Neural responses to negative feedback are related to negative emotionality in healthy adults

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Prior neuroimaging and electrophysiological evidence suggests that potentiated responses in the anterior cingulate cortex (ACC), particularly the rostral ACC, may contribute to abnormal responses to negative feedback in individuals with elevated negative affect and depressive symptoms. The feedback-related negativity (FRN) represents an electrophysiological index of ACC-related activation in response to performance feedback. The purpose of the present study was to examine the FRN and underlying ACC activation using low resolution electromagnetic tomography source estimation techniques in relation to negative emotionality (a composite index including negative affect and subclinical depressive symptoms). To this end, 29 healthy adults performed a monetary incentive delay task while 128-channel event-related potentials were recorded. We found that enhanced FRNs and increased rostral ACC activation in response to negative—but not positive—feedback was related to greater negative emotionality. These results indicate that individual differences in negative emotionality—a putative risk factor for emotional disorders—modulate ACC-related processes critically implicated in assessing the motivational impact and/or salience of environmental feedback.

Keywords: feedback-related negativity; depression; negative affect; anterior cingulate cortex; negative feedback; reward

INTRODUCTION

Growing evidence emphasizes the role of individual differences in affective and motivational states in shaping cognition (Savine et al., 2010; Clayson et al., 2011; Santesso et al., 2011). Negative affect, in particular, might have profound influences on cognitive processes, including cognitive control, focusing attention toward task-relevant stimuli and monitoring performance outcomes—functions that have been ascribed to the anterior cingulate cortex (ACC) (Bush et al., 2000; Botvinick et al., 2001). In spite of this evidence, relations between individual differences in negative affect on ACC-related cognitive processes remain largely unexplored.

The feedback-related negativity (FRN) is an event-related potential (ERP) component that has been localized to the ACC (Miltner et al., 1997; Ullsperger and von Cramon, 2003; but see Van Veen et al., 2004; Nieuwenhuis et al., 2005) and has been hypothesized to reflect the function of a performance monitoring/evaluative system that rapidly assesses the motivational impact and/or salience of environmental

feedback (Gehring and Willoughby, 2002; Yeung and Sanfey, 2004; Segalowitz et al., 2010). Fitting this view, the FRN has been found to be sensitive to both errors in reward prediction (e.g. Holroyd and Krigolson, 2007; Wu and Zhou, 2009), negative valence (Gehring and Willoughby, 2002; Pfabigan et al., 2011) and the magnitude feedback outcomes (e.g. Holroyd et al., 2004a; Onoda et al., 2010; Santesso et al., 2011).

Although the majority of studies to date have focused on delineating the cognitive significance of the FRN in performance monitoring (e.g. Holroyd and Krigolson, 2007; Wu and Zhou, 2009), a growing body of research suggests that personality and/or mood—most notably negative affective styles—influence FRN amplitude. This is not surprising given that negative processing biases (e.g. attentional biases toward negative stimuli, exaggerated responses to negative performance feedback and negative self-evaluation) have been observed in individuals with elevated negative affect (Halberstadt et al., 1995; Rusting, 1999), major depressive disorder (Beck, 1976; Gotlib and Krasnoperova, 1998; Kring and Bachorowski, 1999) and subclinical depression (Wenzlaff and Eisenberg, 2001). For example, using the FRN as an indirect index of ACC-related performance monitoring, one study demonstrated that higher negative affectivity (a dispositional tendency to experience negative affect)—but not positive affectivity—was related to error feedback, suggesting that individuals with elevated negative affect were more likely to assign a negative value to unfavorable outcomes compared to those with low negative affectivity (Sato et al., 2005). Similarly, individuals highly sensitive to punishment were characterized by enhanced FRN

amplitudes in response to external feedback (Balconi and Crivelli, 2010) and monetary loss feedback (Santesso et al., 2011). These findings echo reports of enhanced FRNs to negative or monetary loss feedback in both currently and formerly depressed participants (Tucker et al., 2003; Santesso et al., 2008a). Collectively, these results suggest that individual differences in negative affect might be lawfully associated with ACC responses to negative outcomes.

