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Research paper

Aberrant social feedback processing and its impact on memory, social evaluation, and decision-making among individuals with depressive symptoms

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ABSTRACT

Background: Depression is associated with aberrant social feedback processing. However, little is known about the impact of these deficits on individuals' memory, social evaluation, and social decision-making.
Methods: We examined event-related potentials (ERPs) during the processing of social feedback with different emotional valences and intensities, among individuals with high and low depressive symptoms. After three days, participants performed a recall test, along with social evaluation and money allocation.
Results: Compared with the control group, participants with depressive symptoms showed larger occipital P1 and parietal P3 amplitudes to negative social feedback, as well as larger frontal feedback-related negativity toward highly positive social feedback; this indicates toward altered attentional allocation, encoding, and anticipation in social feedback processing. After three days of social feedback processing, individuals in the depressive symptom group recalled negative social feedback better and gave less positive evaluations and allocated less money to the senders of highly negative social feedback compared with control group participants. Notably, ERPs predicted subsequent memory, social evaluation, and decision-making, suggesting a significant impact of aberrant social feedback processing on social cognition and behaviors in depression.
Limitations: Individuals with depressive symptoms rather than patients with depressive disorders were recruited and therefore caution is needed in applying the findings to clinical populations.
Conclusions: Individuals with depressive symptoms exhibit negative bias in anticipation, attentional allocation, and encoding processes during social feedback processing, which further influences their memory, social evaluation, and social decision-making in the long run. These aberrant biases should be targeted to prevent the development of major depressive disorders.

1. Introduction

Social feedback refers to interpersonal information conveying the evaluations of or attitudes toward the receiver, such as social acceptance/rejection and praise/criticism. Social feedback processing plays a vital role in human life, affecting interpersonal connections and guiding adaptive social behaviors (Weightman et al., 2014). Abnormal responses to social feedback are associated with multiple internalizing psychopathologies, such as social anxiety and depression (Hsu and Jarcho, 2020; Rappaport and Barch, 2020). Cognitive distortion of social feedback has long been observed in depressive individuals (Stone and Glass, 1986), and interest in this topic has revitalized in recent years (Rappaport and Barch, 2020; Reinhard et al., 2020). Research has identified three primary deficits in social feedback processing among clinically and sub-clinically depressed populations: (1) reduced anticipation for positive social feedback (Caouette and Guyer, 2016; Davey

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et al., 2011; He et al., 2020a), (2) anhedonia for positive social feedback (He et al., 2019; Zhang et al., 2020, 2017), and (3) heightened sensitivity to negative social feedback and sustained negative affective experiences afterward (Hsu et al., 2015; Jankowski et al., 2018; Kumar et al., 2017; Silk et al., 2014). These deficits significantly contribute to maladaptive social functioning in depression (Hames et al., 2013; Pulcu and Elliott, 2015).

Neuroimaging studies have demonstrated that depression is associated with aberrant brain responses to social feedback (for a review, see Rappaport and Barch, 2020). Specifically, depressed individuals robustly showed hyperactivation in brain regions associated with negative emotions and "social pain" in response to negative social feedback (e.g., the amygdala, subgenual and dorsal anterior cingulate cortices, and anterior insula; Jankowski et al., 2018; Kumar et al., 2017; Silk et al., 2014). When receiving positive social feedback, they demonstrated attenuated neural responses in reward systems (e.g., the ventral striatum and putamen), which is believed to be the key mechanism of social anhedonia (He et al., 2019, 2020a; Olino et al., 2015; for a review, see Kupferberg et al., 2016). Meanwhile, event-related potential (ERP) studies have demonstrated that depressed people show blunted P3 in response to social inclusion (Zhang et al., 2017) and social rewards (Zhang et al., 2020) relative to healthy controls. Although these findings reveal the neurocognitive processing of social feedback, it remains unclear whether and how the altered social feedback processing in depressed people influences their subsequent memory, social evaluation, and decision-making behaviors.

Answering these questions is important because memory deficits and social dysfunctions are critically involved in the etiology and consequences of depression (Gibbs and Rude, 2004; Kupferberg et al., 2016). Specifically, distressing memories associated with unpleasant interpersonal experiences are among the most common complaints of individuals seeking psychotherapy (Kennedy and Adolphs, 2012; Rappaport and Barch, 2020). Although negative memory bias has received considerable attention (Barry et al., 2004; Gaddy and Ingram, 2014), existing studies primarily use non-social materials that are less self-relevant (e.g., emotional pictures), which prevents a sophisticated understanding of social memory deficits in depression. Meanwhile, deficits in social cognition and decision-making are among the prominent features of depression (see Kupferberg et al., 2016 for a review). For example, Pulcu et al. (2015) found multiple behavioral alterations in depressed people during social interactions in various social-economical decision-making tasks. However, to date no study has investigated the causal relationship between social feedback processing and subsequent social evaluation and decision-making in depression. Untangling this question can help shed light on the pathological mechanisms underlying social dysfunction in depression and aid in the development of therapeutic and preventative strategies to improve social functions in patients.

In this study, we examined possible deficits in anticipation, perception, and encoding of social feedback, as well as their influence on subsequent memory and social behaviors, in individuals with depressive symptoms. To this end, we adapted a social judgment task (Somerville et al., 2006) in which participants were fictitiously relayed feedback from their peers. Specifically, they were informed of their peers' willingness to become their friends. Given the significant role of intensity in emotion processing (Barrett, 1998; Brehm, 1999; Reisenzein, 1994), we integrated this factor into the social feedback processing (SFP) task. We used the ERP technique to examine the neural responses during SFP and focused on three ERP components along the information processing stream. The first was the occipital P1, which reflects an early attentional allocation to salient social/emotional stimuli (Batty and Taylor, 2003; Meeren et al., 2005; Zhang and Luck, 2008). We expected to observe enhanced P1 for negative social feedback in the depressive group, compared with the control group, given the well-established relationship between negativity attention bias and depression (Gotlib et al., 2004; Mennen et al., 2019). Next, we examined feedback-related negativity (FRN), a frontally distributed negative-going waveform peaking between 200 and 300 ms, which is often observed in SFP and indicates expectancy violation (Gu et al., 2020; van der Molen et al., 2017, 2018). Given the evidence that depressed people have reduced anticipation for positive social feedback (Caouette and Guyer, 2016; Davey et al., 2011; He et al., 2020a), we expected a larger FRN for positive social feedback in the depressive symptoms group than in the control group, especially when the positive feedback was with a high intense. The third ERP is the parietal P3 (also known as late positive potential), which has been associated with sustained attentional allocation and elaborative processing of emotional stimuli (Hajcak and Olvet, 2008; Kayser et al., 2000). A larger P3 amplitude for positive social feedback was observed among healthy individuals, indicating an encoding bias for desirable or self-affirming information (Funkhouser et al., 2020; van der Veen et al., 2016; Yao et al., 2021). In accordance with previous findings (Zhang et al., 2017, 2020), we predicted a smaller P3 amplitude for positive social feedback in the depressive group than in the control group. We also predicted a larger P3 amplitude for negative social feedback in depression than positive social feedback because of the encoding bias for negative self-relevant information in the group (Benau et al., 2019; Webb et al., 2017).

