ERP responses to others' feedback were similar to those elicited by the outcome of participants themselves (Fukushima & Hiraki, 2006, 2009; Hu, Xu, & Mai, 2017; Liu, Hu, Shi, & Mai, 2018; Yu & Zhou, 2006; Zhu et al., 2018). Yu and Zhou (2006) reported that the FRN was elicited when individuals observed others' performance. They asked participants to perform a gambling task for their own interest, or merely observe another person's performance, while the other's gain or loss having no impact on observer's own interests. Results showed that the FRN effect was identified in both situations with similar morphology and scalp distribution, suggesting that there are similar neural mechanisms underlying the evaluation processing of outcomes of one's own and others' actions. Although the processing of others' outcomes is similar to that of one's own outcomes, the valence effect of the FRN and P300 amplitude are consistently smaller for others' outcomes than for one's own outcomes. (Fukushima & Hiraki, 2006, 2009; Koban, Pourtois, Bediou, & Vuilleumier, 2012; Leng & Zhou 2010; Li et al., 2010; Li, Han, Lei, Holroyd, & Li, 2011; Liu, Hu, Shi, & Mai, 2018; Marco-Pallares, Kramer, Strehl, Schroder, & Munte, 2010).

Marco-Pallares et al. (2010) further explored the temporal processing of outcome evaluation when participants' interests were relevant to the others' performance. The gambling task they used included parallel, reverse, and neutral situations, which meant that the other's performance resulted in the same or opposite income of the participants or had no impact on the participants. They found that the participants in the parallel and neutral situations showed a similar FRN response to the performer's losses, whereas the participants in the reverse situations showed the FRN for wins of the performer. The authors believe that the neural responses of observers are driven by two evaluative processes: one is related to the gain/loss of oneself, and the other is related to the gain/loss of another person. Leng and Zhou (2014) extended previous findings from passive observing to active performance. They asked participants to complete the gambling task for others' interests rather than themselves. Results showed that others' gains and losses also elicited the FRN and P300. These findings suggest that neural responses to the interests of others can be evoked not only in the observation situation but also in the self-participation situation.

Although ERP responses to others' outcomes have been revealed in some studies, the neural mechanisms underlying the evaluative processing of others' outcomes have not been well identified. Some researchers believe that the others-ERPs are possibly associated with empathy, an ability of sharing the mental and emotional states of others (Fukushima & Hiraki, 2006, 2009; Leng & Zhou, 2010; Singer, 2006; Liu, Hu, Shi, & Mai, 2018; Ma et al., 2011; Martin, Kwak, Pearson, Woldorff, & Huettel, 2016). Fukushima and Hiraki (2006) used a competitive gambling task, in which two persons alternately played a game, and one player's gain meant the other's loss. The results showed that the participants' subjective ratings of trait empathy were linearly correlated with the amplitude of the others-FRN, indicating the possible association between the others-ERP and empathy. Fukushima and Hiraki (2009) further examined the relationship between the others-FRN and participants' traits empathy by using two sets of self-report questionnaires: the interpersonal reactivity index (IRI) and the empathy quotient (EQ). They found that only the emotional aspect of trait empathy was correlated with the others-FRN, whereas the cognitive aspect of trait empathy was not related to the others-FRN.

In addition to examining the relationship between the others-FRN and the trait empathy, some researchers suggest that the evaluative processing of other's outcomes has relationship with state empathy, which could be induced for a particular individual in a particular situation (Liu, Hu, Shi, & Mai, 2018; Ma et al., 2011). Ma et al. (2011) asked the participant to observe two others playing the gambling game in turn, one of whom was a friend and the other was a stranger to the participant. Results showed that the enhanced FRN was elicited when observing friend-related outcomes compared with those related to a stranger, indicating that the context-dependent empathy, which was induced towards socially closer persons, possibly was the key factor modulating the evaluative processing of others' outcomes. However, another explanation was proposed by Leng and Zhou (2010, 2014), who believe that interpersonal relationship between the participants and others is actually the important factor modulating evaluating processing of others' outcomes. Because the relationship between participants and friends is closer, the FRN effect induced by friends is greater than that induced by strangers. Until now, it remains unclear which factor modulates the evaluative processing of others' outcomes: "empathic emotion" or "interpersonal relationship"? Some fMRI studies have demonstrated that when a person's close friends receiving negative stimuli, the brain areas related to empathy, such as the anterior insula and the anterior cingulate cortex, are activated, which supports the former modulator to some extent (De et al., 2012; Harrison, Singer, Rotshtein, Dolan, & Critchley, 2006; Singer et al., 2004). Moreover, if the hypothesis of interpersonal relationship is true, empathy may lack the power to modulate the processing of outcome evaluation when interpersonal relationship is controlled.

The purpose of the current study was to examine whether situational induced empathy would modulate the evaluative processing of others' outcomes when interpersonal relationship was controlled. Empathic concern is considered as state empathy, which would be elicited by and congruent with the perceived welfare of a person in need (Batson & Ahmad, 2001; Stocks, Lishner, Waits, & Downum, 2011; Woltin, Corneille, Yzerbyt, & Forster, 2011). In this study, we revised the classical gambling task (Gehring & Willoughby, 2002) and required each participant to perform it under three conditions: gambling for himself or herself (self condition) and for two strangers. One of the strangers was described as an underprivileged student in distress (stranger-in-need condition), whereas the other was depicted as a general student studying in a regular urban school (stranger-not-in-need condition). The interpersonal distance between participants and others was controlled, because both others were strangers to the participants. Based on the empathy–altruism hypothesis, which posits that people feel strong empathic emotions for others who are in need or in distress (Batson & Ahmad, 2001; Batson & Moran, 1999), we considered that the stranger-in-need scenario was the high-empathy condition and the stranger-not-in-need scenario was the low-empathy condition. Given the hypothesis that empathic concern affects evaluations of others' outcomes, we predicted that the FRN and P300 effects would be larger in the stranger-in-need condition than in the stranger-not-in-need condition.

Methods

Participants

Twenty-four undergraduate and graduate students (12 females; mean age: 22.18 ± 2.05 years) at Renmin University of China participated in this study. All participants received 60 Chinese yuan for participation and a bonus of up to 20 Chinese yuan based on their task performance. All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. None of them consumed caffeine or alcohol on the day of the experiment. The average of sleep time was more than 7 hours on the day of experiment. Data from one female participant were excluded due to excessive movement artifacts. Thus, the final sample consisted of 23 participants. Written, informed consent was obtained from all participants. The study was approved by the Institutional Review Board of the Department of Psychology at Renmin University of China.

Procedure

At the beginning of the experiment, each participant was instructed to play the gambling game three times for different beneficiaries: himself or herself (self condition) and two strangers. The personal profiles of two strangers were predesigned and read by each participant. In the stranger-in-need condition, the beneficiary was an economically underprivileged student from a school in a remote, impoverished region (high-empathy condition). In the stranger-not-in-need condition, the beneficiary was a general student studying in a normal urban school (low-empathy condition). All participants were informed that they would receive the amount of money earned when playing for themselves; however, when the participants played games for each of the two strangers, the reward money would be donated to the beneficiaries and had nothing to do with participants. All participants were informed of how much money they earned for themselves and strangers after the experiment concluded.