The goal of the present study was to test this hypothesis. Specifically, using low-resolution electromagnetic tomography (LORETA) in conjunction with 128-channel ERPs, our aim was to examine FRN and ACC responses to negative outcomes in relation to negative emotionality in a sample of healthy adults. To this end, participants performed a monetary incentive delay (MID) task, in which they received negative and positive monetary feedback following a motor response to speeded target stimuli. Negative emotionality was operationalized as a composite score of negative affect and (subclinical) depressive symptoms. This choice was justified by the fact that (i) negative affect and depression typically co-occur, (ii) both are strongly related to punishment sensitivity (Depue and Iacono, 1989, Gray, 1994; Watson et al., 1999; Pinto-Metza et al., 2006) and (iii) high negative affect often predicts the onset and course of depression (Clark and Watson, 1999; for a review, see Klein et al., 2011). Thus, in addition to providing evidence that individual differences in negative affect might influence performance monitoring, the present study might yield important clues to understanding neural correlates conferring increased vulnerability to emotional disorders. In light of the findings reviewed above, we hypothesized that negative emotionality would be associated with potentiated FRNs and increased ACC activation in response to negative—but not positive—feedback. Analyses focusing on different ACC subdivisions (subgenual, rostral and dorsal) and stimulus-locked ERP components (i.e. N1, P2, P2–N2 complex and P3 to positive and negative cues) were conducted to evaluate the specificity of putative FRN findings.

MATERIALS AND METHODS

Participants

Data from 30 adults (15 men, mean age: 21.6 years) were analyzed (see Santesso et al., 2008b for further detail). Adults were recruited from Harvard University and the surrounding community for a larger study investigating the neurobiology and molecular genetics of reward processing. Findings from this larger sample investigating links between anhedonia and resting EEG data (Wacker et al., 2009), the effects of specific genotypes on reward-related fMRI activation (Dillon et al., 2010) and ERP data collected using a different probabilistic reward task (Santesso et al., 2008b) have been recently published. ERP data collected during the MID task have not been presented before. Participants meeting the following criteria were excluded: present medical or neurological illness (ADHD, head injury, loss of consciousness and

seizures), current alcohol/substance abuse or smoking, lifetime dependence, claustrophobia, use of psychotropic medications during the last 2 weeks and pregnancy. The Structured Clinical Interview for DSM-IV Axis I Disorders (SCID-I), which was administered by a trained, master-level clinical interviewer, indicated that three participants included in the final sample reported one past occurrence of a major depressive episode (untreated) and no participants had a history of drug use. All eligible participants were right handed (Chapman and Chapman, 1987) and provided written informed consent. All procedures were approved by the Committee on the Use of Human Subjects at Harvard University. One subject was excluded from all analyses because of an extreme score on the BDI-II depression measure (>3 s.d. above the mean), resulting in a final sample of $N = 29$.

Procedures

Monetary incentive delay task

Participants completed five blocks of 48 trials each. Each trial began with an anticipation phase in which one of three equally probable cue stimuli was presented for 1.5 s signaling potential reward (+$), loss (−$) or no incentive (0$). Following a jittered inter-stimulus interval (ISI: 3−3.5 s), a red square was presented, and participants were instructed to respond to the target with a button press. Following a second ISI (3−3.5 s), there was an outcome phase in which performance feedback was presented for 1.5 s. If participants successfully responded to the target following a reward cue, 'gain' feedback was presented (range: $1.96 to $2.34; mean: $2.15); if they were unsuccessful, 'no gain' feedback was presented. If participants successfully responded to the target following a loss cue, 'no penalty' feedback was presented; if they were unsuccessful, 'penalty' feedback was presented (range: −$1.81 to −$2.19; mean: −$2.00). No-incentive trials always resulted in a no change feedback.