Ours is the first study to investigate the long-term effects of aberrant SFP on social cognition and behaviors. Specifically, we examined participants' memory of social feedback, their social evaluation, and decision-making with regard to those who had given the feedback, after a three-day interval. Research has consistently suggested that people have an intrinsic motivation to remember positive, self-affirming information, which supports self-protection and the maintenance of self-esteem (Sedikides and Green, 2004; Walker et al., 2003). People tend to selectively forget self-threatening information—a phenomenon known as mnemic neglect (MN; Rigney et al., 2020; for a review, see Sedikides et al., 2016). Absent or reduced MN has been observed in individuals with dysphoria and social anxiety (Saunders, 2011; Zengel et al., 2015). Accordingly, we predicted impaired MN in the depressive group, that is, higher recall accuracy for negative social feedback compared with the control group. Lastly, we predicted that aberrant SFP would have long-term downstream influence on social evaluation and money allocation tasks; compared with the control group, the depressive group would have lower evaluation and allocate less money to peers who gave them negative social feedback.

2. Methods

2.1. Participants

Participants were recruited from Shenzhen University and prescreened using the Beck Depression Inventory-II (BDI-II; Beck et al., 1996). Of the 850 undergraduate and postgraduate students who completed the prescreening session, we excluded participants with lifetime axis I disorders according to the Structured Clinical Interview for DSM-IV-TR Axis I Disorders, Research Version, Non-Patient Edition (First et al., 2002). Other exclusion criteria included: (1) seizure disorder, (2) a history of head injury with possible neurological sequelae, (3) self-reported prior use of any psychoactive drugs, and (4) current alcohol or drug dependence. Participants who scored > 13 were assigned to the depressive group ($n = 40$) and those who scored < 13 were assigned to the control group ($n = 40$). Three participants in the depressive group failed to complete the experiment due to technical problems, and therefore there were a total of 37 individuals in the depressive group.

Demographics and BDI-II scores are presented in Table 1. Participants in the depressive group reported higher depression levels compared with those in the control group, and there were no significant differences between the two groups in terms of gender, age, and handedness. Written informed consent was obtained from all the participants prior to the experiment. The study was approved by the Ethics

Table 1
Demographic characteristics of the participants (means and standard deviations).

Items	Depressive group ($n = 37$)	Control group ($n = 40$)	Control group versus Depressive group
Gender (man/woman)	18/19	24/16	$\chi^2 = 0.99$, $p = 0.318$
Age (years)	19.97 ± 1.86	19.95 ± 1.75	$T = 0.06$, $p = 0.956$
Handedness (right/left)	37/0	40/0	
BDI-II	19.08 ± 5.41	2.08 ± 2.40	$T = 18.05$, $p < 0.001$***

BDI-II: the Beck Depression Inventory Second Edition.
*** $p < 0.001$.

Committee of Shenzhen University.

2.2. Experimental design and stimuli

We employed a 2 (valence of social feedback: positive vs. negative) × 2 (intensity of social feedback: high vs. low) × 2 (group: depressive vs. control) mixed design. We used 100 front-view headshots of young adults (50 women and 50 men) with neutral facial expressions. Each photo was standardized with respect to the size, luminance, and background. These photos were assigned to the 2 (valence) × 2 (intensity) conditions and a baseline condition, with 20 photos in each condition. Attractiveness ratings of faces were counterbalanced across the conditions.

2.3. Procedure

The experimental task included the following three phases (Fig. 1A).

Phase 1: Cover story. Participants were told that they would take part in a study on first impression-based evaluations and were asked to submit an identity photograph immediately after they were included in the study. They were told that their photograph would be sent to a panel of peers from another university to judge whether they would like to be their friends based on their first impressions.

Phase 2: SFP task. Once in the lab, participants completed the BDI-II again (Table 1). After the electroencephalogram (EEG) equipment and electrodes were set up, the participants were presented with photos of their peers together with the evaluative feedback. In each block, a total of 80 photos were presented sequentially, and each photo was presented only once. As shown in Fig. 1B, the photo was presented for 1.5 s followed by feedback (either a plus + or minus - sign) presented below the photo for 2.5 s. Participants were told that the feedback signaled whether the peer would like to make friends with them ("+" = yes and "-" = no). Together with the +/- feedback, we also presented a number (1 or 5) representing their level of willingness (i.e., intensity, with 1 for low and 5 for high). This gave us four levels of social feedback: "+1" indicated positive/low willingness (i.e., slightly willing to make friends with the participant), "+5" indicated positive/high willingness (i.e., strongly willing to make friends with the participant), "-1" indicated negative/low unwillingness, and "-5" indicated negative/high unwillingness. The probabilities of these four types of feedback were equal, with each block containing 20 photos per feedback condition. The 80 photos were mixed and presented in a random order. To ensure sufficient trials for ERP averaging, the same block was repeated three times, resulting in 240 trials in total and 60 trials per condition. The task lasted for approximately 20 min, during which the EEG data were continuously recorded.

Phase 3 Delayed tests. After an interval of three days, participants were invited to the lab again and performed the following three tasks.

Memory recall test. Each of the 80 photos used in Phase 2 was presented in a random order. Participants recalled the valence of feedback given by the peer and responded with a keyboard within 3 s ("*f*" for positive and "*j*" for negative).