Participants were seated comfortably in front of a computer screen in an electrically isolated room. They were asked to play the gambling game adapted from a task designed by Gehring and Willoughby (2002). As illustrated in Fig. 1, each trial began with a white fixation cross presented for 500 ms on a black background. Then, two gray cards were presented on either side of the fixation point along with a numeral cue (5 or 10), denoting the amount of money in the task (i.e., "5" = 0.5 Chinese yuan; "10" = 1 Chinese yuan). Participants were required to choose between the two alternatives by pressing a corresponding response button (either the F or J key on the keyboard) with their left or right index finger. When the participant responded, the chosen

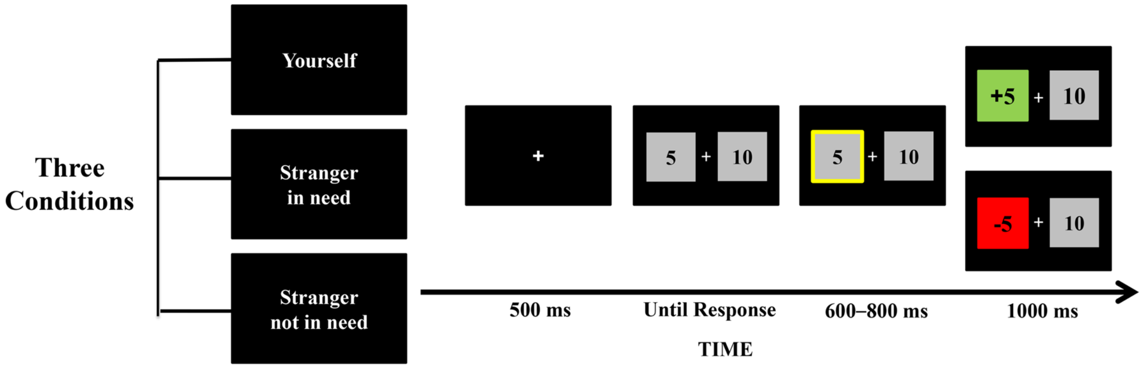

Fig. 1. A single trial in the gambling task. Each trial began with a fixation cross. Participants viewed two gray cards with a numeral cue and were required to choose one by pressing the corresponding key. Their choice was then highlighted for 600–800 ms. Thereafter, outcome feedback was presented for 1000 ms

card was highlighted by a thick yellow border for 600–800 ms, and then the outcome behind the chosen card was displayed for 1,000 ms with "+" indicating a gain and "−" indicating a loss. The intertrial interval was 600–800 ms. In order to increase the salience of the valence of the outcome, the chosen card turned red or green to indicate a gain or loss outcome. Half of the participants were assigned red as the gain color and green as the loss color, and half were assigned green as the gain color and red as the loss color. The experiment included 270 trials, divided into 3 blocks of 90 trials per beneficiary condition. At the start of each block, participants were informed of the beneficiary for whom they would be playing and were encouraged to earn as much money as possible. Unbeknownst to the participants, gain/loss feedback was manipulated according to a random sequence, and each participant received equal exposure to each feedback condition. The order of the three blocks was counterbalanced across participants.

Stimuli were presented using the E-prime 2.0 software package (PST, Pittsburgh, PA). The formal experiment began after five practice trials per participant. After finishing the gambling task, participants were asked to complete a simple 5-point scale to rate their subjective motivation to win the game and their feeling about the loss outcome. Specifically, they were asked to rate their willingness to play the game (1 = "not at all" to 5 = "very much"), willingness to win the game (1 = "not at all" to 5 = "very much"), and feeling about loss (1 = "very unhappy" to 5 = "very happy") for themselves, the stranger in need, and the stranger not in need, respectively. The first item measured participants' general motivation to exert effort on this task, and the second item measured participants' motivation to increase the welfare of oneself and others. Scores on these two questions were combined to create a composite measure of the motivation to win on behalf of each beneficiary. The last question measured whether participants felt positive or negative emotions when losing money for themselves or for strangers, which can be an indirect measure of empathic emotion toward others.

EEG recording and data processing

EEGs were recorded via a Neuroscan Synamps 2 amplifier (Compumedics, Charlotte, NC) using an elastic cap with 64 tin electrodes according to the international 10/20 system. Signals were amplified with a band-pass filter of 0.01–100 Hz and continuously sampled at 1,000 Hz/channel for offline analysis. All rows of electrode recordings were referenced to an electrode placed over the left mastoid and re-referenced offline to the average of the left and right mastoids. Vertical and horizontal electrooculograms (EOGs) were collected with electrodes placed on the left supraorbital and infraorbital and on the outer canthi of the left and right eyes, respectively. All interelectrode impedances were less than 5 kΩ.

EEG data were processed offline using Neuroscan 4.5 software. Ocular artifacts were corrected using a regression procedure implemented in Neuroscan software (Semlitsch, Anderer, Schuster, & Presslich, 1986). Raw EEG data were segmented into epochs from 200 ms before to 800 ms after feedback onset; 200 ms preceding the feedback stimulus served as baseline. Epochs containing artifacts exceeding ±75 μV were excluded from analysis. Finally, the number of artifact-free ERP trials was 79.6 (± 5.84), 78.78 (± 5.15), and 76.26 (± 5.97) for the self, stranger-in-need, and stranger-not-in-need condition respectively. Data were digitally low-pass filtered below 30 Hz and then averaged for each condition.

Average ERPs analysis

The analyses focused on the FRN and P300 elicited by outcome feedback. The FRN was measured as the mean amplitudes in the time window of 230–320 ms following feedback presentation. The P300 was defined as the most positive peak in the window of 280–400 ms after onset of feedback stimuli. Based on the topographical distribution of each ERP component and previous research (Leng &

Zhou, 2014; Liu, Hu, Shi, & Mai, 2018; Yeung & Sanfey, 2004), the FRN was preliminarily calculated across three electrodes (Fz, FCz, and Cz), and the P300 was quantified across two electrodes (CPz and Pz). Results indicated that the effect of the FRN was greatest at the FCz site, and the effect of the P300 was largest at the CPz site. Hence, we focused on FCz and CPz electrodes for more detailed analyses of where the ERP effects were maximal.

Temporospatial PCA analysis

Due to the possibility that the FRN and the P300 are overlapping in averaged ERP waveforms, it is necessary to use the principal component analysis (PCA) for the decomposition of ERP components (Foti, Weinberg, Dien, & Hajcak, 2011). ERP PCA Toolkit (version 2.47), a Matlab-based software package, was employed to conduct the temporo-spatial PCA in this study (Dien, 2010). The averaged ERPs of each condition of each participant were imported to the toolbox, and then a two-step PCA procedure was performed as in the previous studies (Wang, Zhang, Jing, Valadez, & Simons, 2016; Zhang et al., 2013). In the first step, a temporal PCA with promax rotation was performed on all time points for each participant's average ERPs. In the second step, a spatial PCA was conducted for each of the resultant temporal factors using all of the recording electrodes with an infomax rotation. Finally, eight temporal factors × one spatial factors were extracted based on the Scree plot, yielding eight temporospatial factor combinations. Two of them were identified as the PCA-FRN and PCA-P300, because they accounted for more than 5% of the variance in the averaged ERPs and shared the time course of the FRN and P300. Based on the visual inspection of the factor combinations, the PCA-FRN and PCA-P300 were measured as the mean amplitudes in the time window of 250–350 ms and 350–450 ms respectively, at the channel Cz where they reached maximum.

Statistics

The FRN, P300, and PCA factor data were all subjected to repeated-measures analysis of variance (ANOVA) for two within-subjects factors: beneficiary (self vs. stranger-in-need vs. stranger-not-in-need) and reward valence (gain vs. loss). The significance level was set at 0.05 for all statistical analyses. Bonferroni corrections were performed for post hoc testing of significant main effects, whereas simple effect analysis was used to test significant interactions. Greenhouse-Geisser correction of the ANOVA assumption of sphericity was applied as appropriate. Effect sizes in all ANOVA analyses were reported by partial eta-squared (η_p^2), with 0.05 representing a small effect, 0.10 representing a medium effect, and 0.20 representing a large effect (Cohen, 1973). All statistical analyses were performed in SPSS 23.0 (SPSS, Inc., Chicago, IL).