Participants were told that their response time (RT) to the target affected trial outcomes, such that rapid RTs increased the probability of winning money on reward trials and decreased the probability of losing money on loss trials. In fact, outcomes were predetermined in order to guarantee a fully balanced design. Two manipulations were used to maximize task believability (see Pizzagalli et al., 2009 for additional detail). First, duration of the target presentation was varied across successful and unsuccessful trials based on an individual titration procedure. Specifically, for successful trials (i.e. a gain outcome in a reward trial or no penalty in a loss trial), the target was presented for a duration corresponding to the 85th percentiles of the individual's mean RT measured during a practice block (25 trials). For unsuccessful trials (i.e. a no gain outcome in a reward trial or a penalty in a loss trial), the target was presented for a duration corresponding to the 15th percentiles of the practice RTs. Second, participants were instructed that strong performance in the first five blocks would give them the

opportunity to qualify for a 'bonus' block that included larger payoffs ($3.63–$5.18) and few penalties. Each participant 'qualified' for this bonus block.

Affective ratings

Immediately following blocks two and four, participants rated their affective responses to the incentive cues and the outcomes. On a scale of 1–5, participants rated the arousal (1 = low intensity and 5 = high intensity) and valence (1 = negative and 5 = positive) of the affect experienced while waiting to respond on a reward or punishment trial (incentive cue rating) and after receiving gain, no penalty, no gain and penalty feedback (outcome rating).

The Beck Depression Inventory II (BDI-II; Beck et al., 1996) is a 21-item scale used to assess levels of depressive symptoms. The mean total BDI-II total score in this unselected sample was 5.7 (s.d. = 4.37, range 1–17). Total scores between 0 and 13 indicate minimal depression; scores between 14 and 19 reflect mild depression (Beck et al., 1996).

The Positive and Negative Affect Schedule (PANAS; Watson et al., 1988) was used to measure state positive and negative affect over two experimental sessions, which were separated, on average, by 36.55 days (s.d. = 24.97). During the first session, participants completed a probabilistic reward task (Bogdan et al., 2010) and several self-report questionnaires; during the second session, participants performed the MID task, as detailed here. For the PANAS, participants responded to 10 adjectives each for positive (e.g. excited) and negative (e.g. nervous) affect describing how they felt at that moment. PANAS scores for each scale were significantly correlated across sessions (PA: $r = .66$, $P < 0.001$; NA: $r = .37$, $P = 0.048$) and were averaged to capture dispositional affect. Further justifying using aggregate PANAS scores, Watson et al. (1988) demonstrated that state PA and NA exhibit a significant level of stability suggesting that even momentary moods are, to a certain extent, reflections of one's general affective level.

Data collection and reduction
Behavioral and affective ratings data

In light of the fact that the BDI-II and PANAS NA scores were highly correlated (see Results), a composite measure of negative emotionality was computed by totaling standardized (Z-scored) values from each measure. The average RT to the target following reward and loss incentive cues was calculated. Arousal and valence ratings in response to cue and feedback stimuli were averaged separately across blocks two and four.

Scalp ERP data

EEG was recorded using a 128-channel Electrical Geodesics system (EGI Inc., Eugene, OR, USA) at 250 Hz with 0.1–100 Hz analog filtering. The vertex was used as recording reference; impedances were kept at ~50 kΩ or below. Data were processed using BrainVision Analyzer (Brain Products