After the memory recall test, there was a rest period that lasted for approximately 5–10 min, followed by the attractiveness evaluation and

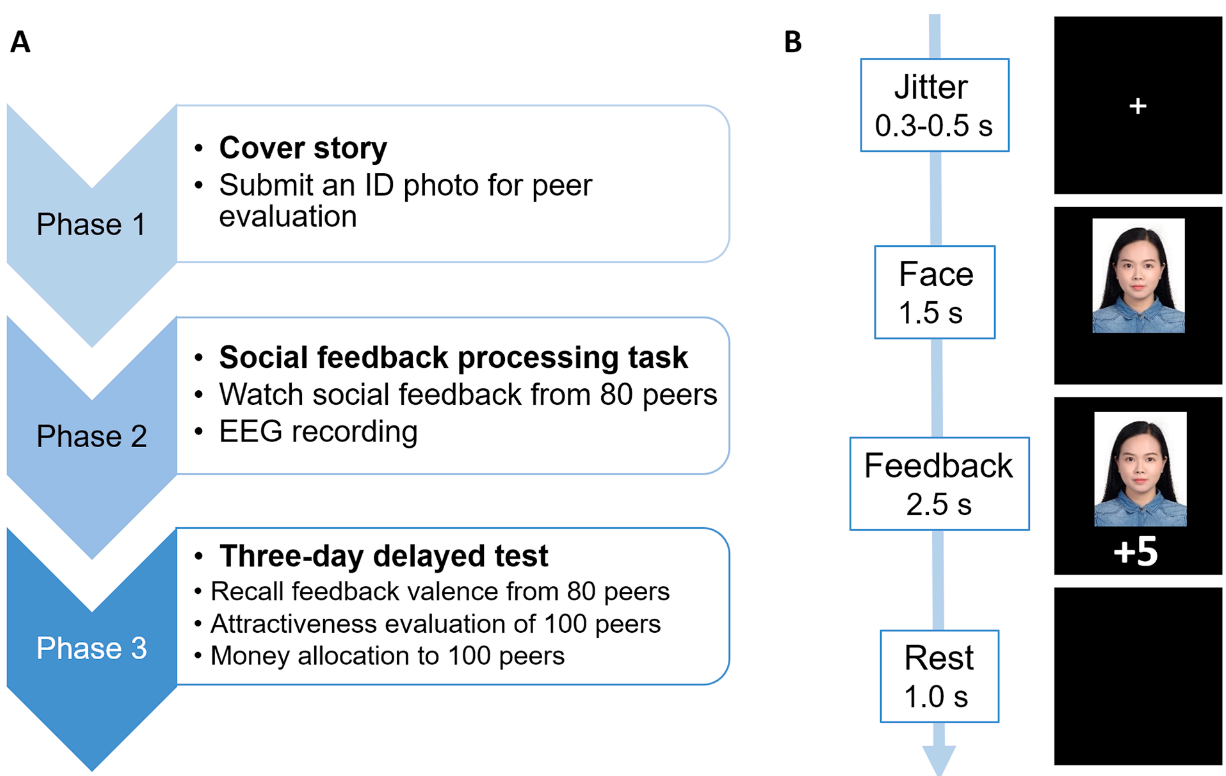

Fig. 1. Experimental procedure. A: Three phases of the study. B: Illustration of one trial in the social feedback processing task. Note: the individual depicted in the photo is the first author (H. X.) of the present study.

money allocation tasks; the order of the two tasks was counterbalanced across participants.

Attractiveness evaluation task. In this task, 100 photos of peers (80 photos used in Phase 2 and 20 new photos) were presented randomly. Participants rated the attractiveness of each face on a 9-point scale (1 = extremely low to 9 = extremely high) within 5 s.

Money allocation task. Each of the 100 photos of peers was randomly presented. Participants had allocate ?10 RMB (approximately $1.5) between themselves and the peer depicted in the photo within 5 s. Participants were told that the average amount of money they kept for themselves across all trials would be paid as a bonus, and the peers would receive the amount of money that the participants allocated to them.

2.4. EEG recording and analysis

Continuous EEG signals were recorded during the SFP task with the online reference against the TP9 electrode using a 32-channel EEG amplifier with a sampling rate of 250 Hz (NeuSen.W32, Neuracle). The electrode impedances were maintained below 10 kΩ. Data were re-referenced offline to average activities over the scalp, followed by ocular artifact removal using a regression procedure implemented in the NeuroScan software (Scan 4.3: NeuroScan, Inc., Herndon, VA).

EEG data were filtered offline (0.1–30 Hz with a slope of 24 dB/oct) and segmented into -200–1200 ms epochs according to the time of feedback. Trials contaminated with significant artifacts (peak-to-peak deflection exceeding ±100 μV) were excluded from further analyses. All epochs were baseline-corrected using the mean amplitude of the pre-feedback 200 ms baseline, followed by averaging within each condition.

As mentioned in the introduction, this study included the P1, FRN, and P3 components. The electrode sites and time windows for ERP analyses were determined a priori based on previous related studies. For the occipital P1, we calculated the 100–150 ms mean amplitude at O1/2 (Gu et al., 2020; Luck and Gaspelin, 2017; Raz et al., 2014). For the frontal FRN, we calculated the 250–350 ms mean amplitude at FCz, FC1/2 (Carlson et al., 2011; Kujawa et al., 2013; Wang, Gu, Luo, and Zhou, 2017). For the parietal P3, we calculated the 300–1000 ms mean amplitude at Pz, P3/4 (He et al., 2020b; Juravle et al., 2017; Solomon et al., 2012).

2.5. Statistics

Statistical analysis was performed using SPSS Statistics 22.0 (IBM Corporation, Armonk, NY, USA). Descriptive data are presented as mean ± standard deviation, unless stated otherwise. The significance level was set at $p < 0.05$. Repeated-measures analysis of variance (ANOVA) was performed on behavioral and ERP measurements, with valence (positive vs. negative) and intensity (high vs. low) of social feedback as two within-subject factors and group (depressive vs. control) as a between-subjects factor. To understand how neural processes influenced downstream behavior, we performed a two-tailed Pearson's r correlation between ERPs during the SFP task (i.e., amplitudes of P1, FRN, and P3) and behavioral indicators (i.e., recall accuracy, attractiveness rating, and allocated money).

3. Results

3.1. Social feedback processing task

3.1.1. Occipital P1 component

Although P1 is located bilaterally in the occipital areas, there is no significant effect associated with the hemisphere. Thus, the P1 amplitude was averaged across the hemispheres to provide waveforms with a high signal-to-noise ratio. A 2 × 2 × 2 ANOVA revealed that the main effect of feedback intensity was significant ($F(1,75) = 21.6$, $p < 0.001$, $\eta_p^2 = 0.224$; high vs. low = 1.46 ± 1.47 vs. 1.00 ± 1.35 μV).

Furthermore, the two-way interaction between group and feedback valence was significant ($F(1,75) = 14.2$, $p < 0.001$, $\eta_p^2 = 0.159$; Fig. 2A). Simple effect analysis revealed that while control group showed a tendency of having a larger P1 amplitude following positive (1.37 ± 1.62 μV) rather than negative feedback (1.13 ± 1.44 μV; $F(1,75) = 3.7$, $p = 0.059$, $\eta_p^2 = 0.047$), depressive group participants, had a larger P1 amplitude following negative (1.42 ± 1.22 μV) feedback rather than positive feedback (0.99 ± 1.36 μV; $F(1,75) = 11.5$, $p = 0.001$, $\eta_p^2 = 0.133$).