Results

Behavioral results

The mean (±SD) reaction times (RTs) for choice responses in the three conditions were 716 ± 56 ms (self), 659 ± 69 ms (stranger-in-need), and 456 ± 74 ms (stranger-not-in-need). One-way ANOVA revealed a significant effect of the beneficiary on RTs [$F(2,66) = 3.76$, $p < 0.05$, $\eta_p^2 = 0.10$]. Post hoc tests indicated that participants responded more quickly in the stranger-not-in-need condition than in the self and stranger-in-need conditions ($ps < 0.05$). No differences were observed between the self condition and the stranger-in-need condition ($p = 0.20$). These results indicated that compared with the low-empathy condition, the high level of empathy may result in increased deliberation times when individuals make decisions for a stranger (Lewinsohn & Mano, 1993; Paulus, 2005).

We defined option "10" as the risky choice (high risk and high reward) and option "5" as the risk-avoidant choice in the gambling task. The ratio of the selection of "10" in the gambling task was 51.32 (±12.92) %, 53.25 (±15.52) %, and 55.61 (±14.21) % for the self, stranger-in-need, and stranger-not-in-need conditions respectively. One-way ANOVA was used to compare the ratio of risky choices from each participant among the three beneficiaries, but no significant difference was found among them [$F(2,66) = 0.82$, $p = 0.4$, $\eta_p^2 = 0.021$].

Subjective ratings

Figure 2 presents subjective ratings of motivation to win and feelings of loss. As the data of subjective ratings were not normally distributed, the differences of subjective winning motivation among three conditions were determined by Friedman test. The results revealed a significant effect of the beneficiary [$F(2,66) = 27.78$, $p < 0.001$]. Bonferroni-corrected post hoc tests showed that participants' motivation to win for the stranger not in need was lower than that for the self and for the stranger in need, ($ps < 0.001$), whereas the latter two did not differ ($p = 0.363$).

Friedman test on subjective ratings of participants' feelings of losing money for the beneficiary revealed a significant effect of the beneficiary [$F(2,66) = 18.43$, $p < 0.001$]. Bonferroni-corrected post hoc tests showed that participants felt more empathy toward the underprivileged student than the general student ($p < 0.001$); a similarly negative feeling was identified when participants lost money for themselves and for the underprivileged student ($p = 0.68$).

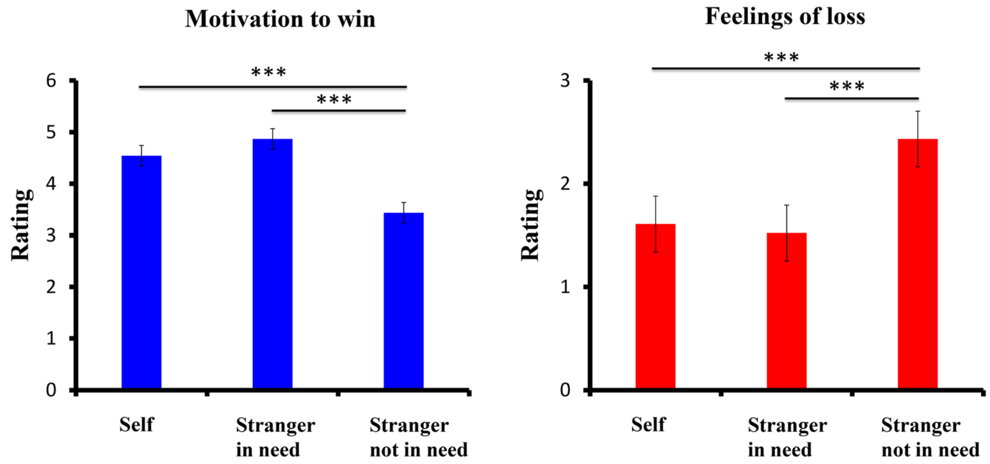

Fig. 2. Subjective ratings of motivation to win and feelings of loss. Error bars indicate standard error of the mean. ***$p < 0.001$

ERP results: conventionally averaged ERPs

FRN

Figure 3a illustrates grand-average ERP waveforms at the FCz site. The mean amplitude of the FRN was analyzed by a 3 (beneficiary: self vs. stranger-in-need vs. stranger-not-in-need) × 2 (reward valence: gain vs. loss) repeated-measures ANOVA. Results showed that the main effect of the beneficiary was significant [$F(2, 21) = 11.61$, $p < 0.01$, $\eta_p^2 = 0.49$], indicating that the FRN amplitude differed among the three beneficiary conditions. The main effect of reward valence was also significant [$F(1,22) = 55.15$, $p < 0.01$, $\eta_p^2 = 0.72$], with a more negative FRN when participants received a loss outcome rather than a gain outcome. More importantly, findings revealed a significant interaction effect of beneficiary × valence [$F(2,21) = 6.25$, $p < 0.01$, $\eta_p^2 = 0.37$], suggesting that the FRN effects of win and loss differed among the beneficiaries. Further simple effect analyses were conducted to investigate this interaction. The results indicated that the valence effect of the FRN was more pronounced for the stranger-in-need condition [$F(1, 22) = 57.40$, $p < 0.001$, $\eta_p^2 = 0.72$] and the self condition [$F(1, 22) = 50.09$, $p < 0.001$, $\eta_p^2 = 0.69$] than for the stranger-not-in-need condition [$F(1, 22) = 24.53$, $p < 0.001$, $\eta_p^2 = 0.52$].

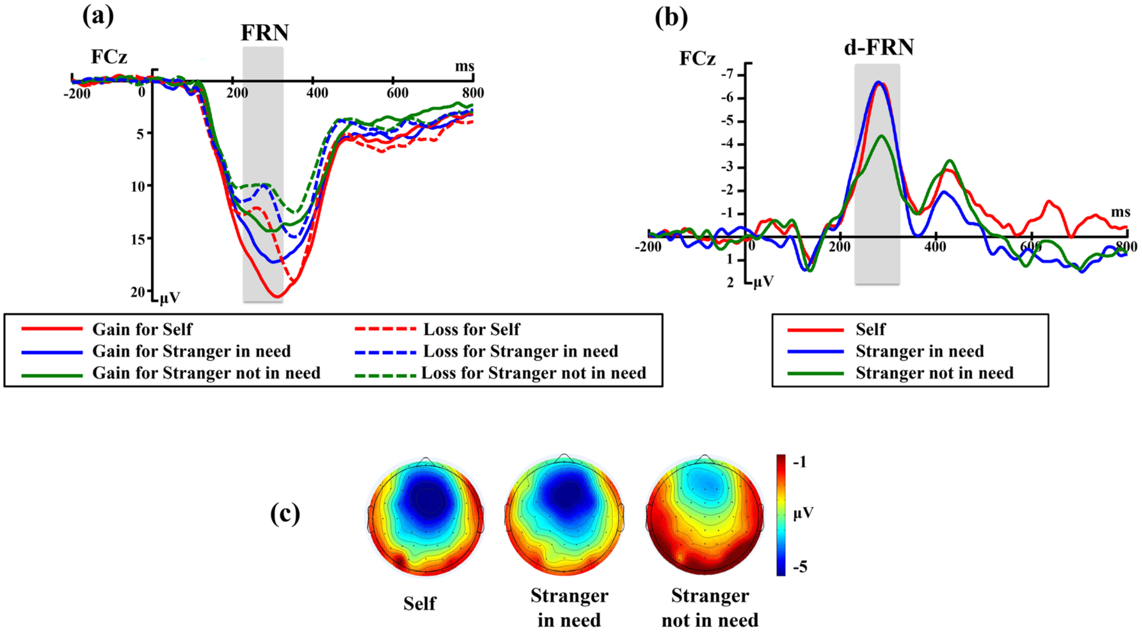

Fig. 3. (**a**) Grand-average ERP waveforms at FCz electrode site; gray areas indicate the time window of the FRN (230–320 ms) used for statistical analysis. (**b**) Difference waveforms of loss minus gain; gray areas indicate the time window of the d-FRN (230–320 ms) used for statistical analysis. (**c**) Topographic maps of different waveforms (loss minus gain) in the 230–320 ms time window for self, stranger-in-need, and stranger-not-in-need conditions

