

The impact of social comparison on the neural substrates of reward processing: An event-related potential study

Jiang Qiu^{a,b,c,*}, Caiyun Yu^{a,b}, Hong Li^{a,b}, Jerwen Jou^d, Shen Tu^{a,b}, Ting Wang^{a,b}, Dongtao Wei^{a,b}, Qinglin Zhang^{a,b,*}

^a Key Laboratory of Cognition and Personality (Southwest University), Ministry of Education, Chongqing 400715, China

^b School of Psychology, Southwest University, Chongqing, 400715, China

^c Key Laboratory of Human Development and Mental Health in Hubei (Central China Normal University), Wuhan 430000, China

^d Department of Psychology & Anthropology, University of Texas-Pan American, Edinburg, TX, USA

ARTICLE INFO

Article history:

Received 10 May 2009

Revised 4 August 2009

Accepted 10 August 2009

Available online 18 August 2009

Keywords:

Social comparison

Reward processing

Event-related potentials (ERPs)

ABSTRACT

Event-related potentials (ERPs) were recorded to explore the electrophysiological correlates of reward processing in the social comparison context when subjects performed a simple number estimation task that entailed monetary rewards for correct answers. Three social comparison stimulus categories (three relative reward levels/self reward related to the other subject's) were mainly prepared: Self:Other = 1:2 (Disadvantageous inequity condition); Self:Other = 1:1 (Equity condition); and Self:Other = 2:1 (Advantageous inequity condition). Results showed that: both Disadvantageous and Advantageous inequity elicited a more negative ERP deflection (N350–550) than did Equity between 350 and 550 ms, and the generators of N350–550 were localized near the parahippocampal gyrus and the medial frontal/anterior cingulate cortex, which might be related to monitor and control reward prediction error during reward processing. Then, Disadvantageous and Advantageous inequity both elicited a more late negative complex (LNC1 and LNC2) than did Equity between 550 and 750 ms. The generators of LNC1 and LNC2 were both localized near the caudate nucleus, which might be related to reward processing under social comparison.

© 2009 Elsevier Inc. All rights reserved.

Introduction

Social comparison is a critical psychological context and it with other individuals is a central phenomenon in human societies (Festinger, 1954). If social comparison profoundly affects reward processing and subjective well-being, there are crucial implications for individual matters. For example, self-evaluations/maintenance, life satisfaction and subjective well-being are often derived from social comparisons (e.g., Festinger, 1954; Wills, 1981; Bui and Pelham, 1999; Stapel and Koomen, 2001; Mussweiler et al., 2004). Many previous studies (e.g., Elliott et al., 2000; Breiter et al., 2001; Knutson et al., 2001; Akitsuki et al., 2003; Delgado et al., 2004; Holroyd et al., 2004; Nieuwenhuis et al., 2005; Fliessbach et al., 2007) had suggested that reward processing was strongly context dependent (e.g., social comparison), and social comparison theory (e.g., Festinger, 1954; Wills, 1981) predicted that satisfaction with outcomes depended on relative comparisons with other people.

For several decades, psychologists try their best to investigate the cognitive and neural mechanisms of reward processing under different psychological contexts (e.g., Elliott et al., 2000; Breiter et al., 2001; Knutson et al., 2001; Akitsuki et al., 2003; Delgado et al., 2004; Holroyd

et al., 2004; Nieuwenhuis et al., 2005; Fliessbach et al., 2007). Some functional magnetic resonance imaging (fMRI) studies had found that the striatum (e.g., the nucleus accumbens and the caudate nucleus) and other brain areas (e.g., the thalamus and the medial prefrontal cortex) in humans exhibited a high degree of context sensitivity in reward processing (e.g., Akitsuki et al., 2003; Nieuwenhuis et al., 2005; Fliessbach et al., 2007). For example, Fliessbach et al. (2007) pointed out, “brain activation to the same rewards differ depending on the sequence of previous rewards and losses (e.g., Elliott et al., 2000; Akitsuki et al., 2003) and on the set of possible outcomes from which the actual reward was chosen (e.g., Breiter et al., 2001; Nieuwenhuis et al., 2005)”. They also found that social comparison (relative level reward) affected blood oxygenation level-dependent responses in the ventral striatum even if subjects were not actively engaged in decision-making, and their results suggested that mere contextual information about the other person had an immediate impact on reward-related brain processes (Fliessbach et al., 2007).

Although fMRI studies provided many important results to explore the brain mechanism of reward processing under social comparison, the time course of cortical activation could not be studied with precision. We know that the methods of event-related potential (ERP) recordings and voltage maps can provide critical temporal information for analyzing the functional neuroanatomy of cognitive processes of reward processing. Therefore, in our study, high-density (64 channels)

* Corresponding authors. School of Psychology, Southwest University, Beibei, Chongqing 400715 China.

E-mail addresses: qiu318@swu.edu.cn (J. Qiu), zhangql@swu.edu.cn (QL. Zhang).