3.1.2. Frontal FRN component

A 2 × 2 × 2 ANOVA showed no significant main effects. The two-way interaction between group and feedback valence was significant ($F(1,75) = 18.4$, $p < 0.001$, $\eta_p^2 = 0.197$). Simple effect analysis revealed that although control group showed a larger (i.e., more negative-going) FRN amplitude following negative (0.62 ± 1.43 μV) feedback than they did following positive feedback (1.04 ± 1.70 μV; $F(1,75) = 15.8$, $p < 0.001$, $\eta_p^2 = 0.174$), depressive participants had a smaller (less negative-going) FRN amplitude following negative (0.53 ± 1.12 μV) feedback than they did following positive feedback (0.30 ± 1.39 μV; $F(1,75) = 4.5$, $p = 0.036$, $\eta_p^2 = 0.057$).

More importantly, the three-way interaction was significant ($F(1,75) = 17.4$, $p < 0.001$, $\eta_p^2 = 0.188$; Fig. 3). To break down the three-way interaction, we tested the feedback valence × intensity in the two groups. For control participants, both the main effect of feedback valence ($F(1,39) = 20.7$, $p < 0.001$, $\eta_p^2 = 0.346$) and the two-way interaction was significant ($F(1,39) = 11.8$, $p = 0.001$, $\eta_p^2 = 0.232$). In addition, a simple effect analysis demonstrated that while control participants exhibited larger FRN (more negative-going) for negative feedback than for positive feedback, this valence effect was significant for high-intensity feedback ($F(1,39) = 30.0$, $p < 0.001$, $\eta_p^2 = 0.435$; positive vs. negative = 1.27 ± 1.71 vs. 0.52 ± 1.40 μV) but not low-intensity feedback ($F < 1$; positive vs. negative = 0.81 ± 1.68 vs. 0.73 ± 1.48 μV). For the depressive group, only the two-way interaction was significant ($F(1,36) = 6.0$, $p = 0.019$, $\eta_p^2 = 0.144$). Simple effect analysis demonstrated that depressed participants exhibited a smaller FRN (less negative) amplitude following highly negative feedback (0.70 ± 1.15 μV) than after highly positive feedback (0.26 ± 1.58 μV; $F(1,36) = 7.8$, $p = 0.008$, $\eta_p^2 = 0.178$); this valence effect was not found in low-intensity conditions ($F < 1$; positive vs. negative = 0.34 ± 1.19 vs. 0.35 ± 1.08 μV).

3.1.3. Parietal P3 component

A 2 × 2 × 2 ANOVA showed that the main effect of feedback valence was significant ($F(1,75) = 12.1$, $p = 0.001$, $\eta_p^2 = 0.139$; positive vs. negative = 0.84 ± 1.92 vs. 0.47 ± 2.09 μV). The main effect of feedback intensity was also significant ($F(1,75) = 39.5$, $p < 0.001$, $\eta_p^2 = 0.345$; high vs. low = 1.06 ± 1.99 vs. 0.25 ± 1.96 μV). Furthermore, the two-way interaction between feedback valence and intensity was significant ($F(1,75) = 10.6$, $p = 0.002$, $\eta_p^2 = 0.124$). Simple effect analysis revealed that the P3 amplitude evoked by positive feedback was much larger in the high intensive condition (1.41 ± 1.79 μV) compared with the low intensive condition (0.27 ± 1.88 μV; $F(1,75) = 52.3$, $p < 0.001$, $\eta_p^2 = 0.411$), and the intensity effect was smaller for negative feedback ($F(1,75) = 7.5$, $p = 0.008$, $\eta_p^2 = 0.091$; high vs. low = 0.70 ± 2.12 vs. 0.23 ± 2.04 μV).

The most important finding related to the parietal P3 component was the two-way interaction between the group and feedback valence ($F(1,75) = 10.8$, $p = 0.002$, $\eta_p^2 = 0.126$; Fig. 2B). Simple effect analysis revealed that while depressive participants (0.94 ± 2.19 μV) exhibited a larger P3 amplitude following negative feedback compared with control