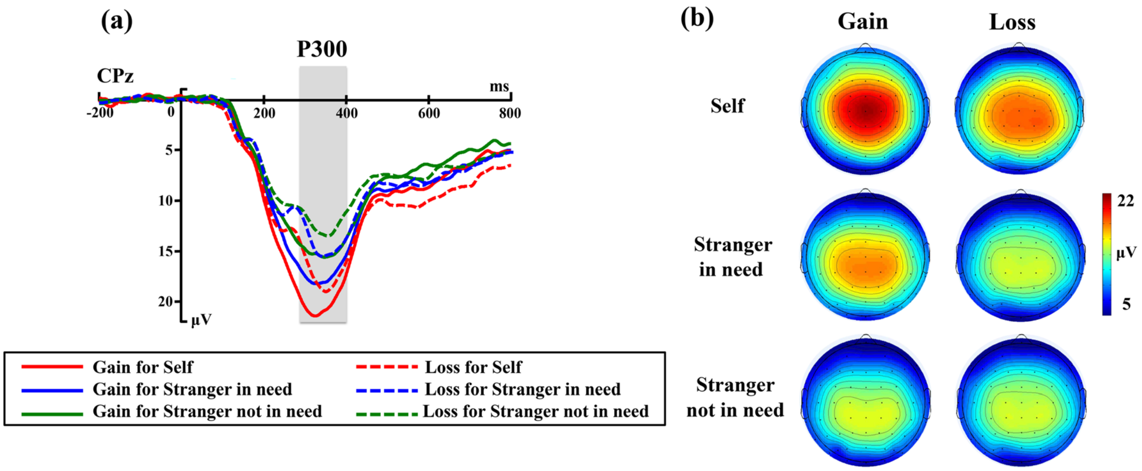

Fig. 4. (**a**) Grand-average ERP waveforms from CPz electrode site; gray areas indicate the time window of the P300 (320–400 ms) in which peak amplitude was measured. (**b**) Topographic maps of the P300 for the self, stranger-in-need, and stranger-not-in-need conditions

Figure 3b and c depict loss-minus-gain difference waveforms and topographic maps in the time window of 230–320 ms, in which we can more intuitively observe the difference of the FRN valence effect among three beneficiaries. We measured the mean amplitude of the FRN on the difference waves (d-FRN). Pearson correlation analysis was conducted between the d-FRN of three beneficiary conditions and task-related state measurements (motivation and state empathy) globally. Results indicated that the d-FRN was negatively correlated with subjective scores of motivation ($r = -0.308$, $p < 0.01$) and marginally negatively correlated with scores of empathic concern ($r = -0.141$, $p = 0.053$).

P300

Figure 4a shows grand-average ERP waveforms at the CPz site. The peak amplitude of the P300 at CPz also was analyzed by a 3 (beneficiary: self vs. stranger-in-need vs. stranger-not-in-need) × 2 (reward valence: gain vs. loss) repeated-measures ANOVA. The main effect of reward valence was significant [$F(1,22) = 6.45$, $p < 0.05$, $\eta_p^2 = 0.226$], indicating that the P300 was larger for gain than for loss. The main effect of the beneficiary was also significant [$F(2,21) = 7.28$, $p < 0.05$, $\eta_p^2 = 0.409$]. Bonferroni-corrected pairwise comparison1s showed that the P300 was larger in the self condition than in both stranger conditions ($ps < 0.05$), whereas there was no difference between the stranger-in-need and stranger-not-in need conditions ($p = 0.092$). The interaction effect of beneficiary and reward valence was not significant [$\mathrm{F}(2,21) = 0.583$, $p = 0.57$, $\eta_p^2 = 0.053$]. Pearson correlation analysis also was conducted between the P300 for gain trails of three beneficiary conditions and task-related state measurements, as well as between the P300 for loss trails of three beneficiary conditions and task-related state measurements. However, neither the P300 of gain trails nor the P300 of loss trails was correlated with the subjective scores of motivation ($r_{\mathrm{win}} = 0.181$, $p = 0.12$; $r_{\mathrm{loss}} = 0.099$, $p = 0.41$) or empathic concern ($r_{\mathrm{win}} = -0.109$, $p = 0.17$; $r_{\mathrm{loss}} = -0.139$, $p = 0.25$).

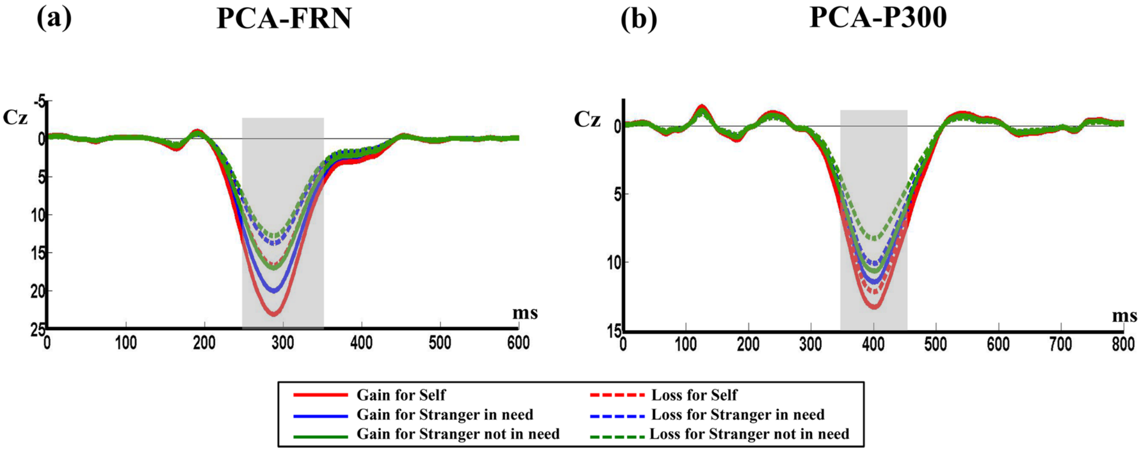

Fig. 5. Grand-average waveforms of the PCA-FRN (**a**) and PCA-P300 (**b**) at Cz electrode site. Gray areas indicate the time window of the PCA-FRN (250–350 ms) and the PCA-P300 (350–450 ms) used for statistical analysis

ERP results: temporospatial PCA factors

Figure 5a shows grand-average waveforms of the PCA-FRN at the Cz site. For the amplitude of the PCA-FRN, the main effect of the beneficiary was significant [$F(2, 21) = 9.17$, $p < 0.01$, $\eta_p^2 = 0.46$], indicating that the PCA-FRN differed among the three beneficiary conditions. The main effect of reward valence was significant [$F(1, 22) = 45.93$, $p < 0.01$, $\eta_p^2 = 0.67$], with a more negative PCA-FRN for loss than for gain. Importantly, there was a significant interaction effect of beneficiary × valence [$F(2, 21) = 5.36$, $p < 0.05$, $\eta_p^2 = 0.33$]. Further simple effect analyses were conducted to investigate this interaction. The results indicated that the valence effect of the PCA-FRN was smaller in the strangers-not-in-need condition [$F(1, 22) = 23.07$, $p < 0.01$, $\eta_p^2 = 0.51$] than in the stranger-in-need condition [$F(1, 22) = 49.15$, $p < 0.01$, $\eta_p^2 = 0.69$] and the self condition [$F(1, 22) = 40.86$, $p < 0.01$, $\eta_p^2 = 0.65$].

