Neuropsychologia 63 (2014) 205–214

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Interpersonal relationship modulates brain responses to outcome evaluation when gambling for/against others: An electrophysiological analysis

Yue Leng [a,b,*], Xiaolin Zhou [c,d]

[a] Research Center for Learning Science, Southeast University, Nanjing 210096, China
[b] Key Laboratory of Child Development and Learning Science (Ministry of Education), Southeast University, China
[c] Center for Brain and Cognitive Sciences and Department of Psychology, Peking University, China
[d] Key Laboratory of Machine Perception (Ministry of Education), Peking University, China

ARTICLE INFO

Article history:
Received 1 November 2013
Received in revised form
13 August 2014
Accepted 29 August 2014
Available online 8 September 2014

Keywords:
Outcome evaluation
Interpersonal relationship
The consequences for the observers
The FRN

ABSTRACT

When individuals play a gambling task and their actions have consequences for observers, how are the brain responses of the performers modulated by their interpersonal relationship with the observers? To address this issue, we examined the event-related potentials responses in performers while they played two gambling games: one during which they tried to earn money for the observers instead of themselves (i.e., Experiment 1) and another gambling game during which they attempted to earn money from the observers (i.e., Experiment 2). In Experiment 1, ERP results showed that when gambling for either the friends or the strangers, the feedback-related negativity (FRN) responses were more negative-going to the losses than to the gains. The FRN effect (loss minus gain) was significantly larger when gambling for the friends than for the strangers. The general P300 response was more positive-going when gambling for the friends than for the strangers. These results suggested that gambling for others enables individuals to assess the outcome from the interests of the other people, consequently, the FRN response may be driven by the evaluative process related to interests of the others. Because one's own economic interests were not involved, the performers' brain responses during both the early, semi-automatic stage (i.e., the FRN) and the later, controlled stage (i.e., the P300) of outcome evaluation were modulated by the interpersonal relationship between the performers and the observers. In Experiment 2, ERP results revealed that when gambling against others, the FRN response was more negative-going to the losses than to the gains, as well. However, neither the FRN effect nor the general FRN response was modulated by interpersonal relationship. The general P300 response was more positive-going when gambling against the stranger than against the friend. These results suggested that when gambling against others, the performers' FRN response may be driven by two evaluative processes: one is related to the interests of their own, and another is related to the interests of the other people; and the former one plays a dominant role. Because of highly self-involvement, only the performers' brain responses during the later controlled stage of outcome evaluation were modulated by interpersonal relationship. The present study extended previous research on brain responses to outcome evaluation when decision making actions have consequences for the other people by suggesting that the FRN response in *the performer* could also be driven by two evaluative processes. In addition, whether the FRN in the performer was modulated by interpersonal relationship depends on which evaluative process plays a dominant role. However, the P300 in the performer could always be modulated by interpersonal relationship. These findings provide evidence on outcome evaluation being composed of an early semi-automatic primitive process and a later controlled cognitive/affective appraisal process.

1. Introduction

In social life, it is common that the actions of one person have consequences for another person. For example, the fund managers make investments for their investors, and children play rock paper scissors. Previous fMRI studies have shown that actions and their

* Corresponding author at: Research Center for Learning Science Southeast University Nanjing 210096 China. Fax: +86 25 83795664.
E-mail address: lengyue@seu.edu.cn (Y. Leng).

http://dx.doi.org/10.1016/j.neuropsychologia.2014.08.033
0028-3932/

consequences to another person can elicit observers' emotional/empathic responses and related neural activities in the anterior insula (AI) and the anterior cingulate cortex (ACC), which can further be modulated by some social factors, such as the intimacy between the observer and the other person (Singer et al., 2004), and the perceived fairness of the other person (Singer et al., 2006).

Neuropsychological studies on outcome processing of action in the gambling task have found a special event-related potentials (ERP) component encoding the valence of outcome. This component named feedback-related negativity (FRN), which is a negative deflection at frontocentral recording sites that reaches maximum between 200 and 300 ms following the onset of feedback stimulus. The FRN is more pronounced for negative than for positive outcomes (Gehring & Willoughby, 2002; Holroyd & Coles, 2002; Miltner, Braun, & Coles, 1997; Nieuwenhuis, Holroyd, Mol, & Coles, 2004). In some situation, the FRN valence effect can be interpreted by reinforcement learning theory (Holroyd & Coles, 2002; Nieuwenhuis et al., 2004), which proposes that the FRN reflects the impact of midbrain dopamine signals upon anterior cingulate cortex (ACC). The phasic decreases in dopamine inputs elicited by negative prediction errors (i.e., "the result is worse than expected") give rise to the increased ACC activity that is reflected as larger FRN amplitudes. The phasic increases in dopamine signals elicited by positive prediction errors (i.e., "the result is better than expected") give rise to decreased ACC activity that is reflected as smaller FRN amplitudes. In other context, the motivational/affective account (Gehring & Willoughby, 2002; Masaki, Takeuchi, Gehring, Takasawa, & Yamazaki, 2006; Yu, Luo, Ye, & Zhou, 2007) fares better, suggests that the FRN does not reflect the cognitive processes of evaluating performance or detecting prediction errors per se, but rather, it reflects the processes of assessing the motivational/affective impact of outcome, i.e., the processes of putting subjective values onto the outcome. To date, the FRN effect upon outcome valence has been found to be modulated by a number of social factors including interpersonal relationship in rewarding process (Ma et al., 2010; Wu, Leliveld, & Zhou, 2011), the extent of others including in the "self" concept (Kang, Hirsh, & Chasteen, 2010), the extent of personal responsibility for the outcome (Li, Han, Lei, Holroyd, & Li, 2011; Li et al., 2010; Zhou, Yu, & Zhou, 2010), the extent of trust relationship between individuals (Long, Jiang, & Zhou, 2012), and the frame effect (Ma, Feng, Xu, Bian, & Tang, 2012).

Recently, a growing amount of studies began to investigate electrophysiological responses to outcome evaluation in observers when the actions of one person have consequences for the other people (Fukushima & Hiraki, 2006; Itagaki & Katayama, 2008; Marco-Pallares, Kramer, Strehl, Schroder, & Munte, 2010). Yu and Zhou (2006) firstly reported a similar FRN effect elicited when the participant observed the feedback given resulted from another person's action (Yu & Zhou, 2006). However, in this experiment, the consequence of the performer's action is irrelevant to the observer. Thereafter, Fukushima and Hiraki (2006) contrasted the brain activity in perception to one's own and another's monetary gains or losses in a competitive two-person gambling game, in which one's monetary gain (loss) resulted in the other's loss (gain). The authors found the female participants instead of the male participants exhibited the classical FRN when observing the opponent's loss. Importantly, the FRN in such situation was negatively correlated to the affect score. These findings altogether reflect the empathic response of females to another person's losses (Fukushima & Hiraki, 2006). In Itagaki and Katayama's (2008) study, the observers experienced two situations in the gambling task, one is the cooperative situation in which they could gain or lose the same amount of money as another virtual participant, and the other is the antagonistic situation in which they could gain or lose the opposite amounts of money to the virtual participant. The results showed that the losses of the cooperators as well as the gains of the opponents elicited the observers' FRN. Therefore, the authors explained that the FRN in observers reflects the outcome evaluation on the basis of one's own evaluative criteria, instead of the monetary outcome for the other people. Then, Marco-Pallares et al. (2010) compared the FRN responses of the observers in three different groups. In the neutral group, the observer just looked at the performer's action, which had no consequences for the observers. In the parallel group, the gains (losses) of the performer led to the gains (losses) of the observer. In the reverse group, the gains of the performer led to the losses of the observer and vice versa. The results showed that the FRN responses of the observers in the neutral and parallel groups were similar, with more negative-going for the performer's losses than for the performer's gains, whereas, the differential FRN effect of the observers upon valence in the reverse group was reversed, being more negative-going FRN response for the performer's gains than for the performer's losses. In consideration of previous findings, the authors suggested that the FRN response in observers is driven by two evaluative processes, one is related to the benefit/loss for oneself and another is related to the benefit/loss of another person (Marco-Pallares et al., 2010).