GmbH, Germany). Data were re-referenced offline to an average reference and filtered (1–30 Hz). Eye-movement artifacts were corrected by independent component analysis. Across blocks, EEG epochs were extracted beginning 200 ms before and ending 800 ms after the incentive cue and feedback presentation. EEG was visually inspected and trials were automatically removed with a ±75 μV artifact criterion. Feedback-locked ERPs were averaged separately for each feedback type (gain, no penalty, no gain, penalty) with a 200 ms time window prior to feedback onset serving as a baseline. The FRN was scored at the midline sites Fz, FCz and Cz, where the FRN is maximal (e.g. Gehring and Willoughby, 2002; Santesso et al., 2008a). The FRN was scored as the most negative peak occurring 200–400 ms following feedback onset. Each participant's average had a minimum of 30 feedback trials. No change feedback was excluded because the FRNs were characteristically different from gain and penalty feedback as this component was heavily influenced by the preceding P2 and following P3 positivity (the P2 and P3 were significantly attenuated for no change feedback compared with all other feedback outcomes, P's > 0.05). Additionally, we had no a priori hypotheses about the relation between negative emotionality and no change feedback.

A secondary goal was to examine the relation between incentive cue processing and negative emotionality, and whether links with negative emotionality were specific to the FRN. To this end, we also analyzed stimulus-locked ERPs (e.g. N1, P2, P2–N2 complex, P3) to positive and negative cues. For reward and loss cue stimuli, the N1 and P2 were evaluated because these components are thought to reflect automatic stimulus processing that is influenced by early attention and orientation processes (e.g. Näätänen, 1992). Following cue presentation, the N1 was scored as the most negative peak within 50–150 ms, the P2 was measured as the most positive peak within 150–250 ms, and the N2 was measured as the most negative peak within 200–350 ms. The N1, P2 and N2 were all scored at Fz, FCz and Cz. The P2–N2 complex was computed as a peak-to-peak, N2 minus P2 amplitude difference (Poulsen et al., 2009). The P3 was also analyzed as this component reflects orientation and is sensitive to motivationally relevant stimuli (Isreal et al., 1980; Duncan-Johnson and Donchin, 1982; Schupp et al., 2004). The P3 was measured as the most positive peak 300–500 ms after cue presentation at Pz where this component was maximal.

ERP source localization

Current density underlying the FRN was estimated using LORETA (Pascual-Marqui et al., 1999) in structurally defined regions of interest (ROIs) in the rostral ACC (BA 24, 32; 37 voxels, volume: 12.69 cm³), dorsal ACC (BA 24', 32'; 68 voxels, volume: 23.32 cm³) and subgenual ACC (BA 25; 17 voxels, volume: 5.83 cm³) (for details, see Pizzagalli et al., 2006). Current density was computed within a time

window from 248 to 288 ms after feedback onset (thus capturing the mean latency of the FRN) and computed as the linear, weighted sum of the scalp electric potentials (units are scaled to amperes per square meter, A/m^2). For each subject, LORETA values were normalized to a total power of one and then log-transformed before statistical analyses.

Statistical analyses

RT and affective ratings for incentive cue stimuli were analyzed using paired *t*-tests. Affective ratings and ERP data for outcome/feedback stimuli were analyzed using ANOVAs with *cue type* (reward, loss) and *outcome valence* (positive, negative) as within-subject factors. Gain and no penalty feedback were considered positively valenced, whereas no gain and penalty feedback were considered negatively valenced. When applicable, the Greenhouse–Geisser correction was used. Follow-up paired *t*-tests (two-tailed) were performed to decompose significant ANOVA effects. Pearson correlations (two-tailed) were run to evaluate putative links between (i) negative emotionality and (ii) FRN amplitude and ACC current source density.

RESULTS

RT data

Consistent with independent findings (Dillon *et al.*, 2008; Pizzagalli *et al.*, 2009), RTs for cued reward trials (mean ± s.d.: 216.81 ± 33.28 ms) were faster than those for loss trials [234.29 ± 40.89 ms; $t(28) = 4.67$, $P < 0.001$]. These results indicate that the task was successful in eliciting motivated behavior.

Affective ratings for incentive cues

For valence, loss cues (2.22 ± 0.15) were rated more negatively than reward cues [3.52 ± 0.13; $t(28) = 7.12$, $P < 0.001$]. No differences emerged in arousal ratings for loss and gain cues ($P > 0.16$).