Figure 5b illustrates grand-average waveforms of the PCA-P300 at the Cz site. For the amplitude of the PCA-P300, the main effect of reward valence was significant [$F(1, 22) = 4.61$, $p < 0.05$, $\eta_p^2 = 0.17$], with a larger PCA-P300 for gain than for loss. The main effect of the beneficiary also was significant [$F(2, 21) = 6.07$, $p < 0.01$, $\eta_p^2 = 0.36$]. Bonferroni-corrected pairwise comparisons showed that the PCA-P300 was larger in the self condition than in both stranger conditions ($ps < 0.05$), whereas there was no difference between the stranger-in-need condition and stranger-not-in-need condition ($p = 0.29$). However, the interaction between beneficiary and reward valence did not reach significance [$F(2, 21) = 1.76$, $p = 0.19$, $\eta_p^2 = 0.14$].

To confirm the component identification, Pearson correlations between the amplitude of PCA components and conventionally averaged ERP components were computed. Results indicated the significant correlations between the FRN and the PCA-FRN ($r = 0.97$, $p < 0.01$), as well as between the P300 and the PCA-P300 ($r = 0.94$, $p < 0.01$).

Discussion

In this study, using a gambling task in which participants earned money for themselves and for two strangers, we examined the neural mechanism of empathic concern modulating the evaluation processes of others' outcomes when the interpersonal relationship was controlled. The ERP results showed that a larger FRN effect emerged in the stranger-in-need condition (high empathic concern) than in the stranger-not-in-need condition (low empathic concern), but no difference was found in the FRN effect between the self condition and the stranger-in-need condition. In addition, the P300 was larger in the self condition than in the two stranger conditions, but no difference emerged between the stranger-in-need and stranger-not-in-need conditions. Moreover, the PCA was applied to decompose ERP components, which were possibly overlapping in grand-averaged waveforms. The PCA factors showed a similar FRN and P300 pattern, which repeated our ERP results. These findings suggest that empathic concern can modulate the early stage of outcome processing. When gambling for strangers in need, individuals' neural responses to outcomes demonstrated an enhanced FRN effect.

The FRN was more negative-going to loss than to gain when gambling for each beneficiary, replicating the results of previous studies (Gehring & Willoughby, 2002; Kang, Hirsh, & Chasteen, 2010; Leng & Zhou, 2010, 2014; Ma et al., 2011; Zhu et al., 2016). These findings indicated that the FRN can be elicited by one's own outcomes and others' outcomes. More importantly, as expected, the FRN effect (loss minus win) was larger for the stranger in need than for the stranger not in need, suggesting that outcome feedback elicited a larger FRN effect in the high-empathy condition than in the low-empathy condition. Furthermore, subjective ratings of emotional empathy revealed marginally negative correlations with the FRN effect. Together, these results imply that the level of empathy modulated evaluative processing of others' outcomes. Based on the affective/motivational theory that the FRN reflects the early, rapid evaluation of the affective or motivational impact of outcomes (Gehring & Willoughby, 2002; Yu, Luo, Ye, & Zhou, 2007), a larger FRN effect in the high-empathy condition suggests stronger empathic emotional/altruistic motivational impacts of others' outcomes.

Some scholars have argued that the modulator of others' outcomes should be interpreted as an interpersonal factor (Kang, Hirsh, & Chasteen, 2010; Leng & Zhou, 2014; Ma et al., 2011; Zhu et al., 2016). Leng and Zhou (2014) reported increased FRN amplitude when participants played a gambling game on behalf of their best friends than for a stranger. Zhu et al. (2016) found similar results when participants made decisions for their mothers and for strangers. However, in the present study, we still observed the FRN effect after controlling for interpersonal factors. Larger FRN effects emerged when participants played the gambling game for a stranger in need than for one not in need. In addition, the study has shown that empathic responses can be modulated by the context of an interpersonal interaction (Dewall & Baumeister, 2006). Thus, it is possible that interpersonal factors modulate individuals' sense of empathy first, and then the empathy level directly affects evaluative processing of others' outcomes.

The FRN effect showed no difference between the self condition and stranger-in-need condition in this study, indicating that in the early processing stage of outcomes, neural responses to outcome feedback for oneself were similar to those for others upon inducing empathic concern. This result might support the notion of shared neural representations in empathy, which suggests that either observing or imagining affective states in others activates neural networks involved in first-hand experiences of these states (Cacioppo & Decety, 2009; Cui, Abdelgabar, Keysers, & Gazzola, 2015; Lamm, Decety, & Singer, 2011; Marsh et al., 2014; Singer et al., 2004). Singer et al. (2004) asked volunteers to observe their loved ones suffering from painful stimuli. Findings revealed that relevant brain areas, such as the anterior insula and dorsal-anterior midcingulate cortex, were activated in direct pain and vicarious pain situations, and the neural response to another's pain was as strong as that to one's own pain. Hence, the "shared representative network" was markedly activated in the vicarious pain condition when empathy was induced for others. Further evidence has substantiated the extent of empathy for basic human emotions, such as fear (Gelder et al., 2004), anger (De et al., 2012), sadness (Harrison, Singer, Rotshtein, Dolan, & Critchley, 2006), and disgust (Benuzzi, Lui, Duzzi, Nichelli, & Porro, 2008). Mobbs et al. (2009) extended pain-related empathy to social emotions by contrasting neural responses to earning rewards for socially desirable others versus earning money for oneself. The authors identified a similar neural mechanism in both situations, confirming that the shared representation network could apply to complex social emotions elicited by favorable or unfavorable outcomes. Accordingly, the shared neural network could be evoked in outcome processing when individuals expressed high empathic concern, making them more likely to experience another's feelings. Therefore, in the stranger-in-need condition of this study, individuals may feel more empathic concern for underprivileged students and express a strong altruistic motivation to help them, which could influence evaluative processing of others' outcomes.

Findings related to the P300 showed that the amplitude was larger for monetary wins than for losses when gambling for each beneficiary, consistent with previous studies (Goyer, Woldorff, & Huettel, 2008; Hajcak, Moser, Holroyd, & Simons, 2007; Leng & Zhou, 2010; Wu & Zhou, 2009). Interestingly, the P300 amplitude was larger in the self condition than in the two stranger conditions. It is consistent with the previous finding that the P300 was larger for the self-related outcomes than for the others' outcomes (such as friends or strangers) (Ma et al., 2011). Research also has found the P300 to be larger for self-relevant stimuli relative to control stimuli (Gray, Ambady, Lowenthal, & Deldin, 2004; Tacikowski & Nowicka, 2010). The P300 has been thought to be related to attentional allocation as well (Gray, Ambady, Lowenthal, & Deldin, 2004; Linden, 2005). Our findings indicate that participants allocated more attentional resources to their own outcome feedback than to that of others.

In contrast to the FRN, the P300 showed no difference between the high-empathy and low-empathy conditions, indicating that empathic concern did not modulate the late evaluative processing of others' outcomes. Moreover, subjective scores of empathic emotion were only related to the FRN, not the P300. These results indicate that the allocation of attentional resources reflected by the P300 cannot be modulated by empathic concern. The possible explanation is that the empathic emotion elicited in the present study is not strong enough to affect the allocation of attentional resources. The FRN could be modulated by the empathic concern, indicating that the empathic emotion toward others is indeed induced in the stranger-in-need condition. This further supports the affective/motivational theory of the FRN (Gehring & Willoughby, 2002). Leng and Zhou (2010) reported that the P300 was larger when gambling for friends than for strangers; therefore, the P300 could likely be modulated by an interpersonal relationship but not by empathic concern. As the others in the high-empathy and low-empathy conditions were strangers to the participants in this study, it is unsurprising that the P300 showed no differences between these conditions. However, because little work has considered this effect thus far, we must treat such speculative conclusions cautiously.

