International Journal of Psychophysiology 85 (2012) 145–152

Contents lists available at SciVerse ScienceDirect

International Journal of Psychophysiology

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

Brain potentials in outcome evaluation: When social comparison takes effect

Yan Wu [a,b,c,*], Dexuan Zhang [a], Bill Elieson [a], Xiaolin Zhou [b,d]

[a] *Department of Psychology, School of Educational Sciences, Hangzhou Normal University, Hangzhou 310036, China*
[b] *Center for Brain and Cognitive Sciences and Department of Psychology, Peking University, Beijing 100871, China*
[c] *Key Laboratory of Child Development and Learning Science, Ministry of Education, Southeast University, Nanjing 210096, China*
[d] *Key Laboratory of Machine Perception, Ministry of Education, Peking University, Beijing 100871, China*

ARTICLE INFO

Article history:
Received 29 November 2011
Received in revised form 4 June 2012
Accepted 6 June 2012
Available online 13 June 2012

Keywords:
Outcome evaluation
Social comparison
ERP
FRN
P300
LPP

ABSTRACT

Social comparison, in which people evaluate their opinions and abilities by comparing them with the opinions and abilities of others, is a central feature of human social life. Previous work has highlighted the importance of social comparison in reward processing. However, the time-course of the social comparison effect in outcome evaluation remains largely unknown. The purpose of this study was to explore to what extent brain activity is modulated by social comparison between an individual and their anonymous partner. Event-related potentials (ERPs) were measured while the participants viewed their own and their partner's gain and loss outcomes based on their performance in a dot estimation task. Analysis of ERPs revealed that the feedback-related negativity (FRN) amplitude differences between gains and losses were not modulated by social comparison. In contrast, the P300 was larger for gains and showed an effect of social comparison independent of feedback valence. A late component, the late positive potential (LPP), was also modulated by social comparison, but it was insensitive to feedback valence. The data suggest that social comparison modulates outcome evaluation at several points in the information processing stream. Social comparison has no effect on the early coarse evaluation stage, but modulates the late cognitive/affective appraisal and re-appraisal processes. These findings provide neurophysiological evidence for the importance of social comparisons in outcome evaluations by the human brain.

1. Introduction

Social comparison is the process through which people come to know themselves by evaluating their own attitudes, abilities, outcomes, and beliefs in comparison with others (Wood, 1996). Since Festinger's first proposal of social comparison theory (Festinger, 1954), work on social comparison has been growing. Research on social comparison has developed into a complex area encompassing cognitive mechanisms and applications (Buunk and Gibbons, 2007; Fazio, 1979; Fishbein et al., 1963; Gibbons, 1999; Greenberg et al., 2007; Kumar, 2004; McCreary and Saucier, 2009; Poeschl, 2001; Ruble et al., 1980; Stapel and Marx, 2006; Zell and Alicke, 2009). Social comparison has been recognized as an important social psychological phenomenon, and extensive effort has been devoted to understanding its causes and their cognitive and emotional consequences. However, very little is known about the neural mechanisms underlying social comparison and how it affects and illuminates outcome evaluation.

Recent studies in social neuroscience have begun to identify brain networks involved in social comparison. Evidence from imaging research suggests that brain activity in reward-related regions is affected by contextual information about the other person's payment. Specifically, the activation in the bilateral ventral striatum, a region known to be critically involved in reward processing, was lowest for when less money was earned when compared to the other player, followed by the condition of equal payment. Activation was highest when a participant earned more money than the other player. The effect of relative comparisons is independent of the level of payment (high or low) (Fliessbach et al., 2007). Social comparison has also been shown to be related to activation of the dorsal striatum, midbrain/thalamus, anterior insula and medial prefrontal cortex (MPFC) in an interactive, simulated social context (Zink et al., 2008), suggesting a role of social comparison in reward processing. A study using electroencephalographic (EEG) recordings identified event-related brain potential (ERP) correlates with this social comparison effect. Both disadvantageous and advantageous unequal payoff elicited a larger late negative component (LNC), between 550 and 750 ms, when compared to equal payoff conditions (Qiu et al., 2010). Source analysis revealed that the generators of the LNC were localized near the caudate nucleus. This result is consistent with imaging studies that showed the influence of social comparison on outcome evaluation when monetary reward was involved.

Most research on social comparison has focused on the neural mechanisms of reward processing, especially positive rewards (e.g., gains). Only recently have researchers begun to address the fact that social comparison usually arises when people are facing adversity or unfortunate

---

* Corresponding author at: Department of Psychology, Hangzhou Normal University, Hangzhou, 310036, China.
E-mail address: lewuyan@126.com (Y. Wu).

0167-8760/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijpsycho.2012.06.004

circumstances (e.g., losses or punishment). In an fMRI study, for example, researchers investigated the emotional and neural responses associated with upward social comparison (comparison with those who have more) and downward social comparison (comparison with those who have less) (Dvash et al., 2010). Interestingly, even when participants lost money, they expressed joy and schadenfreude (gloating) if the other player had lost more money. On the other hand, when they actually won money, but the other player had won more, they expressed envy. This pattern was reflected in the activities of the ventral striatum. These results highlight the emotional consequences of social comparison in the loss domain. Less clarity, however, exists about the time course of brain responses to the social comparison effect of losses.