ERP recording was used to determine whether social comparison affected the spatiotemporal cortical activation patterns of reward processing and subjective well-being. Furthermore, the present study might be the first one using ERP to investigate the impact of social comparisons on the neural substrates of reward processing. We used a simple number estimation task, similar to that used by [Fliessbach et al. \(2007\)](#). However, we only selected their relative reward levels (Self:Other = 1:2, Disadvantageous inequity; Self:Other = 1:1, Equity; Self:Other = 2:1, Advantageous inequity) as our experimental conditions because many previous studies had found that the influence of relative comparison on reward processing was independent of the absolute level of payment (e.g., [Knutson et al., 2001](#); [Nieuwenhuis et al., 2005](#); [Fliessbach et al. 2007](#)). Based on previous studies (e.g., [Akitsuki et al., 2003](#); [Delgado et al., 2004](#); [Nieuwenhuis et al., 2005](#); [Fliessbach et al., 2007](#)) and social comparison theory (e.g., [Festinger, 1954](#); [Wills, 1981](#)), we hypothesized that neural substrates for processing of Disadvantageous inequity (Not satisfaction with inequitable outcomes), Advantageous inequity (Satisfaction with inequitable outcomes) and Equity (Satisfaction with equitable outcomes) might be different and some ERP components [e.g., error-related negativity (ERN), P3 and LPC (late positive component)] might be elicited in reward processing under social comparison. Specifically, we predicted that Disadvantageous and Advantageous inequity would elicit a greater ERN than did Equity in the early processing of reward feedback, then Disadvantageous and Advantageous inequity would elicit a greater negativity than did Equity. Moreover, we also anticipated that Disadvantageous inequity would elicit a more negative LPC than did Advantageous inequity in the late processing of reward feedback. The anatomic specificity data of fMRI mapping obtained from previous studies and the time resolution of ERP recordings would enable the characterization of the functional roles of specific brain areas in the context-dependent reward processing.

Experimental procedure

Subjects

As paid volunteers, twelve healthy undergraduate students (average age 20.8, range 20–23, six men, six women) from Southwest University (Chongqing) in China participated in the study. We had obtained appropriate ethics committee approval for the research, and all subjects gave written informed consent. All subjects were right-handed, had no history of current or past neurological or psychiatric illness, and had normal or corrected-to-normal vision.

Stimuli

The stimuli of reward feedback was composed 240 pairs of one subject's and the other pseudo subject's monetary rewards with respective performance. The size of stimulus was Song Ti No.20, and stimulus angle is 2.5° (horizontal) \times 1.4° (vertical). The stimuli were displayed in the center of a 17-in. screen. Specifically, these stimuli included six categories according to subjects' performance. That is, reward feedback conditions were as follows: when both subjects were incorrect, both received nothing. When only one of the subjects was correct, this subject received some money while the other subject was not rewarded. When both subjects were correct, one of three possible conditions was randomly selected: Self:Other = 1:2 (30:60; 40:80; 50:100. Disadvantageous inequity); Self:Other = 1:1 (30:30; 40:40; 50:50. Equity); Self:Other = 2:1 (30:15; 40:20; 50:25. Advantageous inequity).

Procedure

Before the experiment began, each subject was told that he/she would perform a simple number estimation task with the other subject in the next laboratory simultaneously. In fact, the other

subject was a pseudo subject and his performance and reward feedback were predetermined. That is, there was a high possibility (95%) of making a correct judgment for the pseudo subject when our subject was correct. Each subject was also told that he/she could earn additional money (e.g., 30 Yuan) which depended on his/her performance related to the other subject's in each trial. The amount of money which he/she received at the end of experiment included the additional money and the primary show-up fee.

The time course of a trial was illustrated in [Fig. 1](#). First, the fixation point appeared with 0.3 s duration at the center of the screen. Subsequently, subjects saw a screen with a varying number (10 to 50) of black dots for 1.5 s. Then, a number (e.g., 24) was presented. Subjects were required to judge whether the number of black dots was lower or higher than the number 24, and to rest their right index and right middle finger on the keys "1" and "2" of a keyboard. They need to press "1" if they thought that it was higher than the number 24 and to press "2" if they thought that it was lower than the number 24. After a correct response feedback (0.3 s) and a short delay (0.2–1 s), a reward feedback screen informed the subject about his and the other subject's performance and the respective monetary rewards (1 s). Finally, they were required to make a satisfaction judgment, and to press "1" if they thought that they were satisfied with the payments and to press "2" if not. The next trial started after a time interval of 1–1.5 s.

The total experiment was divided into a practice phase and a test phase. To familiarize the subjects with the procedure of this task and pressing of the response buttons, a practice phase was designed during which subjects had to finish 20 trials. The formal test stage was composed of 6 blocks and each block had 40 trials. Subjects could take a rest after finishing one block. They were seated in a semidark room facing a monitor placed at 60 cm distance from the eyes, and were instructed to avoid blinking and eye movement of any sort, to keep their eyes fixated on the monitor during task performance.

ERP recording and analysis

Brain electrical activity was recorded from 64 scalp sites using tin electrodes mounted in an elastic cap (Brain Product), with the average reference electrode on the left and right mastoids and a ground electrode on the medial frontal aspect. The vertical electro-oculograms (EOGs) were recorded supra- and infra-orbitally at the left eye. The horizontal EOG was recorded from the left versus right orbital rim. All interelectrode impedance was maintained below 5 k Ω . The EEG and EOG were amplified using a 0.05–80 Hz bandpass and continuously sampled at 500 Hz/channel for offline analysis. Eye movement artifacts (blinks and eye movements) were rejected offline. Trials with EOG artifacts (mean EOG voltage exceeding

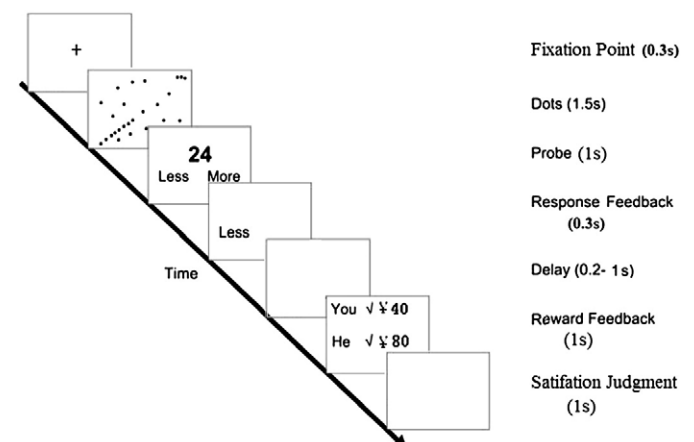


Fig. 1. Time course of a trial (see Fig. 1 in the study of [Fliessbach et al., 2007](#)).