In summary, we found that empathic concern could modulate the early evaluative processing of others' outcomes. A stronger FRN effect in the stranger-in-need condition than in the stranger-not-in-need condition implies stronger empathic emotional/altruistic motivational impacts of outcomes for strangers in need. Despite our findings, this study had several limitations. For instance, we manipulated the level of empathic concern based on vulnerable strangers, which could activate altruistic motivations; thus, it was difficult to exclude the influence of motivation in the evaluative processing of others' outcomes. In future studies, it would be worthwhile to separate the factors of altruistic motivation and empathic concern and delineate their influences on evaluations of others' outcomes. In addition, accumulating evidence has revealed differences in women's and men's capacity for empathy (Christov-Moore et al., 2014; Gardner, Sorhus, Edmonds, & Potts, 2012; Schirmer, Simpson, & Escoffier, 2007) as well as among individuals with different social value orientations (Declerck & Bogaert, 2008). Fukushima and Hiraki (2006) found that discernable medial frontal negativity to opponents' outcomes emerged only for female participants but not for males. Therefore, individual differences in how empathy modulates outcome evaluations warrant further investigation.

Acknowledgements This work was supported by grants from the National Natural Science Foundation of China (31771206 and 31970986).

Open practices statement The data of this study are available from the corresponding author upon request. The study was not preregistered.

References

Batson, C.D., & Moran, T. (1999). Empathy-induced altruism in a prisoner's dilemma. *European Journal of Social Psychology, 29*(7), 909–924. doi:https://doi.org/10.1002/(SICI)1099

Batson, C.D., & Ahmad, N. (2001). Empathy-induced altruism in a prisoner's dilemma II: what if the target of empathy has defected? *European Journal of Social Psychology, 31*(1), 25-36. doi:https://doi.org/10.1002/ejsp.26

Bellebaum, C., & Daum, I. (2008). Learning-related changes in reward expectancy are reflected in the feedback-related negativity. *European Journal of Neuroscience, 27*(7), 1823-1835. doi:https://doi.org/10.1111/j.1460-9568.2008.06138.x

Benuzzi, F., Lui, F., Duzzi, D., Nichelli, P.F., & Porro, C.A. (2008). Does it look painful or disgusting? Ask your parietal and cingulate cortex. *Journal of Neuroscience, 28*(4), 923. doi:https://doi.org/10.1523/JNEUROSCI.4012-07.2008.

Cacioppo, J.T., & Decety, J. (2009). What are the brain mechanisms on which psychological processes are based? *Perspectives on Psychological Science, 4*(1), 10-18. doi:https://doi.org/10.1111/j.1745-6924.2009.01094.x.

Cao, J., Gu, R., Bi, X., Zhu, X., & Wu, H. (2015). Unexpected acceptance? patients with social anxiety disorder manifest their social expectancy in erps during social feedback processing. *Frontiers in Psychology, 6*, 1745. doi:https://doi.org/10.3389/fpsyg.2015.01745

Cohen, J. (1973). Eta-squared and partial eta-squared in fixed factor ANOVA designs. *Educational and Psychological Measurement, 33*(1), 107-112. doi:https://doi.org/10.1177/001316447303300111.

Christov-Moore, L., Simpson, E.A., Coude, G., Grigaityte, K., Iacoboni, M., & Ferrari, P.F. (2014). Empathy: gender effects in brain and behavior. *Neuroscience & Biobehavoral Reviews, 46*(4)604-627. doi:https://doi.org/10.1016/j.neubiorev.2014.09.001.

Cui, F., Abdelgabar, A.R., Keysers, C., & Gazzola, V. (2015). Responsibility modulates pain-matrix activation elicited by the expressions of others in pain. *NeuroImage, 114*, 371-378. doi:https://doi.org/10.1016/j.neuroimage.2015.03.034

Declerck, C.H., & Bogaert, S. (2008). Social value orientation: related to empathy and the ability to read the mind in the eyes. *The Journal of Social Psychology, 148*(6), 711. doi:https://doi.org/10.3200/SOCP.148.6.711-726.

De, G.M., Wang, G., Yang, X., Wang, X., Northoff, G., & Han, S. (2012). Neural substrates underlying intentional empathy. *Social Cognitive and Affective Neuroscience,7*(2), 135. doi:https://doi.org/10.1093/scan/nsq093.

Dewall, C.N., & Baumeister, R.F. (2006). Alone but feeling no pain: effects of social exclusion on physical pain tolerance and pain threshold, affective forecasting, and interpersonal empathy. *Journal of Personality & Social Psychology, 91*(1), 1-15. doi:https://doi.org/10.1037/0022-3514.91.1.1.

Dien, J. (2010). The EAP PCA toolkit: an open source program for advanced statistical analysis of event-related potential data. *Journal of Neuroscience Methods, 187*(1), 138-145. doi:https://doi.org/10.1016/j.jneumeth.2009.12.009

Foti, D., Weinberg, A., Dien, J., & Hajcak, G. (2011). Event-related potential activity in the basal ganglia differentiates rewards from nonrewards: response to commentary. *Human Brain Mapping, 32*(12), 2267-2269. doi:https://doi.org/10.1002/hbm.21358

Fukushima, H., & Hiraki, K. (2006). Perceiving an opponent's loss: gender-related differences in the medial-frontal negativity. *Social Cognitive and Affective Neuroscience, 1*(2), 149-157. doi:https://doi.org/10.1093/scan/nsl020.

Fukushima, H., & Hiraki, K. (2009). Whose loss is it? Human electrophysiological correlates of non-self reward processing. *Social Neuroscience, 4*(3), 261-275. doi:https://doi.org/10.1080/17470910802625009.

Gardner, M.R., Sorhus, I., Edmonds, C.J., & Potts, R. (2012). Sex differences in components of imagined perspective transformation. *Acta Psychologica, 140* (1), 1–6. doi:https://doi.org/10.1016/j.actpsy.2012.02.002.

Gehring, W.J., & Willoughby, A.R. (2002). The medial frontal cortex and the rapid processing of monetary gains and losses. *Science, 295*(5563), 2279-2282. doi:https://doi.org/10.1126/science.1066893.

Gelder, B.D., Snyder, J., Greve, D., Gerard, G., Hadjikhani, N., & Held, R. M. (2004). Fear fosters flight: a mechanism for fear contagion when perceiving emotion expressed by a whole body. *Proceeding of the National of Sciences, 101*(47), 16701-16706. doi:https://doi.org/10.1073/pnas.0407042101.

Gold, J. I., & Shadlen, M. N. (2007). The neural basis of decision making. *Annual review of neuroscience, 30*(1), 535-57. doi:https://doi.org/10.1146/annurev.neuro.29.051605.113038.

Goyer, J.P., Woldorff, M.G., & Huettel, S.A. (2008). Rapid Electrophysiological Brain Responses are Influenced by Both Valence and Magnitude of Monetary Rewards. *Journal of cognitive neuroscience, 20*(11), 2058-2069. doi:https://doi.org/10.1162/jocn.2008.20134.

Gray, H.M., Ambady, N., Lowenthal, W.T., & Deldin, P. (2004). P300 as an index of attention to self-relevant stimuli. *Journal of Experimental Social Psychology, 40*(2), 216-224. doi:https://doi.org/10.1016/S0022-1031(03)00092-1.