To address this question, the present study used EEG recordings aimed at exploring the time-course of the social comparison effect on outcome evaluation when both positive and negative rewards were involved. We were interested in how social comparison affects different stages in the process of outcome evaluation. According to previous neurophysiological studies, two ERP components are particularly sensitive to the aspects of reward and performance outcome. The first component is called feedback-related negativity (FRN) or medial-frontal negativity (MFN), which is a negative deflection in the frontocentral recording sites that reaches maximum amplitude between 250 and 300 ms following the onset of feedback stimulus (Gehring and Willoughby, 2002; Heldmann et al., 2008; Holroyd and Coles, 2002; Holroyd et al., 2004; Miltner et al., 1997; Nieuwenhuis et al., 2004a; Yu and Zhou, 2006a, 2006b, 2009). FRN is more pronounced when there are errors, conflicts, unexpected punishments, aﬁnd negative (t)15.5(h)0(e)-5(e)00.7(5(t)-444(ingt)12.c12.c10)0(25.7(6(i)TD0o)14.3)19.7(.1908(h)0(o)27.9(u)m-8.T

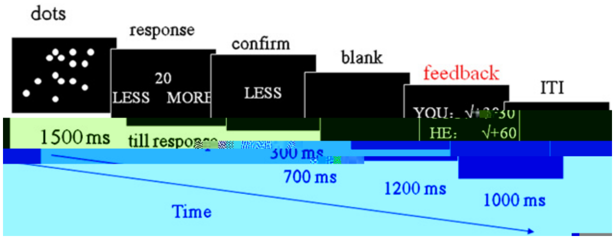

Fig. 1. Experimental task. Subjects participated in a dots-estimation task adapted from the Fliessbach et al. (2007) study. Each trial began with a screen showing between 20 and 48 white dots for 1500 ms. This screen was replaced by a number that was ±1 from the number of dots previously shown. The participant had to decide whether he/she had seen more or fewer dots than this number. The participant indicated his/her answers using a joystick. A response changed the screen display, which then displayed the selected response for 300 ms. After a 700 ms delay, a feedback screen was displayed for 1200 ms. This screen revealed to the participant whether he/she and his/her partner were correct (indicated by a "+" sign) or not (indicated by a "−" sign) as well as the amount of money they earned or lost in this trial.

2.3. Experimental design

The experiment had a 2 (feedback valence: gain or loss) by 3 (relative amounts: 1:1, 1:2, or 2:1) within-participant factorial design, in which we manipulated the relative amounts of gain and loss for the participant and his/her partner (the pseudo-participant, who was a research assistant). The feedback could be either a gain (when the participant made a correct response) or a loss (when the participant made an incorrect response). When both players had a gain, the relative amounts of reward for the participant and his/her partner could be one of the three conditions: +60/+60, +60/+120, or +120/+60, with the number before the forward slash indicating the amount for the participant and the number after the forward slash indicating the amount for the partner. When both players received a loss, the relative amounts of punishment for the participant and his/her partner could be one of the three conditions: −30/−30, −30/−60, or −60/−30, with the number before the forward slash indicating the amount for the participant and the number after the forward slash indicating the amount for the partner. The gain-to-loss ratio of the amount was set at 2:1, in accordance with classic decision-making literature, which suggests that the impact of negative outcomes is larger than that of positive outcomes by a factor of two (Kahneman and Tversky, 1979; Tversky and Kahneman, 1981). To make the experimental setup more realistic, the +60/−30 and −30/+60 feedback were also included for the conditions in which the participant made a correct/incorrect response while his/her partner made an incorrect/correct response. These two conditions were excluded from the statistical analysis because they did not contribute to the objectives of this study.

2.4. Procedure

Each participant was introduced to his/her partner when being led to the EEG lab, and no further communication was allowed. After a brief description of the experiment, EEG sensors were attached and each participant was given detailed task instructions. To become familiar with the task, participants were given a practice block consisting of 20 trials. Following the practice, participants were told that they would earn "¥1.2" or "¥0.6" for each correct response and lose "¥0.3" or "¥0.6" for each incorrect response. Then, they were informed that the relative amounts of gain or loss for the participant and his/her partner would be based on their relative response time (to reduce participants' feeling of being treated differently for the same performance). Thus, participants could earn the most by making their responses as accurately and quickly as possible. The instructions emphasized to the participants that their responses had real outcomes and money would be given or taken according to their own performances, irrespective of their partners' payoff.

At the beginning of each trial, the participant saw a black screen with a varying number (20 to 48) of white dots for 1500 ms. Immediately thereafter, a number was presented that was ±1 from the number of dots that had been shown. Interestingly, in the Fliessbach et al. (2007) study, the number differed by 20% from the number of dots previously shown, resulting in a high accuracy rate of 81%. A pretest using an independent sample of 10 participants showed that, on average, approximately 60% of trials were solved correctly at this difficulty level, thus assuring a sufficient number of negative events for each block of trials. Each participant had to decide whether he/she had seen less or more dots than indicated by the number shown on the screen. He/she indicated his/her answers by means of joysticks. A response changed the screen display, and the selected option was highlighted for 300 ms as a response-feedback. After a 700 ms delay, a feedback screen was displayed for 1200 ms. This display revealed to the participant whether he/she and the partner were correct (indicated by a "+" sign) or not (indicated by a "−" sign) as well as the amount of money they earned or lost in that trial. The next trial started after a time interval of 1000 ms.

The experiment consisted of 10 blocks of 50 trials (500 trials total). The feedback valence was determined by participants' responses, with gains for correct answers and losses for incorrect answers. Unknown to the participant, the relative amounts of gain or loss were predetermined by a computer program instead of relative response time, and four types of outcomes for each feedback valence were of equal probability. As noted above, our pretest with an independent sample, and the average accuracy rate was approximately 60%. Therefore, a sufficient number of trials for each experimental condition were assured.