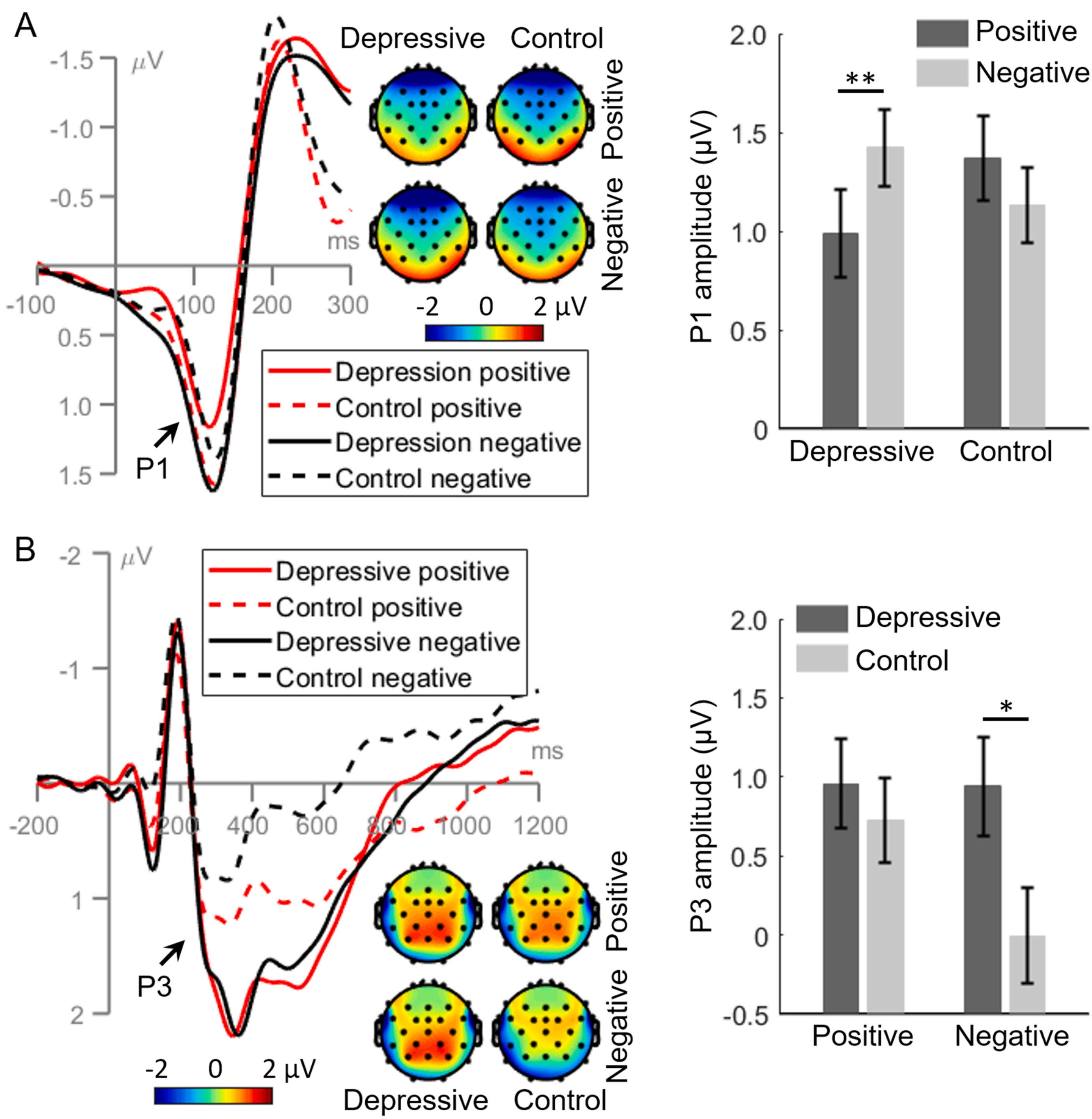

Fig. 2. ERP results for P1 and P3. A: the P1 component. Waveforms are averaged across O1 and O2 electrodes. Time window for topographies is from 100 to 150 ms post feedback onset. B: the P3 component. Waveforms are averaged across Pz, P3, and P4 electrodes. Time window for topographies is from 300 to 1000 ms post feedback onset. $^*p < 0.05$, $^{**}p < 0.01$. Bars represent ± standard error of the mean.

participants (0.00 ± 1.89 μV; $F(1,75) = 4.7$, $p = 0.032$, $\eta_p^2 = 0.060$), the group difference was not significant for positive feedback ($F < 1$; depressive vs. control = 0.96 ± 2.00 vs. 0.73 ± 1.84 μV).

3.2. Memory recall test

First, we examined the recall accuracy rate. The 2 × 2 × 2 ANOVA showed that the main effect of feedback valence was significant ($F(1,75) = 7.5$, $p = 0.008$, $\eta_p^2 = 0.091$; positive vs. negative = 0.627 ± 0.182 vs. 0.551 ± 0.173). The main effect of feedback intensity was also significant ($F(1,75) = 56.5$, $p < 0.001$, $\eta_p^2 = 0.430$; high vs. low intensity = 0.634 ± 0.175 vs. 0.545 ± 0.177). In addition, the two-way interaction of group × feedback valence was significant ($F(1,75) = 6.5$, $p = 0.013$, $\eta_p^2 = 0.080$; Fig. 4A). Simple effect analysis revealed that while the depressive group participants correctly recalled more negative feedback (0.589 ± 0.164) than the control group participants (0.513 ± 0.173; $F(1,75) = 4.9$, $p = 0.029$, $\eta_p^2 = 0.062$), the latter tended to correctly recall more positive feedback (0.660 ± 0.156) than the former (0.595 ± 0.199; $F(1,75) = 3.7$, $p = 0.058$, $\eta_p^2 = 0.047$). Alternatively, this two-way interaction revealed that while control group participants