$\pm 80 \mu\text{V}$) and those contaminated with artifacts due to amplifier clipping, bursts of electromyographic activity, or peak-to-peak deflection exceeding $\pm 80 \mu\text{V}$ were excluded from averaging.

We analyzed the ERP elicited by Disadvantageous inequity, Advantageous inequity and Equity conditions. The averaged epoch for ERP was 1200 ms, including 1000 ms poststimulus and 200 ms prestimulus. As observed in the grand-averaged waveforms (see Fig. 2), the ERPs elicited by Disadvantageous inequity, Advantageous inequity and Equity conditions were clearly distinct from each other. The difference waves were obtained by subtracting the averaged ERP of Equity from the averaged ERPs of Disadvantageous inequity and Advantageous inequity, and all these differences were prominent over the frontal, central and occipital scalp regions. Thus, the following 6 electrode sites were selected for statistical analyses: Fz, FCz, Cz, CPz, Pz and POz. The analyses of variance (ANOVA) factors were stimulus type (Disadvantageous inequity, Advantageous inequity and Equity) and electrode site. For all analyses, *P*-value was corrected for deviations according to Greenhouse Geisser.

Dipole source analysis

Brain Electrical Source Analysis program (BESA, Version, 5.0, Software) was used to perform dipole source analysis. For dipole source analysis, the 4-shell ellipsoidal head model was used. In order to explore and increase the precision of source location, principal component analysis (PCA) was employed in the ERPs difference waves of Disadvantageous inequity minus Advantageous inequity, Disadvantageous inequity minus Equity, Advantageous inequity minus Equity (64 channels). When the dipole points were determined, the software automatically determined the dipoles location. Source locations are described in Talairach–Tournoux coordinates. To evaluate the solutions, the residual variance (RV), which provides an estimate of the amount of ERP power not explained by the seeded dipoles, was calculated by comparing the squared total error to the squared data (data power).

Results

Behavioral performance

In the simple number estimation task, the mean accuracy rate was $94.7\% \pm 5.1\%$ and the mean response time (RT) was 492.8 ± 35 ms. For Disadvantageous inequity, Equity and Advantageous inequity conditions, mean trials of each condition were 65 ± 5 , 75 ± 3 and 70 ± 4 . Repeated measures ANOVA for mean trials showed that there was no main effect of stimulus type [$F(2,22) = 0.07$, $P > 0.05$].

Satisfaction judgment rates for Disadvantageous inequity, Equity and Advantageous inequity conditions were $22.1 \pm 10.4\%$, $85.2 \pm 5.2\%$ and $90.2 \pm 7.3\%$, respectively. Mean RTs for Disadvantageous inequity, Equity and Advantageous inequity conditions were 565.9 ± 50 ms, 551.6 ± 55 ms and 561.6 ± 70 ms. Repeated measures ANOVA for RTs showed that the main effect of stimulus type was not significant [$F(2,22) = 0.03$, $P > 0.05$]. Then, repeated measures ANOVA for satisfaction judgment rates showed that there was a significant effect of stimulus type [$F(2,22) = 6.87$, $P < 0.05$]. Pairwise comparison showed that subjects were more satisfied with Advantageous inequity than Equity ($P > 0.05$) and Disadvantageous inequity ($P < 0.05$) and also more satisfied with Equity than Disadvantageous inequity ($P < 0.05$). These results were consistent with the social comparison theory (e.g., Festinger, 1954; Wills, 1981) which predicted that subject's satisfaction with outcomes (e.g., reward) depended on relative comparisons with other people.

Electrophysiological scalp data

The grand-averaged ERPs waveforms (Fig. 2) showed the following spatiotemporal distribution for the ERP data. After onset of the stimuli, the N1 and the P2 were elicited by Disadvantageous inequity, Equity and Advantageous inequity. Then, Disadvantageous inequity, Equity and Advantageous inequity elicited a late positivity component after 350 ms. Amplitudes and latencies of the N1 and the