After the fulfillment of the computer task, each participant was asked to evaluate the favorability of the eight feedback conditions with a rating of 1 to 7, with 1 being the least favorable and 7 the most favorable. The participant was debriefed, paid, and thanked for their participation at the conclusion of the study.

2.5. EEG recording

Each EEG was 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. Eye blinks were recorded from the left supraorbital and infraorbital rows of electrodes. The horizontal electro-oculogram (EOG) was recorded from the row of electrodes placed 1.5 cm lateral to the left and right external canthi. All rows of electrode recordings were referenced online to an external electrode, which was placed on the left mastoid. They were re-referenced offline to the mean of the left and right mastoid readings. The impedance was maintained below 5 kΩ. Stimulus timing and recording of behavioral data were controlled by Presentation Software (Neurobehavioral Systems Inc., Albany, CA, USA).

The bio-signals were amplified using a 0.05–70 Hz band-pass filter and continuously sampled at 500 Hz/channel for off-line analysis. Ocular artifacts were corrected with an eye-movement correction algorithm, which employs a regression analysis in combination with artifact averaging (Semlitsch et al., 1986). All trials in which EEG voltages exceeded a threshold of ±70 μV during the recording epoch were excluded from analysis. The data were baseline-corrected by subtracting the average activity of that channel during baseline observation from each sample reading. EEG epochs of 1200 ms (with 200 ms pre-feedback baseline) were extracted off-line for feedback-locked ERPs. Each epoch was inspected visually for artifacts. The EEG data were low-pass filtered below 30 Hz.

2.6. ERP analysis

To minimize overlap between the FRN and other ERP components, such as P300, we first off-line filtered the EEG data through a zero phase shift of 2–30 Hz band-pass (Donkers et al., 2005; Heldmann et al., 2008). The FRN was then defined as the mean amplitude in the 200–400-ms time window following feedback stimulus onset. To measure the FRN effect (i.e., the differential ERP responses to negative and positive feedback), difference waves were created by subtracting the ERPs observed following gains from the ERPs observed following losses (after employing a 2–30-Hz band-pass filter). These difference waves were created separately based on the relative amounts of outcome. The FRN effect was then defined as the mean amplitude of these difference waves, within a window between 200 and 400 ms, following feedback at each electrode site.

The P300 component was defined as the most positive peak in the 200–500-ms time window following feedback onset (without 2–30 Hz band-pass filter). The LPP (late positive potential) was evaluated as the average activity in the 450 ms to 750 ms time window after feedback onset (without 2–30-Hz band-pass filter). The ERP potentials and time windows were based on previous literature and visual inspection of the ERPs.

The statistical analyses of the FRN, P300, and LPP components were firstly conducted on the basis of broad electrode sites with the feedback valence and relative amounts of gain or loss as two critical factors. The side (left, midline, right) and row of electrodes were the two topographic factors considered. Based on previous studies, the F3, FC3,C3, Fz, FCz, Cz, F4, FC4 and C4 electrodes were included in calculations of the FRN component. For the P300, the CP3, P3, CPz, Pz, CP4, and P4 electrodes were included. For the LPP, the F3, FC3, C3, CP3, P3, Fz, FCz, Cz, CPz, Pz, F4, FC4, C4, CP4, and P4 electrodes were included. Based on the group analyses, we then selected the Fz electrode for FRN analysis, and the CPz electrode for the P300 and LPP analyses. The results did not significantly vary across electrodes. For simplicity and specificity, we reported the results of a single representative electrode site.

Behavioral and ERP data were statistically evaluated using SPSS software (version 18, SPSS Inc., Chicago, IL, USA). A Greenhouse–Geisser correction for the violation of sphericity assumption was applied when the degrees of freedom were more than one. Post hoc comparisons relied upon the Bonferroni procedure. The significance level was set at 0.05 for all analyses.

3. Results

3.1. Behavioral results

Participants made correct responses in approximately 62% (±11%) of the total trials. Favorability ratings for the different feedbacks are presented in Fig. 2. A 2 (feedback valence: gain and loss) by 3 (relative amounts: 1:1, 1:2, and 2:1) repeated-measures ANOVA revealed a significant feedback valence effect on favorability ratings (F (2, 30) = 51.44, $p < 0.001$, $\eta^2_{\text{partial}} = 0.774$), with a gain outcome (5.02 ± 1.02) rated more favorably than a loss outcome (2.56 ± 0.95). A significant social comparison effect was also observed (F (2, 30) = 6.31, $p < 0.01$, $\eta^2_{\text{partial}} = 0.296$). The interaction of feedback valence and relative payoffs also reached significance (F (2, 30) = 27.62, $p < 0.001$, $\eta^2_{\text{partial}} = 0.648$) (see Fig. 2). Further analysis revealed that following a gain outcome, the comparison effect was significant (F (2, 30) = 21.53, $p < 0.001$, $\eta^2_{\text{partial}} = 0.438$), with a feedback ratio of 2:1 (+120/+60, 6.25 ± 0.85) rated more favorably than the 1:1(+60/+60, 5 ± 1.15) and 1:2 (+60/+120, 3.81 ± 1.47) ratios. Following a loss outcome, the comparison effect was significant (F (2, 30) = 11.67, $p < 0.001$, $\eta^2_{\text{partial}} = 0.589$), with a feedback ratio of 1:1 (−30/−30, 2.88 ± 0.72) and 1:2 (−30/−60, 2.94 ± 1.12) rated more favorable than the 2:1 ratio (−60/−30, 1.88 ± 1.02).