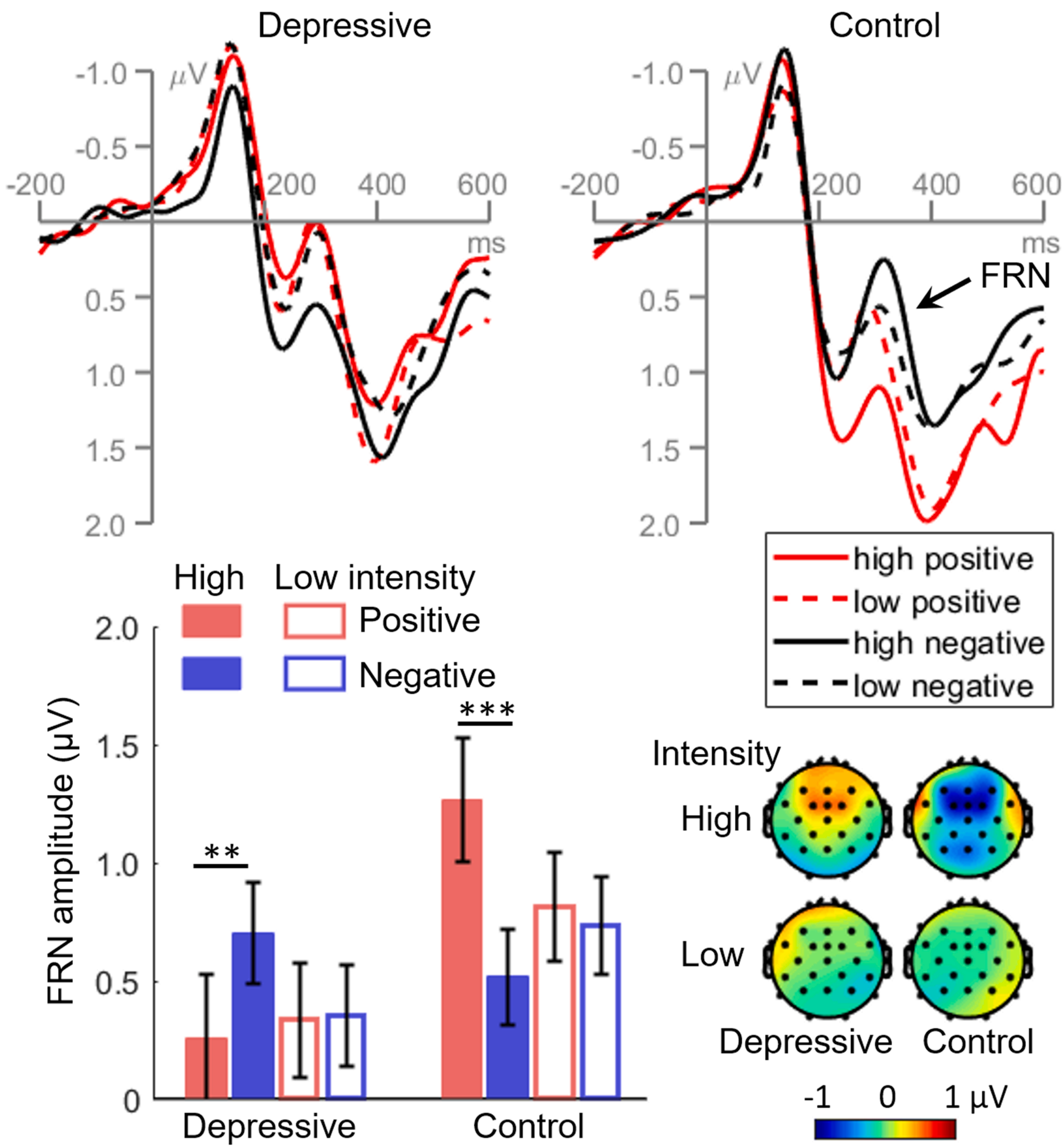

Fig. 3. ERP results of FRN. Waveforms are averaged across FCz, FC1, and FC2 electrodes. ERP topographies are drawn using the difference wave, that is, the FRN amplitudes following the negative conditions are subtracted by those following the positive conditions. Time window for topographies is from 250 to 350 ms post feedback onset. $^{**}p < 0.01$, $^{***}p < 0.001$. Bars represent ± standard error of the mean.

correctly recalled more positive than negative feedback ($F(1,75) = 14.6$, $p < 0.001$, $\eta_p^2 = 0.163$), this valence effect was not significant in the depressive group ($F < 1$).

Next, we examined whether a general response bias (i.e., a tendency to always respond positive/negative) in the recall could influence our results. We compared the positive rate (percentage of positive responses in all responded trials) in high- and low-intensity conditions. A 2 (high/low intensity) × 2 (group) ANOVA revealed neither main nor interaction effects.

3.3. Attractiveness evaluation task

A 2 × 2 × 2 ANOVA showed that the main effect of group was significant ($F(1,75) = 4.1$, $p = 0.045$, $\eta_p^2 = 0.052$); depressive participants (3.80 ± 1.42) reported lower attractive scores compared with control participants (4.36 ± 1.10). Additionally, the main effect of feedback

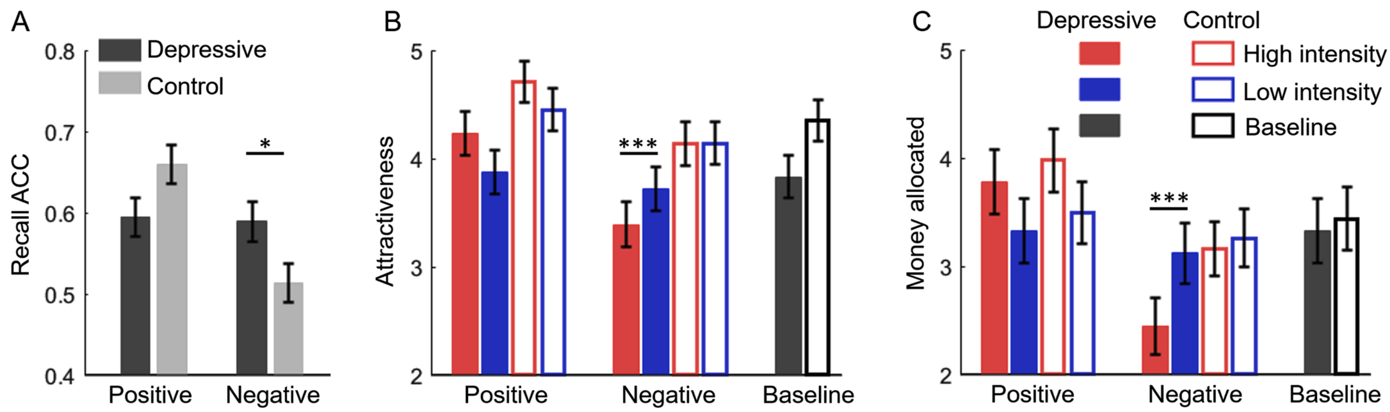

Fig. 4. Behavioral results. A: Recall accuracy in the memory test. Two-way interaction of group × feedback valence is denoted as * ($p < 0.05$); B: Attractiveness scores of others (from 1 = extremely low attractiveness to 9 = extremely high attractiveness); C: Money allocated to others. The total amount was 10 RMB for each trial. Three-way interaction of group × feedback valence × feedback intensity is denoted as *** ($p < 0.001$). Bars represent ± standard error of the mean.

valence was significant ($F(1,75) = 79.9$, $p < 0.001$, $\eta_p^2 = 0.516$; (positive vs. negative = 4.31 ± 1.25 vs. 3.85 ± 1.28). The two-way interaction between feedback valence and intensity was significant ($F(1,75) = 30.3$, $p < 0.001$, $\eta_p^2 = 0.288$). Simple effect analysis revealed that participants considered the individuals who gave them positive feedback with a high intensity to have higher attractiveness (4.48 ± 1.24) than those who gave positive feedback with a low intensity (4.17 ± 1.26; $F(1,75) = 20.6$, $p < 0.001$, $\eta_p^2 = 0.215$); they also considered individuals who gave them negative feedback with a high intensity to have less attractiveness (3.78 ± 1.32) than those who gave negative feedback with a low intensity (3.94 ± 1.26; $F(1,75) = 17.0$, $p < 0.001$, $\eta_p^2 = 0.185$).

The most important finding for the attractiveness evaluation task was the three-way interaction ($F(1,75) = 6.0$, $p = 0.017$, $\eta_p^2 = 0.074$; Fig. 4B). To break down the three-way interaction, we tested the group × feedback intensity under positive and negative conditions. For the positive feedback condition, there was a main effect of feedback intensity, while the two-way interaction was not significant ($F < 1$). For the negative feedback condition, the main effect of feedback intensity and group ($F(1,75) = 17.0$, $p < 0.001$, $\eta_p^2 = 0.185$) and the two-way interaction were significant ($F(1,75) = 16.1$, $p < 0.001$, $\eta_p^2 = 0.177$). Further, simple effect analysis revealed that depressive participants considered individuals who gave negative feedback with a high intensity to have less attractiveness (3.39 ± 1.41) compared with those who gave negative feedback with a low intensity (3.72 ± 1.42; $F(1,75) = 31.9$, $p < 0.001$, $\eta_p^2 = 0.298$); this intensity effect was not significant in the control group ($F < 1$; high vs. low intensity = 4.14 ± 1.13 vs. 4.14 ± 1.06).