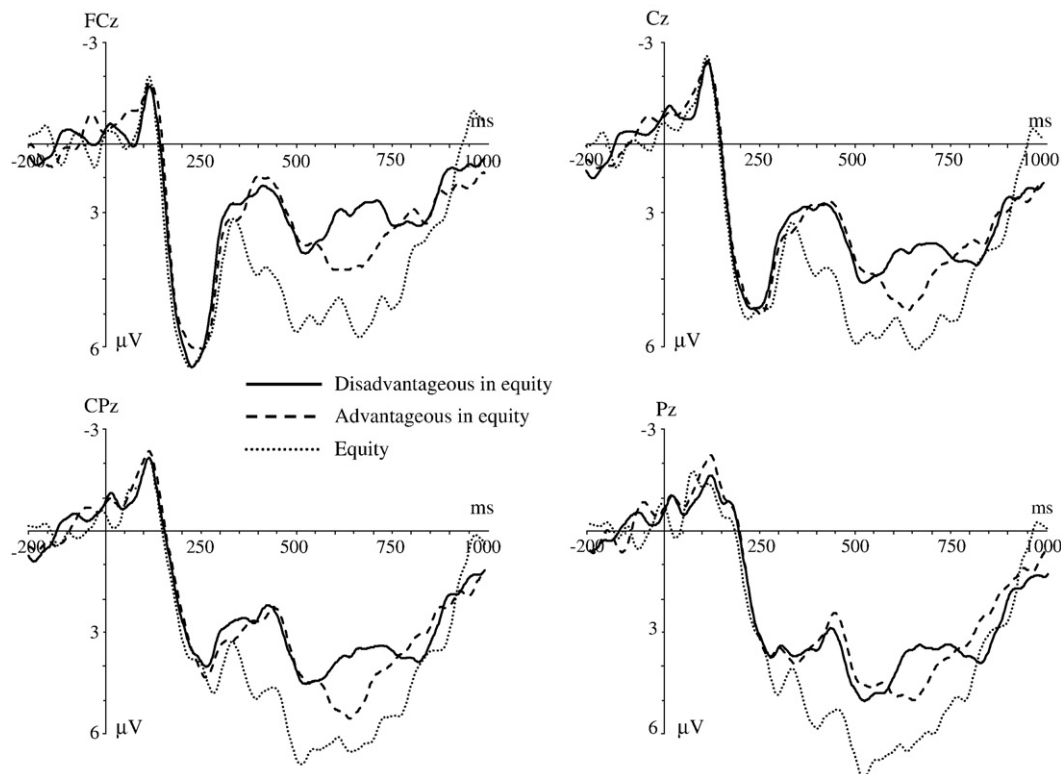


Fig. 2. Grand-averaged ERPs at FCz, Cz, CPz and Pz for the three conditions.

P2 and mean amplitudes in the time windows of 350–550, 550–750 and 750–1000 ms were analyzed using 2-way repeated measures ANOVAs.

The results of the ANOVAs showed that there were no main effects of stimulus type for the amplitude and the latency of the N1. We also did not find main effects of stimulus type for both the amplitude and the latency of the P2. Then, there was a main effect of stimulus type in the time window of 350–550 ms, $F(2,22) = 8.35$, $P < 0.05$. Pairwise comparisons showed that Disadvantageous and Advantageous inequity both elicited a more negative ERP component than did Equity ($P < 0.05$). We did not find a main effect of electrode site in the time window of 350–550 ms [$F(5,55) = 2.13$, $P > 0.05$], and the interaction stimulus type and electrode site was not significant [$F(10,110) = 0.59$, $P > 0.05$]. Between 550–750 ms, there was a main effect of stimulus type, $F(2,22) = 9.47$, $P < 0.05$. Pairwise comparison showed that a more negativity in Disadvantageous (LNC1) and Advantageous inequity (LNC2) as compared to Equity, and Disadvantageous inequity elicited a more negativity (N550–750) than did Advantageous inequity. There was also a main effect of electrode site in the time window of 550–750 ms, $F(5,55) = 7.17$, $P < 0.05$. In addition, the interaction stimulus type and electrode site was not significant, $F(10,110) = 0.53$, $P > 0.05$. In other time windows, we did not find main effects of stimulus type.

Dipole source analysis

Source analysis was performed on the three difference waves of Disadvantageous inequity minus Advantageous inequity, Disadvantageous inequity minus Equity and Advantageous inequity minus Equity. PCA were employed in the 350–550 ms and 550–750 ms time windows because there were main effects of stimulus type and the ERPs elicited by Disadvantageous inequity, Equity and Advantageous inequity were clearly distinct from each other. We determined the number of dipoles on the basis of the results of PCA and our own scientific hypotheses.

First, PCA was employed in the difference wave (Disadvantageous inequity minus Equity) between 350 and 550 ms. PCA indicated that two components were needed to explain 80.4% and 10.3% of the variance in the data. Therefore, two dipoles were fitted with no restriction to the direction and location of dipoles. The result indicated that the first dipole was located near the parahippocampal gyrus (location according Talairach coordinates: $x = 4.9$, $y = -31.2$, $z = 3.1$), and the second located near the anterior cingulate cortex (ACC; $x = 6.9$, $y = -2.1$, $z = 28.0$). This model explained the data best and accounted for most of the variance with an RV of 12.3% and revealed maximal dipoles moment strength at about 450 ms (see

Fig. 3). PCA was also employed in the difference wave (Advantageous inequity minus Equity) between 350 and 550 ms, and we found that there was a similar result (see Fig. 3).

Second, as for the difference wave (LNC1) of Disadvantageous inequity minus Equity between 550–750 ms, PCA indicated that one principal component was required to account for 96.1% of the variance in the data. Therefore, one dipole was fitted with no restriction to the direction and location of dipole. The result showed that this dipole was located approximately in the right caudate nucleus ($x = 5.6$, $y = 4.2$, $z = -0.2$). This model explained the data best and accounted for most of the variance with an RV of 13.6% at the peak activity of this dipole (see Fig. 4). As for the difference wave (LNC2) of Advantageous inequity minus Equity, PCA indicated that one principal component was required to account for 98.1% of the variance in the data. The result showed that this dipole was located approximately in the left caudate nucleus ($x = -14.8$, $y = -4.5$, $z = 15.9$). This model explained the data best and accounted for most of the variance with an RV of 16.6% at the peak activity of this dipole (see Fig. 4). As for the difference wave (N550–750) of Disadvantageous inequity minus Advantageous inequity, PCA indicated that one principal component was required to account for 99.5% of the variance in the data. The result showed that this dipole was located approximately in the left parahippocampal gyrus ($x = -24.0$, $y = -24.8$, $z = -16.9$). This model explained the data best and accounted for most of the variance with an RV of 11.6% at the peak activity of this dipole (see Fig. 4).

In addition, the validities of these models were tested through the following steps. First, the display of the residual maps in the time windows (350–550 ms and 550–750 ms) showed no further dipolar activity; second, no other dipoles could be fitted in the investigated time windows by comparing the solution with other plausible alternatives (e.g., bilaterally symmetric dipoles). These tests might suggest that the models explained the data in the best manner for the time windows.