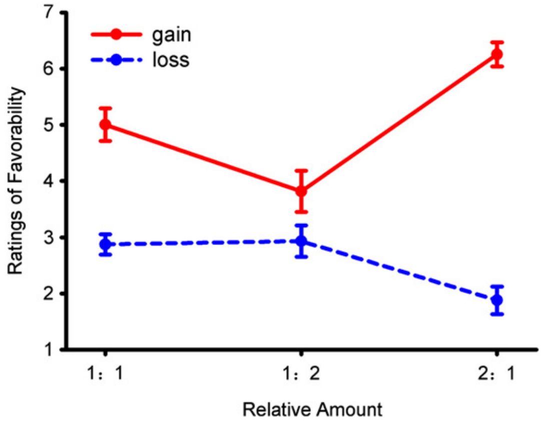

Fig. 2. The evaluation of favorability of the six feedback conditions, ranked from 1 to 7, with 1 being the most unfavorable and 7 the most favorable.

3.2. The ERP results

Fig. 3 presents feedback-locked ERP averages for gain and loss feedback at the Fz and CPz electrodes. Fig. 3 also presents the difference waves obtained by subtracting the gain from the loss for 1:1, 1:2 and 2:1 outcomes at the Fz and CPz electrodes. The N1 potentials (most negative point in the time window of 50–150 ms), FRN, P300, N450 (most negative point in the time window of 400–600 ms) and LPP were extracted according to the visual impression suggested by Fig. 3. A 2 (feedback valence: gain and loss) × 3 (relative amounts: 1:1, 1:2, and 2:1) × 3 (side: left, middle, and right) × 5 (row of electrodes: F*, FC*, C*, CP*, and P*) repeated-measures ANOVA revealed neither main effects nor an interaction effect of feedback valence and relative amounts on N1 and N450. We, therefore, reported only the FRN, P300 and LPP analysis results.

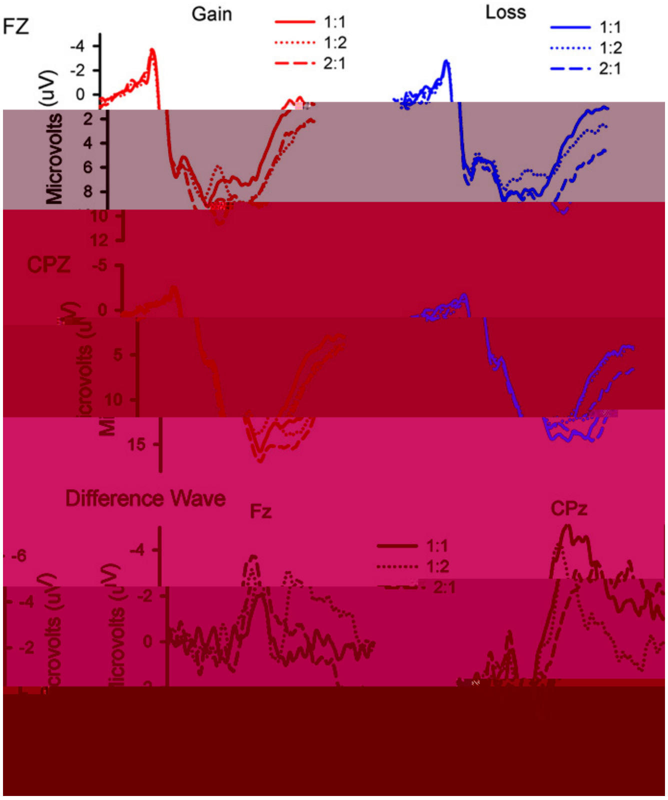

Fig. 3. Grand-average event-related potential (ERP) waveforms at the electrode site of Fz and CPz and loss-minus-gain difference waves at the Fz and CPz electrodes as a function of feedback valence and relative amounts of gain or loss. Feedback stimulus onset occurred at 0 ms.

3.2.1. The FRN

A 2 (feedback valence: gain and loss) × 3 (relative amounts: 1:1, 1:2, and 2:1) repeated-measures ANOVA on FRN mean amplitude found a main effect of feedback valence, F (1, 15) = 34.57, $p < 0.001$, $\eta^2_{\text{partial}} = 0.697$, when the FRN component was more negative-trending for a loss outcome (0.38 μV) than for a gain outcome (0.87 μV). The main effect of relative amounts was significant, F (2, 30) = 4.42, $p < 0.05$, $\eta^2_{\text{partial}} = 0.228$. The post-hoc test showed that equal payoffs elicited more negative deflection than unequal payoffs, with a significant difference between 1:1 and 1:2 (0.53 μV vs. 0.66 μV, $p < 0.05$), and between 1:1 and 2:1 (0.53 μV vs. 0.69 μV, $p < 0.05$). The interaction of feedback valence and relative amounts was not significant, F (2, 30) = 0.76, $p > 0.05$.

To further characterize the effect of social comparisons on the FRN effect, we conducted a one-way ANOVA testing the relative amounts of gain or loss as a factor of the FRN effect magnitude, which is defined as the mean amplitude within a window between 200 and 400 ms in the loss-minus-gain difference waveforms. The analysis, conducted at Fz, where the FRN effect was numerically largest, indicated that the FRN effect did not vary with respect to relative amounts, F (2, 30) = 0.76, $p < 0.05$, $\eta^2_{\text{partial}} = 0.048$, with −0.45 μV, −0.44 μV, and −0.57 μV for 1:1, 1:2, and 2:1 feedback, respectively.