However, little is known about how performers' actions and their consequences to another person modulate *performers*' own psychological and neural responses to outcome evaluation. To address this issue, Li et al. (2010)'s work might give some inspiration. They compared the FRN response under two conditions, one is the participants performing the gambling with other two partners, and another is the participants performing the gambling individually. Playing the gamble with another two people means each performer's action will determine not only one's own but also other two partners' monetary gains or losses. Therefore, in relative to performing the gambling task on one's own, the performer's action having consequence for other partners lowered one's own sense of responsibility. In fact, the results really showed that the FRN effect upon valence was significantly larger under the high-responsibility condition than that under the low-responsibility condition. The authors suggested that such differential FRN effects are associated with different degrees of perceived personal responsibility for the outcome elicited by two conditions (Li et al., 2010). This study successfully investigated how personal responsibility influenced the neural response to outcome evaluation. From another aspect, it also provides some evidence on how performers' actions and their consequences for the other people modulate performers' brain activities in outcome evaluation. Nevertheless, to clarify this question, more research is needed.

Another ERP component, the P300, is usually defined as the most positive peak in the 250–600 ms time window (Ma et al., 2010; Zhou et al., 2010) or mean amplitude in certain time window after 200 ms (Wu et al., 2011) post-onset of feedback on centro-posterior recording sites. The P300 is traditionally believed to be related to the processing of attentional distribution (Gray, Ambady, Lowenthal, & Deldin, 2004; Yeung & Sanfey, 2004). In addition, it has been found to encode various aspects of feedback stimuli, including the magnitude of reward (Sato et al., 2005), the valence of feedback (Hajcak, Holroyd, Moser, & Simons, 2005; Hajcak, Moser, Holroyd, & Simons, 2007; Wu & Zhou, 2009; Yeung & Sanfey, 2004), as well as to be sensitive to some social factors, such as interpersonal relationship in reward processing (Leng & Zhou, 2010; Ma et al., 2010), and the level of personal responsibility for the outcome (Li et al., 2011, 2010).

Our previous study in 2010, first suggested that the brain activity in outcome evaluation can be divided into an early semi-automatic processing indexed by the FRN, and a later controlled processing indexed by the P300, and even found that the later stage rather than the early stage be modulated by interpersonal relationship (Leng & Zhou, 2010). Afterwards, Ma et al. (2010) repeated and extended this study by excluding self-execution condition, just comparing the brain potentials when observing the gambling outcome of the friend with brain responses when observing the gambling outcome of the stranger. Both the brain activities during the early stage (i.e., the FRN) and the later stage (i.e., the P300) were modulated by interpersonal relationship (Ma et al., 2010). To be mentioned here, the economic interests of the participants (i.e., the friend and the stranger) were independent from each other in these two studies. Then, if under the circumstance that the economic interest relationship between the performer and the observer (i.e., either the friend or the stranger) is inter-dependent, how the brain activities in outcome evaluation would be affected by interpersonal relationship?

The first aim of this study is to investigate whether the FRN response in *performers* could also be driven by two evaluative processes, one is related to the interest for oneself and another is related to the interest of another person. Second, we are going to examine whether and how brain responses to outcome evaluation including early and later stage would be modulated by the interpersonal relationship between the performer and the observer, when the performers' action had consequences for the observers. Therefore, we conducted two ERP experiments to measure brain potentials of the performers when they played the gambling task either to earn money for or to make money from the observers (i.e., either the friends or the stranger). In Experiment 1, we created a situation that the performer's gambling action having no consequence for the performer him/herself but leading to the corresponding monetary gains and losses of the observer (i.e., gamble for others). Given that the hypothesis of two evaluative processes for the FRN in observers is also fit for the FRN response in performers, gambling for others enables the participant to assess the outcome only from the interests of the other people, leading to the FRN in performers being more negative-going for the others' losses than for the others' gains. Previous studies found that the interpersonal relationship between one and the other (i.e., familiar vs. strange) might modulate individuals' emotional (empathic) responses to others' outcome, which could be detected by the FRN or the P300 (Leng & Zhou, 2010; Ma et al., 2010). In addition, the performer's own economic interest being irrelevant to the gambling might facilitate the modulation of interpersonal relationship on outcome evaluation including both the early and later stages (Ma et al., 2010). Accordingly, we could obtained the similar results. In Experiment 2, we created another situation that the performer's gambling action not only leading to direct consequences to him/herself, but also leading to inverse consequence to the observer (i.e., gamble against others). Gambling against others makes the participants to assess the outcome from both the interests of their own and of the other people, therefore, two evaluative processes may compete with each other. However, because of self-interest, the FRN in performers would be mainly triggered by the evaluative process related to one's own benefits/losses, with more negative-going for their losses than for their gains. Because of self-engagement, we predicted that interpersonal relationship might modulate the P300 responses rather than the FRN responses.

2. Experiment 1 (gambling for others)

2.1. Method

2.1.1. Participants

Twelve gender-matched pairs of graduate students (4 female pairs) were recruited through the University intranet. All the pairs were self-reported good friends, the mean period of acquaintances was 14.5 months (SD=6.05).The answers to “how much they were familiar/intimate with their friends (1=“not at all” to 5=“extremely”) showed that the participants felt familiar (M=4.33, SD=.52) and intimate with their friends (M=4.50, SD=.50). The mean age of the main participants undergoing the EEG test was 24.1 years, ranging between 21 and 29 years. Two graduate students (1 female and 1 male, aged 24 and 23 years, respectively), who were strangers to the friend pairs, were recruited as confederates. All the participants were healthy and right-handed, and had normal or corrected-to-normal vision. They had no history of neurological or psychiatric disorders. Informed consents were obtained from them before the experiment, which was approved by Academic Committee of Research Center for Learning Science, Southeast University, China.

2.1.2. Procedures

Each EEG participant was instructed to gamble for a same-sex friend and a stranger in a task in which each round began with the presentation of the friend's or the stranger's name and the participant had to bet between two cards encoding monetary reward. While the EEG participant would sit inside a sound-and-electronically shielded chamber, his/her friend and the stranger sat in another room and observed the gambling process through a computer network. The participant was paid 30 Chinese Yuan regardless of their performance, whereas the friend and the stranger were paid according to the participant's performance on top of a 10-Yuan payoff. The experiment had two main factors: agency (friend vs. stranger) and reward valence (gain vs. loss). The EEG participant was asked to be attempting to earn as much as possible for both his/her friend and the stranger.