Discussion

In the present study, we used ERPs to explore the electrophysiological correlates of reward processing in the social comparison context. Our results showed that Disadvantageous and Advantageous inequity both elicited a more negative ERP deflection (N350–550, LNC1 and LNC2) than did Equity in the time windows of 350–550 and 550–750 ms, and Disadvantageous inequity elicited a more negativity (N550–750) than did Advantageous inequity between 550 and 750 ms. Moreover, the medial frontal/ACC and the caudate nucleus might be related to reward processing under social comparison. We would discuss the implication of these findings in our study.

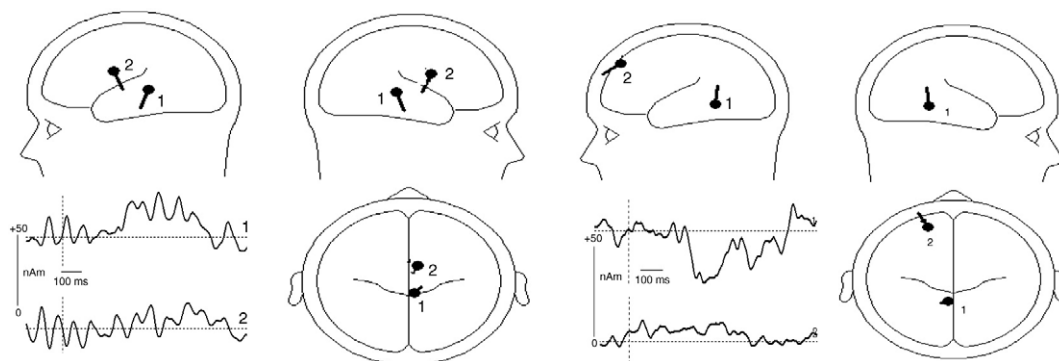


Fig. 3. Results of the dipole source analysis of the difference waves (Disadvantageous inequity vs. Equity and Advantageous inequity vs. Equity) in the time range of 350–550 ms. The left-bottom shows the source activity waveforms, whereas the right figure displays the mean locations of the dipole. Left: as for the difference wave of Disadvantageous inequity vs. Equity, the first dipole is located near the parahippocampal gyrus ($x = 4.9$, $y = -31.2$, $z = 3.1$), and the second dipole is located in the anterior cingulate cortex ($x = 6.9$, $y = -2.1$, $z = 28.0$). Right: as for the difference wave of Advantageous inequity vs. Equity, the first dipole is also located near the parahippocampal gyrus ($x = -4.6$, $y = -44.0$, $z = -6.2$), and the second dipole is located in the medial frontal cortex ($x = -21.4$, $y = 42.9$, $z = 5.2$).

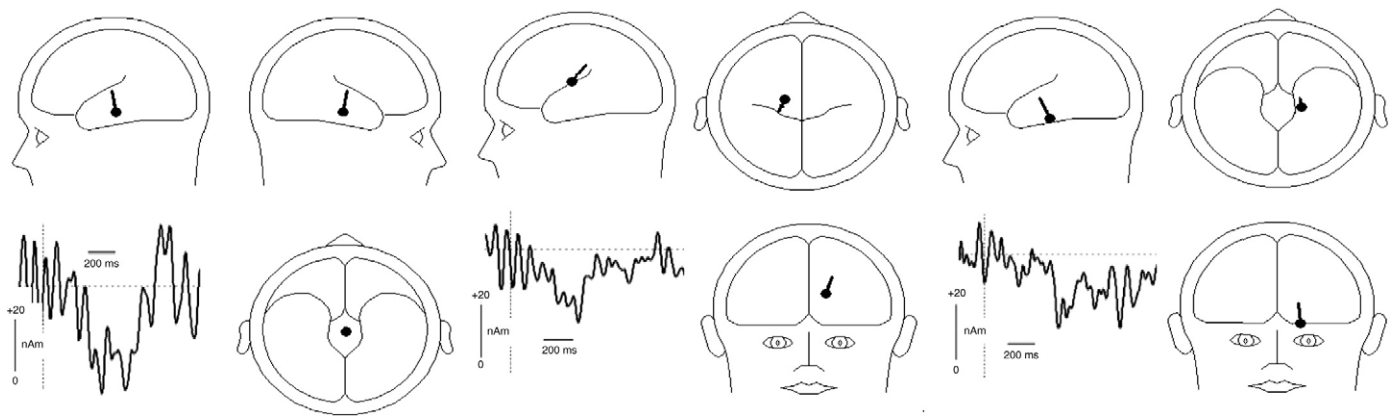


Fig. 4. Results of the dipole source analysis of the difference waves (Disadvantageous inequity vs. Equity, Advantageous inequity vs. Equity and Disadvantageous inequity vs. Advantageous inequity) in the time range of 550–750 ms. The left-bottom shows the source activity waveforms, whereas the right figure displays the mean locations of the dipole. Left: in the time range of 550–750 ms and the difference wave of Disadvantageous inequity vs. Equity (LNC1), the dipole is located approximately in the right caudate nucleus ($x = 5.6, y = 4.2, z = -0.2$); Middle: in the time range of 550–750 ms and the difference wave of Advantageous inequity vs. Equity (LNC2), the dipole is located in the left caudate nucleus ($x = -14.8, y = -4.5, z = 15.9$); Right: in the time range of 550–750 ms and the difference wave of Disadvantageous inequity vs. Advantageous inequity (N550–750), the dipole is located in the left parahippocampal gyrus ($x = -24.0, y = -24.8, z = -16.9$).