3.2.2. The P300

Repeated-measures ANOVA on P300 peak amplitudes revealed the main effect of feedback valence (F (1, 15) = 11.24, $p < 0.01$, $\eta^2_{\text{partial}} = 0.428$) with a more positive P300 value for gain outcomes (16.28 μV) than for loss outcomes (14.46 μV), and the main effect of relative amounts (F (2, 30) = 7.52, $p < 0.001$, $\eta^2_{\text{partial}} = 0.334$). Post-hoc tests showed that the 2:1 feedback (16.13 μV) and 1:1 feedback (15.57 μV) elicited larger P300 than the 1:2 feedback (14.41 μV). The social comparison effect did not interact with feedback valence (F (2, 30) = 2.77, $p > 0.05$).

3.2.3. The LPP

Repeated-measures ANOVA on LPP mean amplitudes found no main effect of feedback valence (F (1, 15) = 1.59, $p > 0.05$), but a significant main effect of relative amounts was found (F (2, 30) = 11.29, $p < 0.001$, $\eta^2_{\text{partial}} = 0.430$). This comparison effect did not interact with the feedback valence (F (2, 30) = 3.02, $p > 0.05$). Post-hoc tests on the comparison effect showed that the 2:1 feedback (12.94 μV) elicited larger LPP than the 1:1 feedback (11.06 μV) and the 1:2 feedback (11.16 μV).

4. Discussion

This study provides insights into the time-course of the social comparison effect on outcome evaluation. The results revealed that although FRN showed a feedback valence effect, the FRN effect was larger for loss than for gain feedback, and it was not affected by social comparison. In contrast, P300 showed both a feedback valence effect and a social comparison effect, with larger amplitude following gain feedback and for 2:1 and 1:1 payoffs. Moreover, late parietal positivity starting 450 ms after onset of feedback was also sensitive to the manipulation of social comparison, with a larger amplitude for 2:1 payoffs irrespective of gain or loss valence. In the following paragraphs, we discuss the implications of these findings.

4.1. FRN effect is not modulated by social comparison

The classic FRN effect of monetary loss feedback eliciting more negative deflection at the frontocentral regions compared with monetary gain feedback is replicated in the current study, which is generally consistent with those observed in previous studies on outcome evaluation (Gehring and Willoughby, 2002; Holroyd and Coles, 2002; Holroyd et al., 2004; Miltner et al., 1997; Nieuwenhuis et al., 2004a; Yu and Zhou, 2006a, 2006b). However, the FRN effect was not modulated by social comparisons, although the equal payoff had a larger FRN magnitude than an unequal payoff. The invariability of the FRN effect on the manipulation of social comparisons is consistent with the argument that FRN reflects the initial, coarse, semi-automatic coding of rewards along the good-bad dimension (Hajcak et al., 2006a; Leng and Zhou, 2010).

We cannot ascribe the difference between a 1:1 payoff and a 2/2:1 payoff to the social comparison effect because FRN is known to be more pronounced for unfavorable feedback (Hajcak et al., 2005, 2006a,b; Holroyd et al., 2006). Differential FRN in response to equal and unequal payoff may reflect the processing of prediction error (Holroyd and Coles, 2002). Previous evidence indicates that FRN is affected by outcome probability, in which FRN is enhanced by unpredicted outcomes (Gibson et al., 2006; Hajcak et al., 2007). The current findings that the FRN effect was largest for equal payoffs may be due to the low probability of this type of feedback, which only accounts for one quarter of the total trials. Participants may form an expectation of unequal payoff, and the equal payoff might be regarded as a prediction error. Another possibility is that the equal payoff feedback is perceptually easier to discriminate than unequal payoff feedback and, thus, yields a larger FRN magnitude. As reported in previous studies, the perceptual salience of the feedback stimuli affected the FRN responses (Nieuwenhuis et al., 2004b), and when feedback stimuli can be discriminated on the basis of a salient visual feature, the resultant FRN is large; otherwise, the resultant FRN is not observed (Liu and Gehring, 2009).

As a key component associated with outcome evaluation, FRN is reliably more pronounced for negative than for positive feedback. The reinforcement-learning theory (RL-theory), an influential theory accounting for FRN, states that FRN reflects the activity of a reinforcement-learning system and codes negative prediction errors, but predicts them more poorly than expected (Holroyd and Coles, 2002). The FRN might also reflect the emotional/motivational impact of ongoing events (Gehring and Willoughby, 2002). However, the evaluation processing of the FRN stage is rather inaccurate. For example, FRN is insensitive to reward magnitude (Hajcak et al., 2006a,b; Sato et al., 2005; Wu and Zhou, 2009; Yeung and Sanfey, 2004). And the FRN effect is not modulated by social distance (Leng and Zhou, 2010), and it cannot differentiate between the outcome for self and the outcome for the other player (Yu and Zhou, 2006b). The current findings of null modulation of the FRN effect by social comparison confirmed the hypothesis that FRN makes a rather superficial evaluation of feedback stimuli, e.g., a coarse distinction between favorable versus unfavorable outcomes (Hajcak et al., 2006a,b). Information beyond this dimension might not be coded by FRN.

Failure to find the social comparison effect on FRN effect indicates that the social comparison process does not take effect as early as 300 ms after feedback onset. This latency is too short to transmit the events into conscious processing (Feinstein et al., 2004; Treisman and Kanwisher, 1998). These results failed to support the idea that social comparison may be a relatively unconscious reaction to the performances of others (Wood, 1996).