Hajcak, G., Holroyd, C.B., Moser, J.S., & Simons, R.F. (2005). Brain potentials associated with expected and unexpected good and bad outcomes. *Psychophysiology, 42*(2), 161-170. doi:https://doi.org/10.1111/j.1469-8986.2005.00278.x.

Hajcak, G., Moser, J. S., Holroyd, C. B., & Simons, R. F. (2007). It's worse than you thought: the feedback negativity and violations of reward prediction in gambling tasks. *Psychophysiology, 44*(6), 905-912. doi:https://doi.org/10.1111/j.1469-8986.2007.00567.x

Harrison, N.A., Singer, T., Rotshtein, P., Dolan, R.J., & Critchley, H.D. (2006). Pupillary contagion: central mechanisms engaged in sadness processing. *Social Cognitive and Affective Neuroscience, 1*(1), 5-17. doi:https://doi.org/10.1093/scan/nsl006.

Hauser, T.U., Iannaccone, R., Stampfli, P., Drechsler, R., Brandeis, D., Walitza, S., & Brem, S. (2014). The feedback-related negativity (FRN) revisited: new insights into the localization, meaning and network organization. *Neuroimage, 84,* 159-168. doi:https://doi.org/10.1016/j.neuroimage.2013.08.028.

Hollerman, J. R., & Schultz, W. (1998). Dopamine neurons report an error in the temporal prediction of reward during learning. *Nature Neuroscience, 1*(4), 304-309. doi:https://doi.org/10.1038/1124.

Holroyd CB, & Coles, M.G. (2002). The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. *Psychological Review, 109*(4), 679-709. doi:https://doi.org/10.1037//0033-295X.109.4.679.

Hu, X., Xu, Z., Li, Y., & Mai, X. (2018). The impact of trust decision-making on outcome processing: Evidence from brain potentials and neural oscillations. *Neuropsychologia, 119*, 136-144. doi:https://doi.org/10.1016/j.neuropsychologia.2018.07.036.

Hu, X., Xu, Z., & Mai, X. (2017). Social value orientation modulates the processing of outcome evaluation involving others. *Social Cognitive and Affective Neuroscience, 12*(11), 1730-1739. doi:https://doi.org/10.1093/scan/nsx102.

Kahnt, T., Heinzle, J., Park, S. Q., & Romo, H. R. (2010). The neural code of reward anticipation in human orbitofrontal cortex. *Proceedings of the National Academy of Sciences, 107*(13), 6010-6015. doi:https://doi.org/10.2307/25665106.

Kang, S.K., Hirsh, J.B., & Chasteen, A. L. (2010). Your mistakes are mine: Self-other overlap predicts neural response to observed errors. *Journal of Experimental Social Psychology, 46*(1), 229-232. doi:https://doi.org/10.1016/j.jesp.2009.09.012.

Kiat, M. A. J., & Cheadle, J. E. (2017). The impact of individuation on the bases of human empathic responding. *NeuroImage, 155,* 312-321. doi:https://doi.org/10.1016/j.neuroimage.2017.05.006

Kirsch, P., Schienle, A., Stark, R., Sammer, G., Blecker, C., Walter, B., … Vaitl, D. (2003). Anticipation of reward in a nonaversive differential conditioning paradigm and the brain reward system: an event-related fMRI study. *NeuroImage, 20*(2), 1086-1095. doi:https://doi.org/10.1016/s1053-8119(03)00381-1

Koban, L., Pourtois, G., Bediou, B., & Vuilleumier, P. (2012). Effects of social context and predictive relevance on action outcome monitoring. *Cognitive. Affective & Behavioral Neuroscience, 12*(3), 460-478. doi:https://doi.org/10.3758/s13415-012-0091-0.

Knutson, B., Adams, C. M., Fong, G. W., & Hommer, D. (2001). Anticipation of increasing monetary reward selectively recruits nucleus accumbens. *The Journal of neuroscience, 21*(16), RC159. doi: https://doi.org/10.0000/PMID11459880.

Knutson, B., Westdorp, A., Kaiser, E., & Hommer, D. (2000). Fmri visualization of brain activity during a monetary incentive delay task. *Neuroimage, 12*(1), 20-27. doi: https://doi.org/10.1006/nimg.2000.0593.

Kreussel, L., Hewig J., Kretschmer N., Hecht, H., Coles, M. G., & Miltner, W. H. (2012). The influence of the magnitude, probability, and valence of potential wins and losses on the amplitude of the feedback negativity. *Psychophysiology, 49*(2), 207-219. doi:https://doi.org/10.1111/j.1469-8986.2011.01291.x

Lamm, C., Decety, J., & Singer, T. (2011). Meta-analytic evidence for common and distinct neural networks associated with directly experienced pain and empathy for pain. *Neuroimage, 54*(3), 2492-2502. doi:https://doi.org/10.1016/j.neuroimage.2010.10.014.

Leng, Y., & Zhou, X. (2010). Modulation of the brain activity in outcome evaluation by interpersonal relationship: an ERP study. *Neuropsychologia, 48*(2), 448-455. doi:https://doi.org/10.1016/j.neuropsychologia.2009.10.002.

Leng, Y., & Zhou, X. (2014). Interpersonal relationship modulates brain responses to outcome evaluation when gambling for/against others: an electrophysiological analysis. *Neuropsychologia, 63*, 205-214. doi:https://doi.org/10.1016/j.neuropsychologia.2014.08.033.

Lewinsohn, S., & Mano, H. (1993). Multittribute choice and affect: the influence of naturally occurring and manipulated moods on choice processes. *Journal of Behavioral Decision Making, 6*(1), 33-51. doi: https://doi.org/10.1002/bdm.3960060103

Li, P., Han, C., Lei, Y., Holroyd, C.B., & Li, H. (2011). Responsibility modulates neural mechanisms of outcome processing: an erp study. *Psychophysiology, 48*(8), 1129-1133. doi:https://doi.org/10.1111/j.1469-8986.2011.01182.x.

Li, P., Jia, S., Feng, T., Liu, Q., Suo, T., & Li, H. (2010). The influence of the diffusion of responsibility effect on outcome evaluations: electrophysiological evidence from an ERP study. *Neuroimage, 52*(4), 1727-1733. doi:https://doi.org/10.1016/j.neuroimage.2010.04.275.

Linden, D.E. (2005). The p300: where in the brain is it produced and what does it tell us? *Neuroscientist, 11*(6), 563-576. doi:https://doi.org/10.1177/1073858405280524.

Liu, X., Hu, X., Shi, K., & Mai, X. (2018). Empathy modulates the evaluation processing of altruistic outcomes. *Frontiers in Psychology, 9*, e407. doi:https://doi.org/10.3389/fpsyg.2018.00407.

Ma, Q., Shen, Q., Xu, Q., Li, D., Shu, L., & Weber, B. (2011). Empathic responses to others' gains and losses: an electrophysiological investigation. *Neuroimage, 54*(3), 2472-2480. doi:https://doi.org/10.1016/j.neuroimage.2010.10.045.

Marco-Pallares, J., Kramer, U.M., Strehl, S., Schroder, A., & Munte, T. F. (2010). When decisions of others matter to me: an electrophysiological analysis. *BMC Neuroscience, 11*, e86. doi:https://doi.org/10.1186/1471-2202-11-86.

Marsh, A.A., Stoycos, S.A., Brethel-Haurwitz, K.M., Robinson, P., VanMeter, J. W., & Cardinale, E. M. (2014). Neural and cognitive characteristics of extraordinary altruists. *Proceeding of the National Academy of Sciences, 111*(42), 15036-15041. doi:https://doi.org/10.1073/pnas.1408440111.