First, observing from the grand-averaged ERPs, we found that the N350–550 might be an obvious N400 component. It is known that the N400 is a negative deflection in the ERP, peaking at approximately 400 ms and elicited by words presented in unexpected or inappropriate sentence contexts (Kutas and Hillyard, 1989). The N400 is associated with the processing of semantic information that is incongruent with semantic expectancy, for example, “He adds some sugar to the coffee” vs. “He adds some socks to the coffee” (McPherson and Holcomb, 1999). A negative wave was evoked when the stimulus “socks” was incongruent with the anticipated information “sugar”. In addition, the N350–550 might be also a feedback-related negativity (FRN) in our study. According to the expectancy-deviation hypothesis of Oliveira et al. (2007), the FRN might be an outcome of a monitoring system that compared the subject’s expected feedback to the actual feedback and be elicited when a mismatch between the two was detected.

Moreover, the N350–550 might be also similar to the ERN in some aspects. The ERN, elicited after the onset of an erroneous response, was maximal at fronto-central recording sites (e.g., Falkenstein et al., 1990; Gehring et al., 1993). Generally, the ERN might be related to error monitoring (Falkenstein et al., 1990; Gehring et al., 1993) or response competition (Carter et al., 1998). Holroyd et al. (2003) found that the ERN might be also elicited by a reward prediction error (e.g., the difference between expectations and actual outcomes), such that unpredicted non-rewards elicited the largest ERNs, and suggested that the ERN might be generated by the impact of reinforcement learning signals carried by the mesencephalic dopamine system (MDS) on the ACC (see also Holroyd and Coles, 2002; Nieuwenhuis et al., 2002, 2004; Schultz, 2002). Therefore, some investigators indicated that these potentials might reflect activation of a reinforcement learning system that rapidly evaluated outcomes of decisions to guide reward-seeking behavior (e.g., Holroyd and Coles, 2002; Nieuwenhuis et al., 2004; Cohen et al., 2007). Most important and interesting, we indeed found that the generators of the N350–550 were localized near the parahippocampal gyrus and the ACC. As early as 1998, Blakemore et al. had found that the right parahippocampal gyrus and right parietal cortex might be associated with the presentation of unpredictable tones, compared to predictable tones (self-monitoring, see also Shergill et al., 2003). Carter et al. (2006) also indicated that activity in the parahippocampal gyrus correlated with contingency awareness during conditioning. In addition, the medial frontal/ACC activity might not be elicited only in response to errors, but also in response to rewards (Walton et al.,

2004; Ito et al., 2003). For example, some studies (e.g., Holroyd and Coles, 2002; Nieuwenhuis et al., 2004) indicated that the ACC might act as part of a more general performance monitoring system (whether feedback was better or worse than expected), and improve performance due to its role in cognitive control and action monitoring (e.g., Botvinick et al., 2004; Kerns et al., 2004; Oliveira et al., 2007). In the present study, we used the simple number estimation task to make subjects generate expectations of feedback based on their and the other subject’s performance. According to our subjects’ subjective reports and behavioral data, they usually expected that their rewards should be the same as the other subject’s when they were both correct (Equity). Then, a difference would be detected under Disadvantageous inequity (Not satisfaction with inequitable outcomes) and Advantageous inequity (Satisfaction with inequitable outcomes) when subjects compared the expected feedback to the actual feedback. That is to say, this most likely contributed to the N350–550 effect under Disadvantageous and Advantageous inequity conditions compared to Equity condition. Thus, we thought that the N350–550 in our study might reflect monitoring and controlling reward prediction error (a difference between expectations and actual outcomes) during reward processing under social comparison.

Second, Disadvantageous and Advantageous inequities both elicited a more late negative component (LNC1 and LNC2) than did Equity between 550 and 750 ms. The generators of LNC1 and LNC2 were both localized in the caudate nucleus, which might be related to reward processing under social comparison. The LNC was commonly characterized as slow waveform, which showed modulation in late time course and reflected higher-order cognitive processes (e.g., Pfützte and Sommer, 2002; Pickering and Schweinberger, 2003; Perrin et al., 2005). Some previous studies also indicated that the LNC might be involved in working memory, such as temporarily storing, manipulating, and maintaining information (e.g., Baddeley, 1992; Ohara et al., 2008). In addition, previous studies had found that the striatum of humans exhibited a high degree of context dependency in reward processing (e.g., Elliott et al., 2000; Breiter et al., 2001; Knutson et al., 2001; Akitsuki et al., 2003; Delgado et al., 2004; Holroyd et al., 2004; Nieuwenhuis et al., 2005; Cromwell et al., 2005). Furthermore, Fließbach et al. (2007) suggested that the ventral striatum responses to a variation in the comparison subject’s payment indicated that people did not evaluate objects solely by their absolute value but that social comparison played a substantial role in the evaluation of reward. The striatum had also been found when

misfortunes happened to envied persons and the results suggested that social comparison played a critical role in the central processing of envy and schadenfreude emotions (Takahashi et al., 2009). In our study, the brain probably recruited processes of elaborated evaluating for the rewards under social comparison after detection of reward prediction error. Subjects might spend much more cognitive resources for reward processing in the social comparison context under Disadvantageous and Advantageous inequity conditions compared to Equity condition. Therefore, this most likely contributed to the conspicuous LNC and the caudate nucleus activities.