4.2. P300 is independently modulated by feedback valence and social comparison

In contrast to FRN, we found that the P300 was modulated by both feedback valence and social comparison. Given that the P300 is generally thought to be related to processes of attentional allocation (Gray et al., 2004; Linden, 2005; Ray, 1993) and/or to high-level motivational/affective evaluation (Nieuwenhuis et al., 2005; Yeung and Sanfey, 2004), it is not surprising that the gain outcomes elicited larger P300 responses than did loss outcomes. In the oddball paradigm, infrequent events reliably elicit the P300 component (Polich, 2007). However, this frequency effect cannot explain the current findings of larger P300 values for gain feedback compared to loss feedback. First, the frequency differences between gains and losses (62% vs. 38%) were well below the typical differences that occurred in previous research (e.g., 75% for frequent stimuli vs. 25% for infrequent stimuli, or 80% for frequent stimuli vs. 20% for infrequent stimuli). Second, the current findings that the P300 was more pronounced for the gain outcome (more frequent) than for loss outcome (less frequent), is contrary to the frequency effect that was found in previous studies. Larger P300 following gain feedback suggests a role of P300 in differentiating favorable outcomes from unfavorable outcomes in feedback processing (Wu and Zhou, 2009).

Importantly, we found the social comparison effect on P300 to be independent of feedback valence. The results were interesting in that the 1:1 payoff and the 2:1 payoff elicited a larger P300 than the 1:2 payoff. One possible explanation is that the P300 reflects an individual's preference for equal payoffs over unequal payoffs. In other words, information related to favorability evaluation receives preferential access to the limited pool of attentional resources, as indexed by the P300 (Gray et al., 2004). The preference for equal payoff coincides with the concept of inequity aversion in the economic literature, which implies that people have a preference for fairness and resist unequal outcomes (Fehr and Schmidt, 1999; Rabin, 1993). This explanation also sheds light on the result of the larger P300 for the 2:1 payoff than for the 1:2 payoff in the gain feedback because the advantageous unequal payoff (i.e., +120/+60) is more favorable than disadvantageous unequal payoff (i.e., +60/+120). The present behavioral data support this speculation. Accordingly, the equal payoffs and advantageous unequal payoff were rated more favorably than disadvantageous unequal payoff following gains. However, the finding of a larger P300 for the 2:1 feedback (i.e., −60/−30) than for the 1:2 feedback (i.e., −30/−60) in the loss feedback cannot be accommodated by the favorability evaluation hypothesis. We hypothesize that the modulation of P300 by the reward magnitude is a possible explanation of this finding.

There is a consensus that the P300 encodes the reward magnitude information in feedback processing. Previous work suggested that the P300 codes reward magnitude information without being sensitive to outcome valence, and enhanced P300 activity correlates with a larger reward amount (Sato et al., 2005; Yeung and Sanfey, 2004). Follow up studies found that the P300 is sensitive to reward valence as well as to reward magnitude, with a more positive amplitude for positive feedback than for negative feedback (Bellebaum et al., 2010b; Hajcak et al., 2007; Holroyd et al., 2006; Leng and Zhou, 2010; Wu and Zhou, 2009). The current finding of a larger P300 for 2:1 −60/−30 feedback than for −30/−60 feedback, suggests a magnitude evaluation within intrapersonal comparison instead of interpersonal comparison. Herein, we suggest that the favorability evaluation and magnitude judgment have an additive impact on P300 amplitude. Evidence suggests being judged as both the most favorable outcome (Fig. 2) and of the highest magnitude for one's own outcome, the +120/+60 feedback elicited the largest P300 amplitude of all the experimental feedback (Fig. 4B).

The social comparison effect on P300 suggests that this effect can appear immediately after the events come into conscious processing (latency approximately 350 ms), demonstrating automatic arousal of the comparison impulse when the partner's payoff is unrelated to the participant's final payoff. These results confirmed a preliminary study demonstrating that social comparison may be a relatively spontaneous, effortless, and unintentional reaction to the performances of others and may occur even when people consider such reactions logically inappropriate (Gilbert et al., 1995).

4.3. The LPP was sensitive to the discrepancy between the individual and the partner's payoffs

Unlike the FRN and the P300 components, the late positive potential LPP was not affected by feedback valence, but it was modulated by social comparison. However, the social comparison effect on LPP was different from that on P300. The LPP was larger when the participant's outcome had a higher magnitude than his/her partner's, e.g., the +120/+60 and the −60/−30 outcomes. Unlike the P300, the LPP appeared to be sensitive to the arousal level of the feedback.

A previous study has observed that the posterior LPP was involved in evaluative processing. Specifically, it is elicited when valenced stimuli are presented in an emotionally incongruous context, e.g., a negative stimulus presented in the context of positive stimuli (Cacioppo et al., 1996), and the amplitude was equally high for positive and for negative stimuli (Schupp et al., 2000). Moreover, it was shown that the amplitude of the LPP was largest for stimuli that were the most arousing, presumably the stimuli with the greatest motivational relevance (Schupp et al., 2000). This finding, together with the finding that the posterior LPP is not valence-specific, suggests that the LPP may not reflect the processing of evaluation per se, but rather may reflect detection of stimuli with motivational significance or downstream categorical processing of output from an evaluation system (Cunningham et al., 2005). Recent studies have shown that the LPP is sensitive to changes in emotional processing resultant from the use of cognitive emotional regulation strategies like reappraisal (Hajcak et al., 2006b; Krompinger et al., 2008; Thiruchselvam et al., 2011), suggesting a role of the LPP in emotional regulation processes.