The EEG participant was seated about 1 m in front of a Dell 22-in. CRT display (screen resolution: 1024 × 768, refresh rate: 120 Hz, color quality: highest 32 bit). Each trial began with a fixation sign (a white dot subtended .4° of visual angle) against black background. After 800, 900, 1000 or 1100 ms, randomly, either the friend's or the stranger's name (white and size 28, font Courier, bold) was presented above the fixation sign (see Fig. 1). After a further 1000 ms, two gray cards (each subtended 2.3° × 3.2°, separated for 3.7° between the centers of the cards) printed with 5 or 25 (white and size 28, font Courier, bold) representing the amount of money involved in the current round of gamble (i.e., “25” representing 2.5 yuan, and “5” representing .5 yuan) were presented on the left and the right side of the fixation sign, respectively. The EEG participant was asked to press one of the two buttons on the keyboard to select one number for the named confederate. Then the background of the selected card turned red or green for 1000 ms, to show whether the named confederate had gained or lost the amount of money indicated by the chosen numeral. The assignment of the two colors as “gain” and “loss” was counterbalanced over participants. To emphasize the valence and the magnitude of outcome and to attract the participant's attention, the “+” or “−” symbol was added before the numeral to represent the gain/loss status of the outcome. The inter-trial interval was 500 ms.

Unknown to the participant, the gain/loss status of the participant's chosen numeral was determined by a pre-specified pseudo-random sequence, with half the times gaining and another half losing, and with the restriction that no more than 4 consecutive trials were the same gain/loss status for both the friend condition and the stranger condition. For half of the participants, each experimental block began with a trial for the friend, followed by a trial for the stranger; for another half, each experimental block began with a trial for the stranger, followed by a trial for the friend. The experiment consisted of 9 blocks of 40 trials each. Each

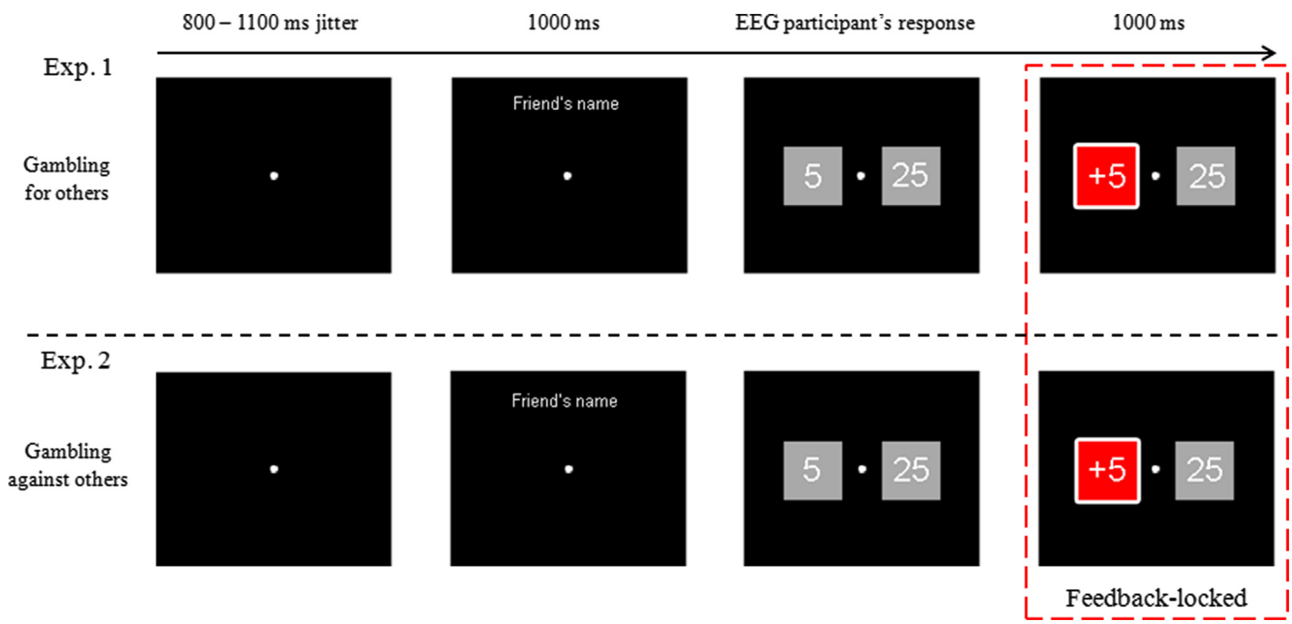

Fig. 1. Sequences of events in a single trial in Experiment 1 and Experiment 2.

block had 20 trials for the "friend" and the "stranger" conditions, respectively. The current state of reward was communicated to the EEG participant and two confederates at the end of each block. A practice block containing 24 trials was administered before the formal test.

After the EEG test, the EEG participants were asked to complete a 5-point scale to rate their subjective feeling of "interest" and "willingness" to the task, "expectancy", "attention" and "emotional response" to the outcomes. Specifically, they were asked to rate how interesting they found the task was (1 = "very boring" to 5 = "very interesting"); how much they were willing to gamble for their friends (or the stranger) (1 = "not at all" to 5 = "extremely"); how much attention they paid to the outcomes (1 = "ignored the outcome" to 5 = "paid close attention to the outcome"); how much they expected to win (lose) money when gambling for their friends (or the stranger) (1 = "not at all" to 5 = "extremely"); how they felt for their choices leading to their friends' (or the stranger's) gains (losses) (1 = "very unhappy" to 5 = "very happy"). Moreover, the EEG participants also reported the period of acquaintance with their friends.

2.1.3. Recording and analysis

EEGs were recorded from 64 scalp sites using tin electrodes mounted in an elastic cap (NeuroScan, Inc. Herndon, Virginia, USA) according to the international 10–20 system, with the reference on the left mastoid. Eye blinks were monitored with electrodes located above and below the right eye. The horizontal electro-oculogram (EOG) was recorded from electrodes placed 1.5 cm lateral to the left and right external canthi. All electrodes impedance was maintained below 5 kΩ. The EEG and EOG signals in .05–70 Hz band-pass were amplified 2010 times, and continuously sampled at 500 Hz for offline analysis.

Separate EEG epochs of 700 ms (with 100 ms pre-stimulus baseline) were extracted offline, time-locked to the onset of feedback stimuli. Epochs were referenced offline to the linked mastoid electrodes. Ocular artifacts were corrected with an eye-movement correction algorithm which employs a regression analysis in combination with artifact averaging(Semlitsch, Anderer, Schuster, & Presslich, 1986). Epochs were baseline-corrected by subtracting from each sample the average activity of that channel during the baseline period. All trials in which EEG voltages exceeded a threshold of $\pm 70\,\mu V$ during recording were excluded from further analysis. The EEG data were low-pass filtered below 30 Hz.

The analyzed ERP components included the FRN and the P300. Time windows were selected for analysis based on visual inspection of the grand-average waveforms and topographic maps (see Fig. 3A, B). For the FRN, we measured the mean amplitudes in the time window of 200–280 ms; for the P300, we measured the mean amplitudes in the time window of 280–360 ms. For statistical analyses, we focused on FCz and Cz, on which the FRN and the P300 were the greatest although we also conducted analyses for amplitudes on a group of electrodes by including electrode as a within-participant factor. Analysis of variance (ANOVA) was conducted with two within-participant factors: agency (friend vs. stranger) and valence (gain vs. loss). The factor of reward magnitude was collapsed in this study because in the preliminary analysis, neither the main effect nor interaction between experimental factors was found in the selected time window. The Greenhouse–Geisser correction for violation of the ANOVA assumption of sphericity was applied where appropriate. Bonferroni correction was used for multiple comparisons.