In addition, Disadvantageous inequity elicited a more negativity (N550–750) (that is a more negative LPC) than did Advantageous inequity between 550 and 750 ms. Specifically, the LPC exhibited smaller mean amplitudes during Disadvantageous inequity than Advantageous inequity across frontal, central and parietal areas. This was consistent with several lines of evidence that negative stimuli elicited smaller LPC amplitudes than positive stimuli or neutral stimuli over a wide range of recording sites in implicit emotional tasks (e.g., Carretié et al., 1996; Delplanque et al., 2004). For example, Delplanque et al. (2004) indicated that frontal and central sites showed smaller LPC amplitudes in response to unpleasant pictures as compared to pleasant ones during an implicit emotional categorization of low-arousing stimuli. Moreover, the generator of N550–750 was localized in the left parahippocampal gyrus. Some previous studies had indicated that the parahippocampal gyrus was detected for unpleasant emotion as compared to pleasant emotion (e.g., Blood et al., 1999; Koelsch et al. 2006; Gosselin et al. 2006). Therefore, the N550–750 might reflect strong unpleasant emotional experience induced by Disadvantageous inequity compared to Advantageous inequity.

In a word, the present study might be the first one using ERP to investigate electrophysiologic correlates of the impact of social comparisons on the neural substrates of reward processing. Results showed that these ERP components (the N350–550, the LNC) and these brain areas (the medial frontal/ACC and the caudate nucleus) might be related to reward processing under social comparison. By recording and analyzing ERPs elicited by Disadvantageous inequity, Equity and Advantageous inequity, ERP data therefore allow for more precise examinations of the time course of activation for reward processing. However, there were still some shortcomings in our study. First, in the experiment of Fliessbach et al. (2007), two subjects really simultaneously and repeatedly performed a simple work task in two adjacent MRI scanners, while we just told subjects that they would perform a simple number estimation task with the other subject in the next laboratory simultaneously. To some extent, this design would partly reduce the credibility of the experiment to the subjects. Second, due to inherent limitations of source localization, the brain areas implied by source localization were only tentative. Regarding the involvement of brain regions in response to Disadvantageous inequity, Equity and Advantageous inequity, the current results only provided a model, rather than empirical data. In addition, the ERP technology and this research had some inevitable limitations. Therefore, further studies should be done using both ERPs and fMRI to investigate spatiotemporal cortical activation patterns underlying the brain mechanism of context-dependent reward processing.

Acknowledgments

This research was supported by the Specialized Research Fund for the Doctoral Program of Higher Education of China (No. 200806351002), the National Natural Science Foundation of China (30800293), the Key Discipline Fund of National 211 Project (NSK08005) and the Key Laboratory of Human Development and Mental Health in Hubei (Central China Normal University) (200803).