In the present study, we found that the LPP was more pronounced for the 2:1 outcomes. One possibility is that these outcomes have a high arousal level, in part caused by perceptual saliency and partly caused by the great gap between the participant and his/her partner's payoff. Another possibility is that 2:1 outcomes are of great motivational importance to the participants because they reinforce previous performance, alert a subsequent response, or represent updated

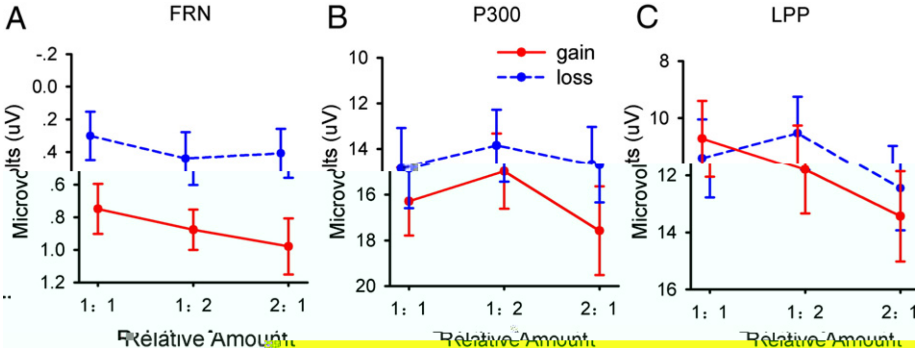

Fig. 4. (A) The mean FRN amplitudes at the Fz electrode in the 200–400-ms time window after feedback onset following the 2–30-Hz band-pass filtering. Standard errors are also depicted. (B) The P300 amplitudes on the CPz electrode in the 200–500-ms time window after feedback onset. (C) The mean LPP amplitudes on the CPz electrode in the 450–750-ms time window after feedback onset.

payment information. An alternative explanation is that 2:1 outcomes involve more engagement of emotional regulation processes. One important direction for future research is to systematically compare hypotheses about the functional role of the LPP in outcome evaluation.

Ultimately, the current findings failed to support the hypothesis that the posterior LPP is a special case of the P300 or a sustained effect of the P300 (Crites et al., 1995) because the LPP activity differed fundamentally from the P300 effect. Instead, these results may indicate re-appraisal cognitive processing of the outputs of earlier evaluative processing (Cunningham et al., 2005). The social comparison effect at this late stage suggests that social comparison has a prolonged effect on outcome evaluation. Social comparison may not only involve spontaneous, effortless, and unintentional reactions to the performances of others (Gilbert et al., 1995), but it may also involve reflective and controlled processes. Future studies using appropriate paradigms can examine whether social comparison can activate cognitive control systems in the brain beyond the reward-related brain regions.

5. Conclusion

People acquire information about their abilities by comparison, and evaluate the outcome of their performance by comparison. By asking the participant and his/her partner to simultaneously complete a dot estimation task and by manipulating their relative payoff, this study found that the social comparison takes effect at different stages of the outcome evaluation. First, information about gain or loss is represented by the early FRN potential. Additionally, elaborated processing is reflected by the P300, and the favorability of the outcome is extracted based on social comparison. Finally, at the re-appraisal stage, as indicated by the LPP, feedback causing high arousal level is manifested by social comparison.

Acknowledgments

We thank the anonymous reviewers for their valuable comments on earlier drafts of the manuscript. This study was supported by grants from the Natural Science Foundation of China (31100744) and the Zhejiang Provincial Natural Science Foundation of China (Y2110381).

References

Bellebaum, C., Kobza, S., Thiele, S., Daum, I., 2010a. It was not my fault: event-related brain potentials in active and observational learning from feedback. Cerebral Cortex 20 (12), 2874–2883.

Bellebaum, C., Polezzi, D., Daum, I., 2010b. It is less than you expected: the feedback-related negativity reflects violations of reward magnitude expectations. Neuropsychologia 48 (11), 3343–3350.

Buunk, A.P., Gibbons, F.X., 2007. Social comparison: the end of a theory and the emergence of a field. Organizational Behavior and Human Decision Processes 102 (1), 3–21.

Cacioppo, J.T., Crites Jr., S.L., Gardner, W.L., 1996. Attitudes to the right: evaluative processing is associated with lateralized late positive event-related brain potentials. Personality and Social Psychology Bulletin 22 (12), 1205–1219.

Crites, S.L., Cacioppo, J.T., Gardner, W.L., Berntson, G.G., 1995. Bioelectrical echoes from evaluative categorization: II. A late positive brain potential that varies as a function of attitude registration rather than attitude report. Journal of Personality and Social Psychology 68 (6), 997–1013.

Cunningham, W.A., Espinet, S.D., DeYoung, C.G., Zelazo, P.D., 2005. Attitudes to the right- and left: frontal ERP asymmetries associated with stimulus valence and processing goals. NeuroImage 28 (4), 827–834.

Donkers, F.C.L., Nieuwenhuis, S., van Boxel, G.J.M., 2005. Mediofrontal negativities in the absence of responding. Cognitive Brain Research 25, 777–787.

Dvash, J., Gilam, G., Ben-Ze'ev, A., Hendler, T., Shamay-Tsoory, S.G., 2010. The envious brain: the neural basis of social comparison. Human Brain Mapping 31 (11), 1741–1750.

Fazio, R.H., 1979. Motives for social comparison: the construction–validation distinction. Journal of Personality and Social Psychology 37 (10), 1683–1698.

Fehr, E., Schmidt, K.M., 1999. A theory of fairness, competition, and cooperation. Quarterly Journal of Economics 114 (3), 817–868.

Feinstein, J.S., Stein, M.B., Castillo, G.N., Paulus, M.P., 2004. From sensory processes to conscious perception. Consciousness and Cognition 13 (2), 323–335.

Festinger, L., 1954. A theory of social comparison processes. Human Relations 7 (2), 117–140.

Fishbein, M., Raven, B.H., Hunter, R., 1963. Social comparison and dissonance reduction in self-evaluation. Journal of Abnormal and Social Psychology 67 (5), 491–501.