3. Results

3.1. Behavior results

Friends and strangers gained on average 11.8 yuan and lost on average 3.3 yuan for extra monetary reward at the end of experiment, respectively. For the friend condition, the distribution of the participants making their bets and getting rewards was as followed: gain "25" (M=29.21%, SD=6.33%), loss "25" (M=25.07%, SD=6.66%), gain "5" (M=20.79%, SD=6.33%), loss "5" (M=24.33%, SD=6.66%). For the stranger condition, the distribution of the participants making their bets and getting rewards was as following: gain "25" (M=26.55%, SD=6.16%), loss "25" (M=27.50%, SD=7.08%), gain "5" (M=23.45%, SD=6.16%), loss "5" (M=22.50%, SD=7.08%).Two-way analysis of variance (ANOVA) on the portion over agency (friend vs. stranger), the selected bet (i.e., reward magnitude: 5 vs. 25) revealed a significant main effect of magnitude, $F(1,44)=6.31$, $p<.05$, suggesting that the participants select large bet (54.60%) significantly more than small bet (45.40%), regardless whether gambling for their friends or for the stranger. Besides, no other main effect or interaction reached significance.

3.2. Subjective ratings

Paired *t*-test showed that participants paid more attention to outcomes when gambling for their friends (4.58) than for the stranger (3.14), $t(11)=2.38$, $p<.05$ (see Fig. 2A).

Two-way ANOVA on the subjective rating of expectancy towards gambling outcome over agency (friend vs. stranger) and valence (gain vs. loss) (see Fig. 2B) revealed a significant main effect of valence, $F(1,44)=169.23$, $p<.001$, indicating that participants expected to win money (4.42) than to lose money (1.92) for others. The interaction between agency and valence reached significance as well, $F(1,44)=22.75$, $p<.001$. Simple effect analysis showed that for both the friend and the stranger trials, the main effect of valence was significant, $F(1,22)=234.06$, $p<.001$, $F(1,22)=25.62$, $p<.001$,indicating that participants expected to win money than to lose money for both their friends and the stranger. For the gain trials, the main effect of agency was significant, $F(1,22)=9.48$, $p<.001$, indicating that participants' expectancy level towards gains was higher for their friends (4.83) than for the stranger (4.00). For the loss trials, the main effect of agency also reached significance, $F(1,22)=13.42$, $p<.001$, indicating that participants' expectancy level towards losses was lower for the friends (1.42) than for the stranger (2.42).

Two-way ANOVA on the subjective rating of feeling of happiness towards gambling outcome over agency (friend vs. stranger) and valence (gain vs. loss) (see Fig. 2C) revealed a significant main effect of valence, $F(1,44)=169.38$, $p<.001$, indicating that participants felt happier after the gain feedback (4.33) than after the loss feedback (1.96). The interaction between agency and valence reached significance as well, $F(1,44)=11.73$, $p<.05$. Simple effect analysis showed that under both the friend and stranger conditions, the main effect of valence was significant, $F(1,22)=222.75$, $p<.001$, $F(1,22)=33.00$, $p<.001$, indicating that whenever gambling for their friends or for the stranger, participants felt happier after the gain feedback than after the loss feedback. For the gain trials, the main effect of agency was significant, $F(1,22)=6.77$, $p<.05$, indicating that participants felt happier when wining for their friends (4.67) than for the stranger (4.00). For the loss trials, the main effect of agency was also significant, $F(1,22)=5.04$, $p<.05$, indicating that participants felt more unhappy when losing for their friends (1.67) than for the stranger (2.25).

3.3. ERP results

3.3.1. The FRN

The two-way repeated-measures ANOVA over agency (friend vs. stranger) and reward valence (win vs. loss) (see Fig. 3B) revealed a significant main effect of agency, $F(1,11)=27.82$, $p<.001$, with ERP responses being more negative-going when gambling for the stranger (8.03 μV) than for their friends (12.56 μV). The main effect of valence was significant, $F(1,11)=42.82$, $p<.001$, with ERP responses being more negative-going for the loss feedback (7.16 μV) than for the gain feedback (13.44 μV). Importantly, the interaction between agency and valence reached significance, $F(1,11)=15.09$, $p<.001$, indicating that the size of FRN effect (loss minus gain) was significantly larger for the friend condition than for the stranger condition.

3.3.2. The P300

The two-way ANOVA of the P300 mean amplitude over agency and reward valence (see Fig. 3B) revealed a significant main effect of agency, $F(1,11)=28.40$, $p<.001$, with the P300 being more positive for the friend condition (17.89 μV) than for the stranger condition (12.51 μV). The main effect of valence was significant, $F(1,11)=32.84$, $p<.001$, with the P300 being more positive for the gain trials (17.74 μV) than for the loss trials (12.66 μV). However, the interaction between these two factors did not reach significance, $p>.1$.

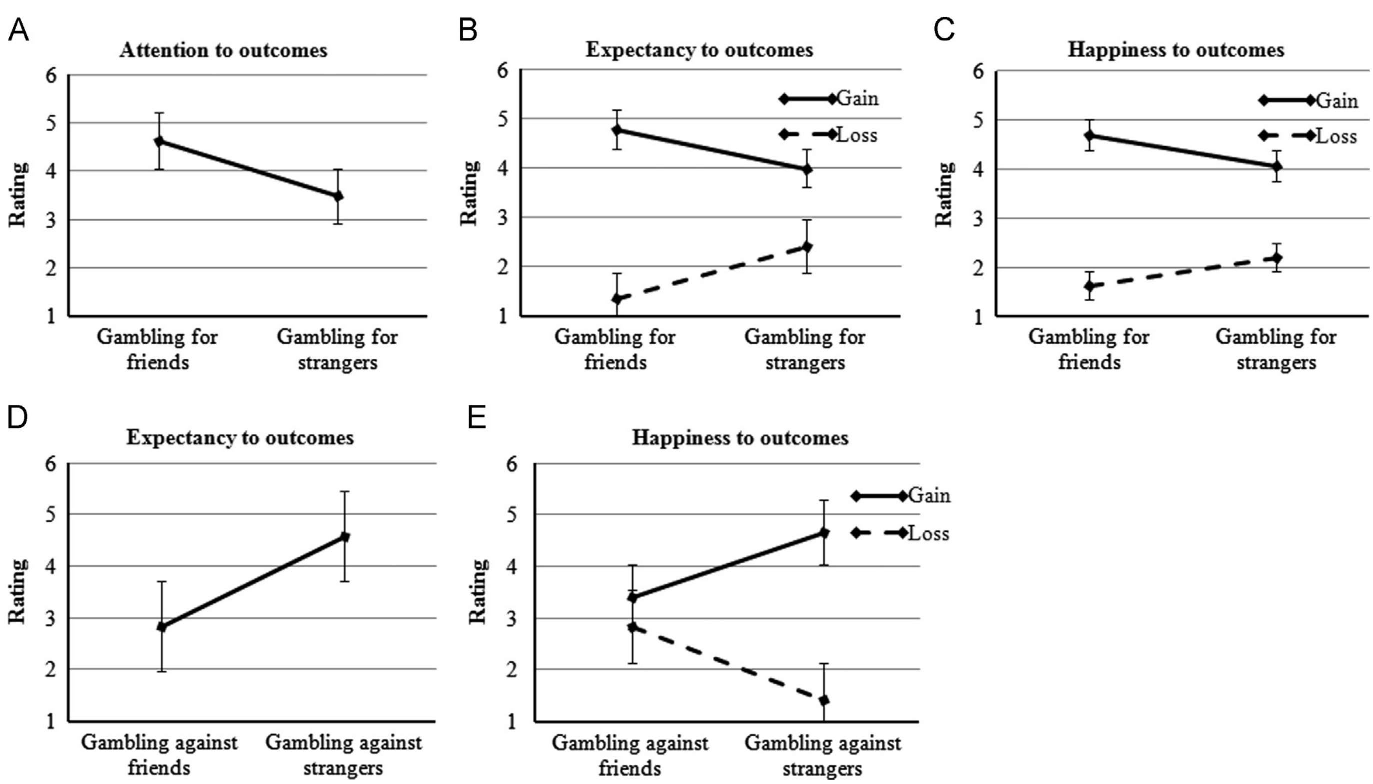

Fig. 2. Subjective ratings results of Experiment 1 and Experiment 2.