In addition, we compared the attractiveness scores between the 80 photos that were used in the social feedback processing task and the 20 photos that were not used (baseline). A 5 × 2 ANOVA (Greenhouse-Geisser corrected) demonstrated a significant main effect of old/new photos ($F(4,300) = 39.9$, $p < 0.001$, $\eta_p^2 = 0.347$). Pairwise comparisons (Bonferroni adjusted) showed that participants gave higher attractiveness ratings to individuals they believed gave them positive feedback ($p < 0.001$) and lower attractiveness ratings to those they believed gave them negative feedback, including both high ($p < 0.001$) and low intensity feedback ($p = 0.012$), compared with the individuals whose photos had not been seen earlier (4.10 ± 1.22). In addition, the main effect of group was significant ($F(1,75) = 4.1$, $p = 0.047$, $\eta_p^2 = 0.052$); depressive group participants rated individuals as having lower attractiveness than control group participants in both the experimental and baseline conditions. The two-way interaction was not significant ($F(4,300) = 2.2$, $p = 0.100$, $\eta_p^2 = 0.029$).

3.4. Money allocation task

A 2 × 2 × 2 ANOVA showed that the main effect of feedback valence was significant ($F(1,75) = 52.0$, $p < 0.001$, $\eta_p^2 = 0.409$; positive vs. negative = ?3.64 ± 1.82 vs. ?3.00 ± 1.66). The two-way interaction between feedback valence and intensity was also significant ($F(1,75) = 58.6$, $p < 0.001$, $\eta_p^2 = 0.439$). Simple effect analysis revealed that for positive feedback, participants allocated more money to the individuals who gave them high positive feedback (?3.88 ± 1.83) than those who gave low positive feedback (?3.41 ± 1.79; $F(1,75) = 59.4$, $p < 0.001$, $\eta_p^2 = 0.442$); regarding negative feedback, participants allocated less money to the individuals who gave them high negative feedback (?2.80 ± 1.64) than those who gave them low negative feedback (3.20 ± 1.67; $F(1,75) = 16.3$, $p < 0.001$, $\eta_p^2 = 0.178$). In addition, the two-way interaction between group and intensity of feedback was also significant ($F(1,75) = 6.7$, $p = 0.011$, $\eta_p^2 = 0.082$).

The most important finding for the money allocation task was the three-way interaction ($F(1,75) = 5.8$, $p = 0.019$, $\eta_p^2 = 0.071$; Fig. 4C). To break down the three-way interaction, we tested the group × feedback intensity under positive and negative conditions. For the positive feedback condition, there was a main effect of feedback intensity ($F(1,75) = 59.4$, $p < 0.001$, $\eta_p^2 = 0.442$; high vs. low intensity = ?3.88 ± 1.83 vs. ?3.41 ± 1.79), but the two-way interaction was not significant ($F < 1$). For the negative feedback condition, both the main effect of feedback intensity ($F(1,75) = 16.3$, $p < 0.001$, $\eta_p^2 = 0.178$) and the two-way interaction were significant ($F(1,75) = 8.7$, $p = 0.004$, $\eta_p^2 = 0.104$). In addition, simple effect analysis revealed that while depressive participants allocated less money to the individuals who gave them high negative feedback (?2.45 ± 1.61) than those who gave low negative feedback (?3.12 ± 1.83; $F(1,75) = 23.5$, $p < 0.001$, $\eta_p^2 = 0.239$), this intensity effect was not significant in the control group ($F < 1$; high vs. low intensity = ?3.16 ± 1.60 vs. ?3.26 ± 1.53).

Next, we compared the amount of money allocated among the 80 photos from the SFP and the 20 baseline and new photos. A 5 × 2 ANOVA (Greenhouse-Geisser corrected) revealed a significant main effect of feedback conditions ($F(4,300) = 26.8$, $p < 0.001$, $\eta_p^2 = 0.263$). Pairwise comparisons (Bonferroni adjusted) showed that participants allocated more money to the individuals who gave them highly positive feedback ($p = 0.001$) and less money to those who gave them highly negative feedback ($p < 0.001$) compared with the individuals whose photos were not seen (?3.39 ± 1.81). The two-way interaction was marginally significant ($F(4,300) = 2.8$, $p = 0.050$, $\eta_p^2 = 0.036$).

3.5. Correlations

3.5.1. Correlation between ERP and behavior indexes

The P1 amplitude for highly positive social feedback correlated with the attractiveness rating ($r = 0.285$, $p = 0.012$) and amount of money allocated to the sender ($r = 0.264$, $p = 0.020$). The FRN amplitude for highly negative social feedback correlated with the sender's attractiveness ($r = -0.286$, $p = 0.012$) and the amount of money allocated to the sender ($r = -0.269$, $p = 0.018$). (Note: Negative correlation suggests more negative FRN, a higher attractiveness rating, and more money allocated.) The P3 amplitude correlated with the recall accuracy for both highly positive social feedback ($r = 0.373$, $p = 0.001$) and highly negative social feedback ($r = 0.340$, $p = 0.002$).

3.5.2. Correlation between behavior indexes

Recall accuracy of highly negative social feedback correlated with the participant's attractiveness rating of the sender ($r = -0.278$, $p = 0.015$). Recall accuracy of highly positive social feedback correlated with the amount of money allocated to the sender ($r = 0.292$, $p = 0.010$).

4. Discussion

This study examined the long-term impact of aberrant social feedback processing among depressive individuals on their later behaviors, including memory, social evaluation, and social decision-making. Using ERPs, we found altered neural activities reflecting deficits in perception, anticipation, and encoding of social feedback in the participants with depressive symptoms. Specifically, compared with the control group, the depressive group had larger occipital P1 and parietal P3 amplitudes in response to negative social feedback, as well as larger frontal FRN amplitudes in response to highly positive social feedback. Three days after receiving the social feedback, the depressive group participants showed enhanced memory of negative social feedback, rated individuals who provided highly negative social feedback as less attractive, and allocated less money to those individuals as compared with the control group participants.

In line with our prediction, we demonstrated impaired MN in depression, as evidenced by higher recall accuracy for negative social feedback in the depressive group. Moreover, recall accuracy correlated with P3 amplitude during social feedback processing, which was consistent with the broad literature showing links between P3 amplitude and subsequent memory performance (e.g., Dolcos and Cabeza, 2002; Yao et al., 2021). The P3 has been widely associated with elaborative processing of emotionally salient stimuli (for a review, see Hajcak and Foti, 2020) and self-relevant information (Benau et al., 2019; Hu et al., 2011; Webb et al., 2017). Thus, enhanced P3 in the depressive group may reflect an encoding bias for negative social feedback that results in stronger memories of self-threatening information in depression. Considering that negative memory is a major endogenous source of mental distress (Engen et al., 2016) and depression is characterized by maladaptive rumination, our findings may explain the prolonged pain experienced following social rejection in depression (Hsu et al., 2015).