Martín, R.S., Kwak, Y., Pearson, J.M., Woldorff, M.G., & Huettel, S. A. (2016). Altruistic traits are predicted by neural responses to monetary outcomes for self vs charity. *Social Cognitive and Affective Neuroscience, 11*(6), 863-876. doi:https://doi.org/10.1093/scan/nsw026.

Miltner, W.H., Braun, C.H., & Coles, M.G. (1997). Event-related brain potentials following incorrect feedback in a time-estimation task: Evidence for a "generic" neural system for error detection. *Journal of Cognitive Neuroscience, 9*(6), 788-798. doi:https://doi.org/10.1162/jocn.1997.9.6.788.

Mobbs, D., Yu, R., Meyer, M., Passamonti, L., Seymour, B., Calder, A.J., & Dalgleish, T. (2009). A key role for similarity in vicarious reward. *Science, 324*(5929), 900-900. doi:https://doi.org/10.1126/science.1170539.

Nieuwenhuis, S., Holroyd, C.B., Mol, N., & Coles, M.G. (2004). Reinforcement-related brain potentials from medial frontal cortex: origins and functional significance. *Neuroscience & Biobehavioral Review, 28*(4), 441-448. doi:https://doi.org/10.1016/j.neubiorev.2004.05.003.

Paulus, M. P. (2005). Neurobiology of decision-making: quo vadis? *Cognitive Brain Research, 23*(1), 2-10. doi:https://doi.org/10.1016/j.cogbrainres.2005.01.001

Paul, K., & Pourtois, G. (2017). Mood congruent tuning of reward expectation in positive mood: evidence from FRN and theta modulations. *Social Cognitive and Affective Neuroscience, 12*(5), 765-774. doi:https://doi.org/10.1093/scan/nsx010.

Preuschoff, K., Bossaerts, P., & Quartz, S. R. (2006). Neural differentiation of expected reward and risk in human subcortical structures. *Neuron, 51*(3), 381-390. doi:https://doi.org/10.1016/j.neuron.2006.06.024.

Proudfit, & Hajcak, G. (2015). The reward positivity: from basic research on reward to a biomarker for depression. *Psychophysiology, 52*(4), 449-459. doi:https://doi.org/10.1111/psyp.12370

Sato, A, Yasuda, A., Ohira, H, Miyawaki, K., Nishikawa, M., Kumano, H., & Kuboki, T. (2005). Effects of value and reward magnitude on feedback negativity and p300. *NeuroReport,16*(4), 407-411. doi: https://doi.org/10.1097/00001756-200503150-00020

Schirmer, A., Simpson, E., & Escoffier, N. (2007). Listen up! Processing of inten-sity change differs for vocal and nonvocal sounds. *Brain Research, 1176*, 103–112. doi:https://doi.org/10.1016/j.biopsycho.2010.03.009.

Schultz, W., Dayan, P., & Montague, P. R. (1997). A neural substrate of prediction and reward. *Science, 275*(5306), 1593-1599. doi:https://doi.org/10.1126/science.275.5306.1593.

Schupp, H.T., Cuthbert, B.N., Bradley, M.M., Cacioppo, J. T., Ito, T., & Lang, P. J. (2000). Affective picture processing: the late positive potential is modulated by motivational relevance. *Psychophysiology, 37*(2), 257–261. doi:https://doi.org/10.1111/1469-8986.3720257.

Semlitsch, H.V., Anderer, P., Schuster, P., &Presslich, O. (1986). A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology, 23*(6), 695-703. doi:https://doi.org/10.1111/j.1469-8986.1986.tb00696.x.

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*(5661), 1157-1162. doi:https://doi.org/10.1126/science.1093535.

Singer, T. (2006). The neuronal basis and ontogeny of empathy and mind reading: review of literature and implications for future research. *Neuroscience & Biobehavioral Reviews, 30*(6), 855-863. doi: https://doi.org/10.1016/j.neubiorev.2006.06.011

Stocks, E.L., Lishner, D.A., Waits, B.L., & Downum, E.M. (2011). I'm embarrassed for you: The effect of valuing and perspective taking on empathic embarrassment and empathic concern. *Journal of Applied Social Psychology, 41*, 1–26. doi:https://doi.org/10.1111/j.1559-1816.2010.00699.x.

Tacikowski, P., & Nowicka, A. (2010). Allocation of attention to self-name and self-face: an erp study. *Biological Psychology, 84*(2), 318-324. doi:https://doi.org/10.1016/j.biopsycho.2010.03.009

Talmi, D., Atkinson, R., & El-Deredy, W. (2013). The feedback-related negativity signals salience prediction errors, not reward prediction errors. *Journal of Neuroscience, 33*(19), 8264-8269. doi:https://doi.org/10.1523/JNEUROSCI.5695-12.2013

Wang, Y., Jing, Y., Zhang, Z., Lin, C., & Valadez, E. A. (2017). How dispositional social risk-seeking promotes trusting strangers: evidence based on brain potentials and neural oscillations. *Journal of Experimental Psychology General, 146*(8). doi:https://doi.org/10.1037/xge0000328

Wang, Y., Zhang, Z., Jing, Y., Valadez, E. A., & Simons, R. F. (2016). How do we trust strangers? The neural correlates of decision making and outcome evaluation of generalized trust. *Social Cognitive and Affective Neuroscience, 11*(10), 1666-1676. doi:https://doi.org/10.1093/scan/nsw079

Woltin, K.A., Corneille, O., Yzerbyt, V.Y., & Förster, J. (2011). Narrowing down to open up for other people's concerns: Empathic concern can be enhanced by inducing detailed processing. *Journal of Experimental Social Psychology, 47*(2), 418–424. doi:https://doi.org/10.1016/j.jesp.2010.11.006.

Wu, Y., & Zhou, X. (2009). The p300 and reward valence, magnitude, and expectancy in outcome evaluation. *Brain Research, 1286*, 114-122. doi:https://doi.org/10.1016/j.brainres.2009.06.032.

Yeung, N., & Sanfey, A. G. (2004). Independent coding of reward magnitude and valence in the human brain. *Journal of Neuroscience. 24*(28), 6258–64. doi:https://doi.org/10.1523/JNEUROSCI.4537-03.2004.

Yu, R., & Zhou, X. (2006). Brain responses to outcomes of one's own and other's performance in a gambling task. *Neuroreport, 17*(16), 1747. doi:https://doi.org/10.1097/01.wnr.0000239960.98813.50.

Yu, R., Luo, Y. J., Ye, Z., & Zhou, X. (2007). Does the FRN in brain potentials reflect motivational/affective consequence of outcome evaluation? *Progress in Natural Science,17*(B07), 136-143. doi: https://doi.org/10.1080/10020070612331343232

Zhang, D., Gu, R., Wu, T., Broster, L. S., Luo, Y., Jiang, Y., & Luo, Y. (2013). An electrophysiological index of changes in risk decision-making strategies. *Neuropsychologia, 51*(8), 1397-1407. doi:https://doi.org/10.1016/j.neuropsychologia.2013.04.014

Zhu, X., Wang, L., Yang, S., Gu, R., Wu, H., & Luo, Y. (2016). The Motivational Hierarchy between the Personal Self and Close Others in the Chinese Brain: an ERP Study. *Frontiers in Psychology, 7*, e91556. doi:https://doi.org/10.3389/fpsyg.2016.01467.

Zhu, X., Zhang, H., Wu, L., Yang, S., Wu, H., Luo, W., … Luo, Y. (2018). The influence of self-construals on the ERP response to the rewards for self and mother. *Cognitive. Affective & Behavioral Neuroscience, 18*(2), 366-374. doi:https://doi.org/10.3758/s13415-018-0575-7