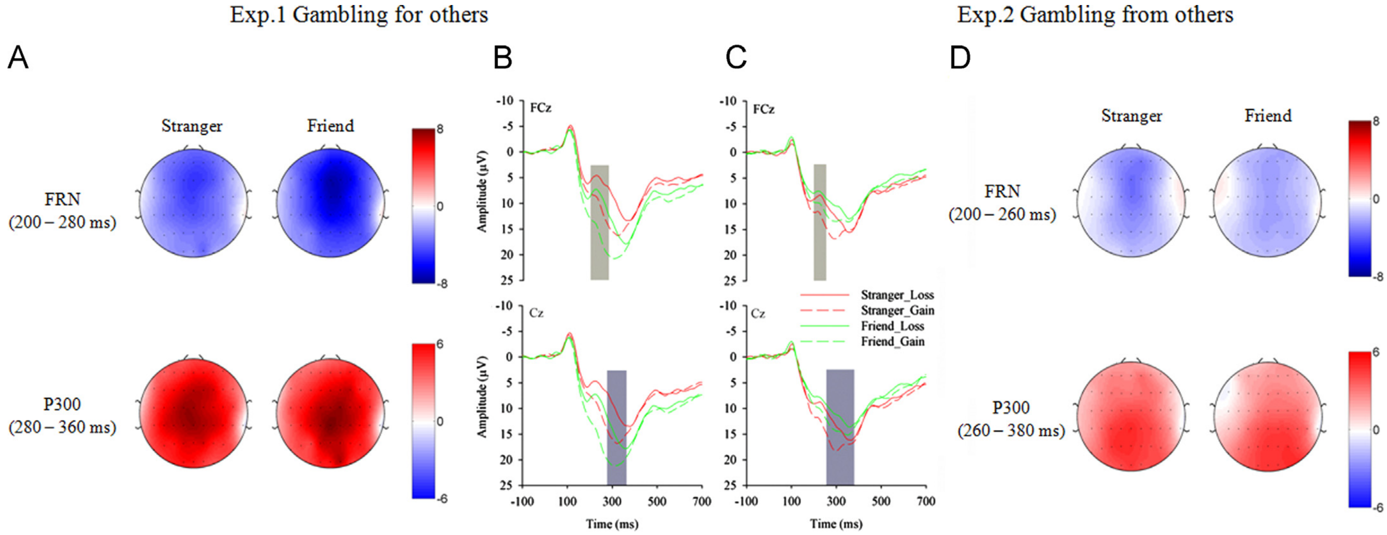

Fig. 3. (A) Topographic maps of the difference wave (loss minus gain) for the stranger and the friend conditions in the 200–280 ms time window (the upper panels) and topographic maps of the difference wave (gain minus loss) for the stranger and the friend conditions in the 280–360 ms time window (the lower panels) in Experiment 1. (B) Grand-average ERP waveforms for loss trials (solid line) and gain trials (dash line) at FCz, under the stranger condition (red lines), and the friend condition (green lines) in Experiment 1. The gray shaded areas indicate the 200–280 ms time window (the upper panels) for measuring the FRN mean amplitude, and 280–360 ms time window (the lower panels) for measuring the P300 mean amplitude. (C) Grand-average ERP waveforms for loss trials (solid line) and gain trials (dash line) at Cz, under the stranger condition (red lines), and the friend condition (green lines) in Experiment 2. The gray shaded areas indicate the 200–260 ms time window (the upper panels) for measuring the FRN mean amplitude, and 260–380 ms time window (the lower panels) for measuring the P300 mean amplitude. (D) Topographic maps of the difference wave (loss minus gain) for the stranger and the friend conditions in the 200–260 ms time window (the upper panels) and topographic maps of the difference wave (gain minus loss) for the stranger and the friend conditions in the 260–380 ms time window (the lower panels) in Experiment 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

The finding of the FRN in performers being more negative-going to losses than to gains when gambling either for their friends or for the strangers, replicated many previous studies (Gehring & Willoughby, 2002; Holroyd & Coles, 2002; Holroyd, Hajcak, & Larsen, 2006; Leng & Zhou, 2010; Yeung, Holroyd, & Cohen, 2005). Although actions by the performers having no consequence to the performers themselves, the FRN valence effect was also found. A recent study demonstrated that the FRN response in the observer may be driven by two evaluative processes when the actions of one person have consequences for the other people, i.e., one is related to the benefit/loss for oneself and another is related to the benefit/loss of another person (Marco-Pallares et al., 2010). In the current experiment, because one's own economic interests are excluded, it is possible that the performer only evaluate the outcomes subjectively from the interests of the other people. Specifically, the losses of others were regarded as the negative outcomes, whereas the gains of others were regarded as the positive outcomes. Therefore, it can be inferred that the FRN response in the performer being more negative for the loss outcome than for the gain outcome may be merely driven by the evaluative process related to the benefit/loss of another person. Importantly, this FRN effect was modulated by interpersonal relationship between the performer and the observer, with larger effect size when gambling for the friend than for the stranger.

Previous studies have shown that the degree of personal responsibility could influence the neural responses to performers' outcome evaluation (Coricelli et al. 2005; Li et al., 2011, 2010). By using fMRI technique, Coricelli et al. (2005) found stronger outcome-related BOLD signal activities in the striatum when the participants performing the gambling on themselves (i.e., with responsibility) than activities when the computer performing the gambling (i.e., without responsibility). Recently, Li et al. (2010, 2011) reported that the FRN can be modulated by the personal responsibility to the action's consequence with larger FRN valence effect for the higher responsibility condition than for the lower responsibility condition either elicited by social pressure (Li et al., 2010) or by the controllability of outcomes (Li et al., 2010). In our experiment, gambling for others means taking responsibility for others. Therefore, the results can be explained that the intimate relationship between the performer and the observer mediates performer's perceived degree of responsibility to outcomes, thereby, leads to the enhanced FRN effect towards gambling outcomes when the performer gambling for his/her friend than for the stranger.

The finding of the P300 response to outcomes over the central sites in the 280–360 ms time window being more positive when wining money than losing money for others was consistent with many previous findings (Goyer, Woldorff, & Huettel, 2008; Hajcak et al., 2005, 2007; Hajcak, Moser, Holroyd, & Simons, 2006; Holroyd & Krigolson, 2007; Holroyd, Larsen, & Cohen, 2004; Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003; Leng & Zhou, 2010; Wu & Zhou, 2009; Yeung et al., 2005; Zhou et al., 2010). In addition, the general P300 response to outcomes was also influenced by interpersonal relationship, with more positive amplitude when gambling for the friend than for the stranger. This result was in agreement with the finding in our previous study (Leng & Zhou, 2010). It is widely known that the P300 is related to distribution of attention resource, therefore, such P300 sensitivity to interpersonal relationship could be interpreted that the familiarity between the performers and the observers influenced individuals' attention involvement. Li et al. (2010) suggested that the P300 reflect the processing of high cognitive function, due to the amplitude of P300 being modulated by perceived degree of responsibility (Li et al., 2010). Thus, it is possible that the interpersonal relationship modulates participants' sense of personal responsibility, thereby affected the later attentional process of outcome evaluation.