In addition to our findings on P3, we found that during the earlier phase of the SFP task, the depressive group showed a larger P1 amplitude for negative social feedback than positive feedback. The occipital P1 has widely been associated with selective attention (Luck and Kappenman, 2012; Mangun et al., 1998), and a larger P1 amplitude indicates attentional bias for emotional stimuli (Eldar et al., 2010; Pool et al., 2016). Our P1 result parallels a previous neuroimaging study suggesting that social threat signals are more emotionally salient and attention capturing for depressed individuals (Jankowski et al., 2018). Another finding related to the SFP task is that while the control group showed a larger FRN amplitude for negative (vs. positive) social feedback, the depressive group showed a reversed pattern, especially for highly negative feedback. The FRN is a sensitive indicator of expectation violation, and a more negative-going waveform indicates a larger prediction error between prior expectations and actual outcomes (Gu et al., 2020; van der Molen et al., 2017; 2018). Thus, the FRN amplitude can serve as a "surprise signal" that indirectly indicates people's prior expectations (Hauser et al., 2014). Therefore, our FRN results support previous literature demonstrating reduced anticipation for positive social feedback in depression (Caouette and Guyer, 2016; Davey et al., 2011; He et al., 2020a); further, they provide evidence of the moderating role of intensity on this deficit.

Intriguingly, the expectation (reflected by FRN) and attentional allocation (reflected by P1) during social feedback correlated with participants' long-term social evaluations and decision-making behaviors. Specifically, the FRN amplitude for highly negative social feedback correlated with participants' attractiveness ratings and the amount of money allocated to feedback senders after three days. This finding suggests that a larger predictive bias (i.e., a smaller FRN amplitude) for highly negative feedback could predict lower social evaluation of and less money shared with the feedback senders. Meanwhile, the P1 amplitude for highly positive social feedback was positively correlated with participants' evaluations and the amount of money allocated to peers who provided the feedback. This result suggests a predictive role of attentional bias in highly positive social feedback on one's social evaluation and decision-making behaviors toward feedback senders. Altogether, our findings indicate that altered expectations and biased attentional allocation of social feedback in depressed individuals have detrimental effects on their long-term social evaluation and decision-making behaviors.

It is also noteworthy that a negative correlation was observed between recall accuracy for highly negative social feedback and participants' social evaluation of peers who provided it. This finding is consistent with our previous report that when individuals have difficulty forgetting negative social feedback, their evaluation of the senders decreases (Xie et al., 2021). The finding also supports the notion that people rely on memory traces of previous experiences during dynamic social interactions (Feldmanhall et al., 2020; Schaper et al., 2019). Thus, it is possible that the impact of aberrant social feedback processing on later social evaluation is mediated by memory deficits in depression. In view of this, we tentatively posit that the negative memory bias may adversely impact depressed people's evaluation of others, such that the altered evaluation further reduces their willingness to reengage in social interactions and hinders benign social integration. Our results corroborate and extend the findings of memory bias that have been well-documented in Beck's cognitive theory of depression (Beck and Bredemeier, 2016), facilitating a sophisticated understanding of the influence of depression on human social cognition and decision-making.

One of the limitations of this study is that we recruited individuals with depressive tendencies rather than patients diagnosed with depressive disorders; therefore, caution is needed when applying the study findings to clinical populations. Another important limitation is that in the cover story, the social feedback was provided by strangers (i.e., peers from another university); therefore, the feedback might not have been viewed as valuable by the participants and did not elicit significant emotional responses. In daily life, people tend to care more about social feedback from those close to them or acquaintances than strangers, which may also evoke stronger emotional responses. Therefore, cover stories or study designs with higher ecological validity are required. In addition, we did not use a post-experiment questionnaire to determine whether the participants believed the cover story, and therefore the data of those who did not believe the story were not excluded.

Nevertheless, our findings have implications for clinical practice. Specifically, aberrant neurocognitive processes for negative social feedback have already been observed among individuals with early signs of depression, and these deficits should be targeted to prevent the onset of major depressive disorders. First, optimism training could be used to facilitate people's overall positive expectations for the future (Shapira and Mongrain, 2010; Vilhauer et al., 2012) and to reduce depressed individuals' abnormal expectations regarding negative social feedback. Second, cognitive interventions such as attention bias modification training (Beevers et al., 2015; Yang et al., 2015) are promising for diminishing the attention bias for negative social feedback in individuals with depressive tendencies. Third, memory control strategies can be used as training programs to help individuals with depressive symptoms limit encoding and facilitate forgetting of negative social feedback. As an important adaptive function in human life, intentional forgetting (for a review, see Anderson and Hanslmayr, 2014) can benefit psychological well-being (Engen and Anderson, 2018; Hu et al., 2017). However, most research on intentional forgetting uses non-social emotional materials. Our prior research provided the first evidence that healthy individuals could intentionally forget negative social feedback by voluntarily truncating the encoding processes (Xie et al., 2021). However, it is still unclear whether intentional forgetting strategies can be employed to facilitate forgetting negative social feedback in depression. Future research is required to fill this gap.

In conclusion, our study was the first to demonstrate the long-term impact of aberrant social feedback processing on social cognition and decision-making behaviors in individuals with depressive symptoms. The heightened expectation (reflected by the FRN amplitude) and excessive attentional allocation (reflected by the P1 amplitude) to negative social feedback in depression correlated with their social evaluation and decision-making after three days. Meanwhile, the elaborative encoding bias (reflected by the P3 amplitude) for negative social feedback was associated with enhanced memory for self-threatening information after three days, which may contribute to the prolonged social pain experiences in depression. Interventions targeting these cognitive deficits could be usefull in preventing the onset of major depressive disorders and the deterioration of patients' social dysfunctions.

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Data and code availability

The data and code of this study would be available upon reasonable request and with approvals of School of Psychology, Shenzhen University. More information on making this request can be obtained from the corresponding author, Prof. Dandan Zhang (zhangdd05@gmail.com).

CRediT authorship contribution statement

Hui Xie: Conceptualization, Writing – original draft, Writing – review & editing. **Licheng Mo:** Data curation, Writing – review & editing. **Sijin Li:** Data curation, Writing – review & editing. **Jialin Liang:** Data curation, Writing – review & editing. **Xiaoqing Hu:** Writing – review & editing. **Dandan Zhang:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

Authors declare no conflicts of interest in relation to the subject of this study.

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