References

- Akitsuki, Y., Sugiura, M., Watanabe, J., Yamashita, K., Sassa, Y., Awata, S., Matsuoka, H., Maeda, Y., Matsue, Y., Fukuda, H., Kawashima, R., 2003. Context-dependent cortical activation in response to financial reward and penalty: an event-related fMRI study. *NeuroImage* 19, 1674–1683.
- Baddeley, A., 1992. Working memory. *Science* 255, 556–559.
- Blakemore, S.J., Rees, G., Frith, C.D., 1998. How do we predict the consequences of our actions. A functional imaging study. *Neuropsychologia* 36, 521–529.
- Blood, A.J., Zatorre, R.J., Bermudez, P., Evans, A.C., 1999. Emotional responses to pleasant and unpleasant music correlate with activity in paralimbic brain regions. *Nat. Neurosci.* 2, 382–387.
- Botvinick, M.M., Cohen, J.D., Carter, C.S., 2004. Conflict monitoring and anterior cingulate cortex: an update. *Trends Cogn. Sci.* 8, 539–546.
- Breiter, H.C., Aharon, I., Kahneman, D., Dale, A., Shizgal, P., 2001. Functional imaging of neural responses to expectancy and experience of monetary gains and losses. *Neuron* 30, 619–639.
- Bui, K.V.T., Pelham, B.W., 1999. Cognitive and affective reactions to social comparison. *J. Soc. Behav. Pers.* 14, 569–583.
- Carretié, L., Iglesias, J., Garcia, T., Ballesteros, M., 1996. N300, P300 and the emotional processing of visual stimuli. *Electroencephalogr. Clin. Neurophysiol.* 103, 298–303.
- Carter, C.S., Braver, T.S., Barch, D.M., Botvinick, M.M., Noll, D., Cohen, J.D., 1998. Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science* 280, 747–749.
- Carter, R.M., O'Doherty, J.P., Seymour, B., Koch, C., Dolan, R.J., 2006. Contingency awareness in human aversive conditioning involves the middle frontal gyrus. *NeuroImage* 29, 1007–1012.
- Cohen, M.X., Elger, C.E., Ranganath, C., 2007. Reward expectation modulates feedback-related negativity and EEG spectra. *NeuroImage* 35, 968–978.
- Cromwell, H.C., Hassani, O.K., Schultz, W., 2005. Relative reward processing in primate striatum. *Exp. Brain Res.* 162, 520–522.
- Delgado, M.R., Stenger, V.A., Fiez, J.A., 2004. Motivation-dependent responses in the human caudate nucleus. *Cereb. Cortex* 14, 1022–1030.
- Delplanque, S., Lavoie, M.E., Hot, P., Silvert, L., Sequeira, H., 2004. Modulation of cognitive processing by emotional valence studied through event-related potentials in humans. *Neurosci. Lett.* 356, 1–4.
- Elliott, R., Friston, K.J., Dolan, R.J., 2000. Dissociable neural responses in human reward systems. *J. Neurosci.* 20, 6159–6165.
- Falkenstein, M., Hohnsbein, J., Hoormann, J., Blanke, L., 1990. Effects of errors in choice reaction tasks on the ERP under focused and divided attention. In: Brunia, C., Gaillard, A., Kok, A. (Eds.), *Psychophysiological Brain Research*. Tilburg Univ. Press, Tilburg, pp. 192–195.
- Festinger, L., 1954. A theory of social comparison processes. *Hum. Rel.* 7, 114–140.
- Fliessbach, K., Weber, B., Trautner, P., Dohmen, T., Sunde, U., Elger, C.E., Falk, A., 2007. Social comparison affects reward-related brain activity in the human ventral striatum. *Science* 318, 1305.
- Gehring, W., Goss, B., Coles, M.G.H., Meyer, D.E., Donchin, E., 1993. A neural system for error detection and compensation. *Psychol. Sci.* 4, 385–390.
- Gosselin, N., Samson, S., Adolphs, R., Noulhiane, M., Roy, M., Hasboun, D., Baulac, M., Peretz, I., 2006. Emotional responses to unpleasant music correlates with damage to the parahippocampal cortex. *Brain* 129, 2585–2592.
- Holroyd, C.B., Coles, M.G., 2002. The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. *Psychol. Rev.* 109, 679–709.
- 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, 2481–2484.
- Holroyd, C.B., Larsen, J.T., Cohen, J.D., 2004. Context dependence of the event-related brain potential to reward and punishment. *Psychophysiology* 41, 245–253.
- Ito, S., Stuphorn, V., Brown, J.W., Schall, J.D., 2003. Performance monitoring by the anterior cingulate cortex during saccade countermanding. *Science* 302, 120–122.
- Kerns, J.G., Cohen, J.D., MacDonald III, A.W., Cho, R.Y., Stenger, V.A., Carter, C.S., 2004. Anterior cingulate conflict monitoring and adjustments in control. *Science* 303, 1023–1026.
- Knutson, B., Adams, C.M., Fong, G.W., Hommer, D., 2001. Anticipation of increasing monetary reward selectively recruits nucleus accumbens. *J. Neurosci.* 21, 1–5.
- Koelsch, S., Fritz, T., von Cramon, D.Y., Müller, K., Friederici, A.D., 2006. Investigating emotion with music: an fMRI study. *Hum. Brain Mapp.* 27, 239–250.
- Kutas, M., Hillyard, S.A., 1989. An electrophysiological probe of incidental semantic association. *J. Cogn. Neurosci.* 1, 387.
- McPherson, W.B., Holcomb, P.J., 1999. An electrophysiological investigation of semantic priming with picture of real objects. *Psychophysiology* 36, 53–65.
- Mussweiler, T., Rüter, K., Epstude, K., 2004. The man who wasn't there: subliminal social comparison standards influence self-evaluation. *J. Exp. Soc. Psychol.* 40, 689–696.
- Nieuwenhuis, S., Ridderinkhof, K.R., Talsma, D., Coles, M.G., Holroyd, C.B., Kok, A., 2002. A computational account of altered error processing in older age: dopamine and the error-related negativity. *Cogn. Affect. Behav. Neurosci.* 2, 19–36.
- Nieuwenhuis, S., Holroyd, C.B., Mol, N., Coles, M.G., 2004. Reinforcement-related brain potentials from medial frontal cortex: origins and functional significance. *Neurosci. Biobehav. Rev.* 28, 441–448.
- Nieuwenhuis, S., Heslenfeld, D.J., Geusau, N.J., Alting, V., Mars, R.B., Holroyd, C.B., Yeung, N., 2005. Activity in human reward-sensitive brain areas is strongly context dependent. *NeuroImage* 25, 1302–1309.
- Ohara, S., Wang, L., Ku, Y., Lenz, F.A., Hsiao, S.S., Hong, B., Zhou, Y.-D., 2008. Neural activities of tactile cross-modal working memory in humans: an event-related potential study. *Neuroscience* 152, 692–702.

- Oliveira, F.T.P., McDonald, J.J., Goodman, D., 2007. Performance monitoring in the anterior cingulate is not all error related: expectancy deviation and the representation of action–outcome associations. *J. Cogn. Neurosci.* 19, 1994–2004.
- Perrin, F., Maquet, P., Peigneux, P., Ruby, P., Degueldre, C., Balteau, E., 2005. Neural mechanisms involved in the detection of our first name: a combined ERPs and PET study. *Neuropsychologia* 43, 12–19.
- Pfütze, E.M., Sommer, W., 2002. Age-related slowing in face and name recognition: evidence from event-related brain potentials. *Psychol. Aging* 17, 140–160.
- Pickering, E.C., Schweinberger, S.R., 2003. N200, N250r, and N400 event-related brain potentials reveal three loci of repetition priming for familiar names. *J. Exp. Psychol. Learn. Mem. Cogn.* 29, 1298–1311.
- Schultz, W., 2002. Getting formal with dopamine and reward. *Neuron* 36, 241–263.
- Shergill, S.S., Brammer, M.J., Fukuda, R., Williams, S.C., Murray, R.M., McGuire, P.K., 2003. Engagement of brain areas implicated in processing inner speech in people with auditory hallucinations. *Br. J. Psychiatry* 182, 525–531.
- Stapel, D.A., Koomen, W., 2001. I, we, and the effects of others on me: how self-construal level moderates social comparison effects. *J. Per. Soc. Psychol.* 80, 766–781.
- Takahashi, H., Kato, M., Matsuura, M., Mobbs, D., Suhara, T., Okubo, Y., 2009. When your gain is my pain and your pain is my gain: neural correlates of envy and schadenfreude. *Science* 323, 937–939.
- Walton, M.E., Devlin, J.T., Rushworth, M.F., 2004. Interactions between decision making and performance monitoring within prefrontal cortex. *Nat. Neurosci.* 7, 1259–1265.
- Wills, T.A., 1981. Downward comparison principles in social psychology. *Psychol. Bull.* 90, 245–271.