All these data demonstrated that the performer's neural response to outcome evaluation can be modulated by interpersonal relationship between the performer and the observer (i.e., the friend or the stranger), when his/her gambling's outcomes only leading to the corresponding monetary gains or losses for the observer rather than one's own. To verify the hypothesis of the FRN in the performer being triggered by two evaluative process, we decided to conduct the next experiment to examine the performer's FRN in another situation that the performer's action would lead to not only his/her own monetary gains or losses, but also the other's reversed monetary outcomes. In addition, we were going to test how the performer's brain response to outcome evaluation in that situation would be modulated by interpersonal relationship.

5. Experiment 2 (gambling against others)

5.1. Method

5.1.1. Participants

Twelve gender-matched pairs of graduate students (5 female pairs) were recruited through the University intranet. All the pairs were self-reported good friends, the mean period of acquaintances was 18.50 months (SD=5.98).The answer to "how much they were familiar/intimate with their friends (1="not at all" to 5="extremely") showed that the participants felt familiar (M=4.50, SD=.67) and intimate with their friends (M=4.58, SD=.67). The mean age of the main participants undergoing the EEG test was 23.7 years, ranging from 21 to 31 years. Two graduate students (1 female and 1 male, aged 24 and 23 years, respectively), who were strangers to the friend pairs, were recruited as opponents. All the participants were healthy and right-handed, and had normal or corrected-to-normal vision. They had no history of neurological or psychiatric disorders. Informed consents were obtained from them before the experiment, which was approved by Academic Committee of Research Center for Learning Science, Southeast University, China.

5.1.2. Procedures

Each EEG participant was instructed to gamble against a same-sex friend and a stranger in a task in which each round began with the presentation of the friend's or the stranger's name and the participant had to bet between two cards encoding monetary reward. While the EEG participant would sit inside a sound-and-electronically shielded chamber, his/her friend and the stranger sat in another room and observed the gambling process through a computer network. The friend and stranger were paid 30 Chinese yuan (about $5) as basic payment, respectively. The EEG participant was paid 60 Chinese yuan (about $10) as basic payment to play against the friend and stranger, alternatively. After the experiment, the friend and stranger were paid 10 Chinese yuan as final payment, respectively. To motivate the EEG participants performing the gambling task against the friend and stranger equally, they were asked to draw lots as to whether the outcomes of gambling against the friend or against the stranger to be the additional monetary rewards. The experiment had two main factors: agency (friend vs. stranger) and reward valence (gain vs. loss). The EEG participant was asked to be attempting to earn as much as possible.

The task for Experiment 2 was identical to Experiment 1 except that the background of the selected card turning red or green indicated the monetary gains or losses for the EEG participants and the reversed monetary outcomes for the named opponents.

After the EEG test, the EEG participants were asked to complete a 5-point scale to rate their subjective feeling of "interest" to the task, "expectancy" and "emotion response" to the outcomes, and "familiarity" and "intimacy" with their friends. Specifically, they were asked to rate how interesting they found the task was (1="very boring" to 5="very interesting"); how much they expected to win (lose) money when gambling against their friends (or the stranger) (1="not at all" to 5="extremely"); how they felt for their monetary gains (losses) when gambling against their friends (or the stranger) (1="not at all" to 5="extremely"); how much they were familiar/intimate with their friends (1="not at all" to 5="extremely"). Moreover, the EEG participants also reported the period of acquaintance with their friends.

5.1.3. Recording and analysis

The EEG recording and data analysis in Experiment 2 were identical to Experiment 1 except that the mean amplitude of the FRN on FCz was measured in the time window of 200–260 ms, and the mean amplitude of the P300 on Cz was measured in the time window of 260–380 ms (see Fig. 3C and D).

6. Results

6.1. Behavior results

The EEG participants gained on average 10.5 yuan when gambling against the friends, and gained 10.1 yuan when gambling against the stranger for extra monetary rewards at the end of experiment, respectively. For the friend condition, the distribution of the participants making their bet and getting rewards was as followed: gain "25" (M=22.87%, SD=11.21%), loss "25" (M=20.14%, SD=10.90%), gain "5" (M=27.13%, SD=11.21%), loss "5" (M=29.86%, SD=10.90%). For the stranger condition, the distribution of the participants making their bets and getting rewards was as following: gain "25" (M=31.25%, SD=8.14%), loss "25" (M=27.82%, SD=8.03%), gain "5" (M=18.80%, SD=8.15%), loss "5" (M=22.18%, SD=8.03%).

The two-way analysis of variance (ANOVA) on the portion over agency (friend vs. stranger), the selected bet (i.e., reward magnitude: 5 vs. 25) revealed a significant interaction between agency and magnitude, $F(1,44)=9.09$, $p<.05$. Simple-effect analysis showed that when gambling against the stranger, the main effect of magnitude was significant, $F(1,22)=8.69$, $p<.05$, indicating that the participant selected big bet (59.10%) more than small bet (41.00%).

6.2. Subjective ratings

Paired t-test showed that participants had higher expectancy to win money when gambling against the stranger (4.58) than against their friends (2.83), $t(11)=-4.08$, $p<.05$ (see Fig. 2D). The two-way ANOVA on the subjective rating of feeling of happiness towards gambling outcomes over agency (friend vs. stranger) and valence (gain vs. loss) (see Fig. 2E), revealed a significant main effect of valence, $F(1,44)=68.86$, $p<.001$, indicating that participants felt happier after they won (4.04) than after they lost (2.13). The interaction between agency and valence reached significance as well, $F(1,44)=33.33$, $p<.001$. Tests of simple effect showed that for the stranger condition, the main effect of valence was significant, $F(1,22)=249.72$, $p<.001$, with higher rating of happiness towards gains (4.67) than towards losses (1.42), whereas for the friend condition, the main effect of valence did not reach significance, $p>.1$. These results suggested that only when gambling against the stranger, participants' feeling of happiness is sensitive to the valence of outcomes. For the gain trials, the main effect of agency was significant, $F(1,22)=13.24$, $p<.001$, indicating that participants felt happier when wining against the stranger (4.67) than against their friends (3.42). For the loss trials, the main effect of agency was also significant, $F(1,22)=21.05$, $p<.05$, indicating that participants felt less unhappy when losing against their friends (2.83) than against the stranger (1.42).

6.3. ERP results

6.3.1. The FRN

The two-way repeated-measure ANOVA over agency (friend vs. stranger) and reward valence (win vs. loss) (see Fig. 3C), revealed a significant main effect of valence, $F(1,11)=6.80$, $p<.05$, with ERP responses being more negative-going after the loss feedback (8.53 μV) than after the gain feedback (11.60 μV). However, the agency factor had neither significant main effect nor interaction effect with valence, $p>.1$.