Fliessbach, K., Weber, B., Trautner, P., Dohmen, T., Sunde, U., Elger, C.E., et al., 2007. Social comparison affects reward-related brain activity in the human ventral striatum. Science 318 (5854), 1305–1308.

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

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.

Gibbons, F.X., 1999. Social comparison as a mediator of response shift. Social Science & Medicine 48 (11), 1517–1530.

Gibson, J., Krigolson, O.E., Holroyd, C.B., 2006. Sensitivity of the feedback error-related negativity to reward probability. Psychophysiology 43, S41–S42.

Gilbert, D.T., Giesler, R.B., Morris, K.A., 1995. When comparisons arise. Journal of Personality and Social Psychology 69 (2), 227–236.

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 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.

Greenberg, J., Ashton-James, C.E., Ashkanasy, N.M., 2007. Social comparison processes in organizations. Organizational Behavior and Human Decision Processes 102 (1), 22–41.

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., 2006a. The feedback-related negativity reflects the binary evaluation of good versus bad outcomes. Biological Psychology 71 (2), 148–154.

Hajcak, G., Moser, J.S., Simons, R.F., 2006b. Attending to affect: appraisal strategies modulate the electrocortical response to arousing pictures. Emotion 6 (3), 517–522.

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, 905–912.

Heldmann, M., Rüsseler, J., Münte, T.F., 2008. Internal and external information in error processing. BMC Neuroscice 9, 33.

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., 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., Hajcak, G., Larsen, J.T., 2006. The good, the bad and the neutral: electrophysiological responses to feedback stimuli. Brain Research 1105 (1), 93–101.

Itagaki, S., Katayama, J., 2008. Self-relevant criteria determine the evaluation of outcomes induced by others. Neuroreport 19 (3), 383–387 ([Article]).

Kahneman, D., Tversky, A., 1979. Prospect theory: an analysis of decision under risk. Econometrica 47 (2), 263–292.

Kobza, S., Thoma, P., Daum, I., Bellebaum, C., 2011. The feedback-related negativity is modulated by feedback probability in observational learning. Behavioural Brain Research 225 (2), 396–404.

Krompinger, J.W., Moser, J.S., Simons, R.F., 2008. Modulations of the electrophysiological response to pleasant stimuli by cognitive reappraisal. Emotion 8 (1), 132–137.

Kumar, P., 2004. The effects of social comparison on inaction inertia. Organizational Behavior and Human Decision Processes 95 (2), 175–185.

Leng, Y., Zhou, X., 2010. Modulation of the brain activity in outcome evaluation by interpersonal relationship: an ERP study. Neuropsychologia 48 (2), 448–455.

Linden, D.E.J., 2005. The P300: where in the brain is it produced and what does it tell us?, vol. 11, pp. 563–576.

Liu, Y., Gehring, W.J., 2009. Loss feedback negativity elicited by single- versus conjoined-feature stimuli. Neuroreport 20 (6), 632–636 (610.1097/WNR. 1090b1013e32832a33250).

McCreary, D.R., Saucier, D.M., 2009. Drive for muscularity, body comparison, and social

Ray Jr., J., 1993. On the neural generators of the P300 component of the event-related potential. Psychophysiology 30 (1), 90–97.

Ruble, D.N., Boggiano, A.K., Feldman, N.S., Loebl, J.H., 1980. Developmental analysis of the role of social comparison in self-evaluation. Developmental Psychology 16 (2), 105–115.

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.

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.

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.

Stapel, D.A., Marx, D.M., 2006. Hardly thinking about others: on cognitive busyness and target similarity in social comparison effects. Journal of Experimental Social Psychology 42 (3), 397–405.

Thiruchselvam, R., Blechert, J., Sheppes, G., Rydstrom, A., Gross, J.J., 2011. The temporal dynamics of emotion regulation: an EEG study of distraction and reappraisal. Biological Psychology 87 (1), 84–92.

Treisman, A.M., Kanwisher, N.G., 1998. Perceiving visually presented objects: recognition, awareness, and modularity. Current Opinion in Neurobiology 8, 218–226.

Tversky, A., Kahneman, D., 1981. The framing of decisions and the psychology of choice. Science 211 (30), 453–458.

Wood, J.V., 1996. What is social comparison and how should we study it? Personality and Social Psychology Bulletin 22 (5), 520–537.

Wu, Y., Zhou, X.L., 2009. The P300 and reward valence, magnitude, and expectancy in outcome evaluation. Brain Research 1286, 114–122.

Yeung, N., Sanfey, A.G., 2004. Independent coding of reward magnitude and valence in the human brain. Journal of Neuroscience 24 (28), 6258–6264.

Yu, R., Zhou, X., 2006a. Brain potentials associated with outcome expectation and outcome evaluation. Neuroreport 17 (15), 1649–1653.

Yu, R., Zhou, X., 2006b. Brain responses to outcomes of one's own and other's performance in a gambling task. Neuroreport 17 (16), 1747–1751.

Yu, R., Zhou, X., 2009. To bet or not to bet? The error negativity or error-related negativity associated with risk-taking choices. Journal of Cognitive Neuroscience 21 (4), 684–696.

Zell, E., Alicke, M.D., 2009. Self-evaluative effects of temporal and social comparison. Journal of Experimental Social Psychology 45 (1), 223–227.

Zink, C.F., Tong, Y., Chen, Q., Bassett, D.S., Stein, J.L., Meyer-Lindenberg, A., 2008. Know your place: neural processing of social hierarchy in humans. Neuron 58 (2), 273–283.