6.3.2. The P300

ANOVA of the mean amplitude of the P300, with the two within-participant factors (agency and reward valence) (see Fig. 3C), revealed a significant main effect of agency, $F(1,11)=4.51$, $p<.05$, with the P300 being more positive when gambling against the stranger (20.54 μV) than gambling against the friend (12.99 μV). However, the valence factor had neither significant main effect nor interaction effect with agency, $p>.1$.

7. Discussion

In consistent with Experiment 1, the FRN in the performer was more negative-going to losses than to gains, whenever gambling against the friend or the stranger. Here, gambling against others means the interest of the performer conflicts with the interest of the observer. Borrowing the idea from two evaluative processes hypothesis of the FRN response in the observer, and due to self-engagement and self-interest, the FRN in the performer can be explained as the outcome evaluative process associated with one's own benefits/losses overcoming the outcome evaluative process associated with the other person's benefits/losses. Therefore, this result indicated again that two evaluative processes hypothesis could be extended to the FRN responses in the performer.

However, neither the general FRN response nor the FRN effect (i.e., loss minus gain) was modulated by interpersonal relationship. These results replicated Leng and Zhou (2010)'s findings. It has been suggested that outcome evaluation entails both the semi-automatic process (indexed by the FRN) and the intentional process (indexed by the P300), and when the performer's own interests are involved, the interpersonal relationship can affect the later process instead of the early process (Leng & Zhou, 2010). In Experiment 2, the participants played the gambling task as the performers and their actions had consequences for both themselves and the observers. According to the two evaluative processes hypothesis, the involvement of one's own interest may enable the performer to neglect whether the opponent is familiar or not, therefore, the evaluative process associated with one's own benefits/losses may be dominant so that neither the FRN nor the FRN effect is modulated by interpersonal relationship.

For the P300 response, we did not find its amplitude was sensitive to reward valence, such null valence effect was consistent with the findings of previous studies on ERP responses to outcome evaluation in the performer when the economic relationship between the performer and the observer is opposite (Fukushima & Hiraki, 2006; Itagaki & Katayama, 2008). However, similar to Experiment 1, the general P300 response to outcomes was modulated by interpersonal relationship, though the pattern was reversed, with more positive amplitude when gambling against the stranger than against the friend. Previous studies have claimed that the P300 reflects high-level cognitive/affective evaluation of the outcome (Nieuwenhuis, Aston-Jones, & Cohen, 2005; Yeung & Sanfey, 2004). It has also been reported that the general P300 response could be modulated by some social factors, including the extent of personal responsibility for outcomes (Li et al., 2011, 2010), interpersonal relationship of rewarding processing (Leng & Zhou, 2010; Ma et al., 2010). In Experiment 2, under the circumstance that the economic interest relationship between the performer and the observer being antagonistic, the feedback of the stranger may be more salient because the impact is more clear—gains are good for the participant, and losses are bad. In contrast, the feedback of the friend seems to be more mixed, since gains are good for the participant but bad for the friend, and vice versa. Therefore, we believed that more positive P300 amplitudes when gambling against the stranger than against the friend may reflect differential distribution of attentional resources to such two types of feedback which had different motivational significances.

8. General discussion

By conducting two experiments, the present study investigated how the performer's psychological and neural responses to outcome evaluation were modulated by interpersonal relationship when the performer's action have consequences for the observer (either his/her friend or the stranger). In Experiment 1, gambling for others (i.e., the friend or the stranger) means the actions by the performer being of no consequence to the performer him/herself; but the positive (negative) outcomes leading to the other person's benefits (losses). The subjective ratings showed that compared with gambling for the strangers, gambling for their friends made the participants feel more willing to gamble, expect to win more but lose less, feel happier when winning and unhappier when losing. In Experiment 2, gambling against others (i.e., the friend or the stranger) means the performer's success of gambling action not only leading to the monetary gains for him/herself, but also leading to the monetary losses for the observer, and vice versa. The results of subjective rating showed that compared with gambling against the strangers, the participants had higher expectancy towards winning money, and larger discrepancy of happiness between gain and loss outcomes when gambling against their friends. Our two experiments obtained consistent findings that the FRN responses in the performer encoded outcome valence. However, the modulations on the FRN and the general P300 response by interpersonal relationship were distinct. In Experiment 1, both the FRN effect upon valence and the general P300 response were modulated by interpersonal relationship. In Experiment 2, only the general P300 response was modulated by interpersonal relationship but with the opposite pattern. In the following paragraph, we discuss these findings separately.

8.1. The FRN response in the performer is triggered by two evaluative processes

In recent years, a few studies investigated how the actions and their consequences for another person would modulate the *observer's* psychological and neural responses. The economic interest relationship between the performer and the observer included parallel (Marco-Pallares et al., 2010) and conflict (Fukushima & Hiraki, 2006; Itagaki & Katayama, 2008; Marco-Pallares et al., 2010). Taking into account all these studies, it has been suggested that the FRN response in *observers* is driven by two evaluative processes, one is related to the benefit/loss for oneself, and the other is related to the benefit/loss of another person. The present study by employing two situations (i.e., gambling for others and gambling against others) attempted to explore whether the FRN response in *performers* could also be driven by such two evaluative processes.

Here, although both experiments showed the FRNs in the performer were more negative for the losses than for the gains, the triggers were completely different. In one situation that the successful action of the performer only had positive consequence for the observer, and vice versa (i.e., gambling for others in Experiment 1), the action in the gambling task had nothing to do with the performer's economic interest. Therefore, the FRN responses were only triggered by the evaluative process associated with the benefit/loss of the observer, with more negative-going ERP responses to loss outcomes than to gain outcomes. However, in another situation that the successful action of the performer not only led to positive consequence for him/herself, but also led to negative consequence for the observer and vice versa (i.e., gambling against others in Experiment 2), the performer's economic interest was also involved in the gambling. Therefore, the FRN responses were mainly triggered by the evaluative process associated with the benefits/losses of the performer, though this process competed with the process related to the benefits/losses of the observer; thereby, leading to more negative-going ERP response to loss outcomes than to gain outcomes.

8.2. Whether the FRN response is modulated by interpersonal relationship depends on which system plays a dominant role

The differential FRN responses to losses and gains in Experiment 1 were modulated by interpersonal relationship, this findings replicated some results in Ma et al. (2010)'s study. In their second experiment, the participant just observed the other people (either his/her friend or the stranger) playing the gambling, and his/her economic interest was not involved. Then, the modulation on the FRN effect upon valence by interpersonal relationship was found, with larger size for the friend's outcomes than for the stranger's outcomes. The authors explained such finding that when the participant was excluded from the game, the interpersonal familiarity with the friend strengthened the empathic response towards the friend's monetary losses and gains (Ma et al., 2010).

However, neither the valence effect on FRN nor the general response of FRN was modulated by interpersonal relationship in Experiment 2. This result replicated some previous findings (Leng & Zhou, 2010; Ma et al., 2010). It has been shown that self-engagement may influence people's perception of the others' losses and gains (Fukushima & Hiraki, 2009). In both our earlier study and the first experiment in Ma et al. (2010)'s study, because of the participant's self-engagement, the early semi-automatic process of outcome evaluation indexed by the FRN can only distinguish the participant's own outcomes from other people's outcomes, but cannot differentiate between outcomes of the friend and outcomes of the stranger further.

Taking into account the hypothesis of two evaluative processes, in Experiment 1, the FRN response in the performer was triggered by the evaluative process associated with observer's benefits/losses; whereas in Experiment 2, the FRN response in the performer was mainly triggered by the evaluative process associated with the performer's own benefits/losses. Therefore, the differential FRN effects in Experiment 1 and Experiment 2 may suggest that only when the evaluative process associated with the benefit/loss of the observer plays a dominant role, the FRN response might be modulated by interpersonal relationship.

8.3. The performer's P300 general response is modulated by interpersonal relationship

It has been claimed that P300 reflects a later high-level cognitive/affective process of outcome evaluation which is attention-sensitive. In the present study, the findings of the general P300 responses in both Experiment 1 and Experiment 2 being modulated by interpersonal relationship were consistent with our previous findings (Leng & Zhou, 2010), which can be explained that being familiar with the friend increased the social/affective significance of his/her outcome. In addition, some previous studies have shown that the general P300 response could be modulated by some other social factors, including extent of personal responsibility for outcomes (Li et al., 2011, 2010). Taken together, we suggested that the P300 reflect the controlled top-down process that is sensitive to factors affecting the allocation of attention resources or high-level social/affective evaluation.

The findings in our study have the implications for outcome evaluation that the actions and their consequences for the other people could not only modulate the observers' but also the performers' psychological and neural responses. Moreover, such responses could be affected by social factors (e.g., interpersonal relationship). This study provides a supplementary for research on brain activities in outcome evaluation when decision making actions have consequences for the other people.

9. Conclusion

The present study extended previous research on neural responses to outcome evaluation when individual's actions have consequences for the other people, and suggested that the FRN response in the *performer* could also be driven by two evaluative processes, one is associated with the interests of their own, and another is associated with the interests of the other people. In addition, whether the FRN in the performer was modulated by interpersonal relationship depends on which evaluative process plays a dominant role. However, the general P300 response in the *performer* could always be modulated by interpersonal relationship. These findings provide evidence on outcome evaluation being composed of an early semi-automatic primitive process and a later controlled cognitive/affective appraisal process.

Acknowledgements

The work was supported in part by the National Natural Science Foundation of China under Grant 61375118, the National Basic Research Program of China under Grant 2015CB351704, and the Natural Science Foundation of Jiangsu Province of China under Grant BK20140621.

References

Coricelli, G., Critchley, H. D., Joffily, M., O'Doherty, J. P., Sirigu, A., & Dolan, R. J. (2005). Regret and its avoidance: a neuroimaging study of choice behavior. *Nature Neuroscience*, *8*(9), 1255–1262.

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.

Fukushima, H., & Hiraki, K. (2009). Whose loss is it? Human electrophysiological correlates of non-self reward processing. *Social Neuroscience*, *4*(3), 261–275.

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.

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.

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.

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.

Hajcak, G., Moser, J. S., Holroyd, C. B., & Simons, R. F. (2006). The feedback-related negativity reflects the binary evaluation of good versus bad outcomes. *Biological Psychology*, *71*(2), 148–154.

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.

Holroyd, C. B., & Coles, M. G. H. (2002). The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, *109*(4), 679–709.
Holroyd, C. B., Hajcak, G., & Larsen, J. T. (2006). The good, the bad and the neutral: electrophysiological responses to feedback stimuli. *Brain Research*, *1105*(1), 93–101.
Holroyd, C. B., & Krigolson, O. E. (2007). Reward prediction error signals associated with a modified time estimation task. *Psychophysiology*, *44*(6), 913–917.
Holroyd, C. B., Larsen, J. T., & Cohen, J. D. (2004). Context dependence of the event-related brain potential associated with reward and punishment. *Psychophysiology*, *41*(2), 245–253.
Holroyd, C. B., Nieuwenhuis, S., Yeung, N., & Cohen, J. D. (2003). Errors in reward prediction are reflected in the event-related brain potential. *NeuroReport*, *14*(18), 2481–2484.
Itagaki, S., & Katayama, J. i. (2008). Self-relevant criteria determine the evaluation of outcomes induced by others. *NeuroReport*, *19*(3), 383–387.
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.
Leng, Y., & Zhou, X. (2010). Modulation of the brain activity in outcome evaluation by interpersonal relationship: an ERP study. *Neuropsychologia*, *48*(2), 448–455.
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.
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.
Long, Y., Jiang, X., & Zhou, X. (2012). To believe or not to believe: trust choice modulates brain responses in outcome evaluation. *Neuroscience*, *200*, 50–58.
Ma, Q., Feng, Y., Xu, Q., Bian, J., & Tang, H. (2012). Brain potentials associated with the outcome processing in framing effects. *Neuroscience Letters*.
Ma, Q., Shen, Q., Xu, Q., Li, D., Shu, L., & Weber, B. (2010). Empathic responses to others' gains and losses: an electrophysiological investigation. *Neuroimage* *54*(3), 2472–2480.
Marco-Pallares, J., Kramer, U., Strehl, S., Schroder, A., & Munte, T. (2010). When decisions of others matter to me: an electrophysiological analysis. *BMC Neuroscience*, *11*(1), 86.
Masaki, H., Takeuchi, S., Gehring, W. J., Takasawa, N., & Yamazaki, K. (2006). Affective-motivational influences on feedback-related ERPs in a gambling task. *Brain Research*, *1105*(1), 110–121.
Miltner, W. H. R., Braun, C. H., & Coles, M. G. H. (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.
Nieuwenhuis, S., Aston-Jones, G., & Cohen, J. D. (2005). Decision making, the P3, and the locus coeruleus–norepinephrine system. *Psychological Bulletin*, *131*(4), 510–532.
Nieuwenhuis, S., Holroyd, C. B., Mol, N., & Coles, M. G. H. (2004). Reinforcement-related brain potentials from medial frontal cortex: origins and functional significance. *Neuroscience & Biobehavioral Reviews*, *28*(4), 441–448.
Sato, A., Yasuda, A., Ohira, H., Miyawaki, K., Nishikawa, M., Kumano, H., et al. (2005). Effects of value and reward magnitude on feedback negativity and P300. *Neuroreport*, *16*(4), 407–411.
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.
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.
Singer, T., Seymour, B., O'Doherty, J. P., Stephan, K. E., Dolan, R. J., & Frith, C. D. (2006). Empathic neural responses are modulated by the perceived fairness of others. *Nature*, *439*(7075), 466–469.
Wu, Y., Leliveld, M. C., & Zhou, X. (2011). Social distance modulates recipient's fairness consideration in the dictator game: an ERP study. *Biological Psychology*, *88*(2), 253–262.
Wu, Y., & Zhou, X. (2009). The P300 and reward valence, magnitude, and expectancy in outcome evaluation. *Brain Research*, *1286*, 114–122.
Yeung, N., Holroyd, C. B., & Cohen, J. D. (2005). ERP correlates of feedback and reward processing in the presence and absence of response choice. *Cerebral Cortex*, *15*(5), 535–544.
Yeung, N., & Sanfey, A. G. (2004). Independent coding of reward magnitude and valence in the human brain. *The Journal of Neuroscience*, *24*(28), 6258–6264.
Yu, R., Luo, Y., Ye, Z., & Zhou, X. (2007). Does the FRN in brain potentials reflect motivational/affective consequence of outcome evaluation? *Progress in Natural Science*, *17*(13), 136–143.
Yu, R., & Zhou, X. (2006). Brain responses to outcomes of one's own and other's performance in a gambling task. *Neuroreport*, *17*(16), 1747–1751.
Zhou, Z., Yu, R., & Zhou, X. (2010). To do or not to do? Action enlarges the FRN and P300 effects in outcome evaluation. *Neuropsychologia*, *48*(12), 3606–3613.