Affective ratings for outcomes

For valence, there was a main effect for *cue type*, $F(1, 28) = 40.82$, $P < 0.001$, with reward cues rated more positively than loss cues. A main effect for *outcome valence*, $F(1, 28) = 211.87$, $P < 0.001$, indicated that gain and no penalty feedback were rated more positively than no gain and penalty feedback. The *cue type × outcome valence* interaction was also significant, $F(1, 28) = 7.63$, $P = 0.010$, and follow-up paired *t*-tests revealed that valence scores ranked as follows (higher scores reflect more positive ratings): gain > no penalty > no gain > penalty (all P's < 0.001).

For arousal, there was a significant *cue type × outcome valence* interaction, $F(1, 28) = 32.40$, $P < 0.001$, indicating that gain feedback was more arousing than no penalty and no gain feedback (all P's < 0.02) and penalty feedback was more arousing than no gain and no penalty feedback (all P's < 0.01) (Figure 1).
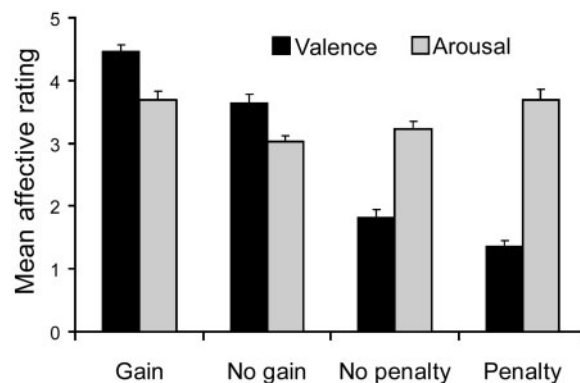

Fig. 1 Mean valence and arousal ratings for feedback outcomes. Error bars represent standard error of the mean.

FRN results

The FRN was maximal at Fz compared with FCz, $t(28) = 2.57$, $P < 0.017$, and Cz, $t(28) = 2.33$, $P < 0.028$. The ANOVA revealed a trend for *outcome valence* in which the FRN was slightly larger (i.e. more negative) for negatively (no gain and penalty) compared to positively (gain and no penalty) valenced outcomes, $F(1, 28) = 3.93$, $P < 0.076$. The *cue type × outcome valence* interaction was significant, $F(1, 28) = 4.64$, $P < 0.044$, due to larger FRN for the no gain compared to the gain condition, $t(28) = 2.34$, $P < 0.028$, but no FRN difference between the no penalty and penalty conditions ($P > 0.90$). Also, the FRN was larger for the penalty compared to the gain condition, $t(28) = 2.74$, $P < 0.010$ (Figure 2). These significant differences remained using a peak-to-peak measure of the FRN in which the FRN was measured as the preceding P2 minus the FRN (all P's < 0.03). No other significant FRN differences emerged.

Correlations with negative emotionality

As expected, total scores on the BDI-II were highly correlated with the aggregate negative affect score, $r = 0.65$, $P < 0.001$, further justifying the use of a negative emotionality composite score. A Pearson correlation indicated that higher negative emotionality was related to more negative FRNs during the penalty condition, $r = -0.40$, $P < 0.032$ (Figure 3A). Critically, correlations involving any other feedback condition (all P's > 0.37) or positive affect (all P's > 0.07) were not significant. Further highlighting the specificity of this finding, a simultaneous regression predicting negative emotionality from the FRN in response to gain, no penalty, no gain and penalty outcomes indicated that only the FRN for penalties accounted for unique variance in negative emotionality (semi-partial $r = -0.36$, $P < 0.053$, R^2 total $= 0.20$). Following prior studies (e.g. Holroyd and Krigolson, 2007; Foti and Hajcak, 2009), we also computed FRN difference scores for gain minus penalty feedback and for gain minus no gain feedback. A significant correlation between FRN difference scores and negative emotionality
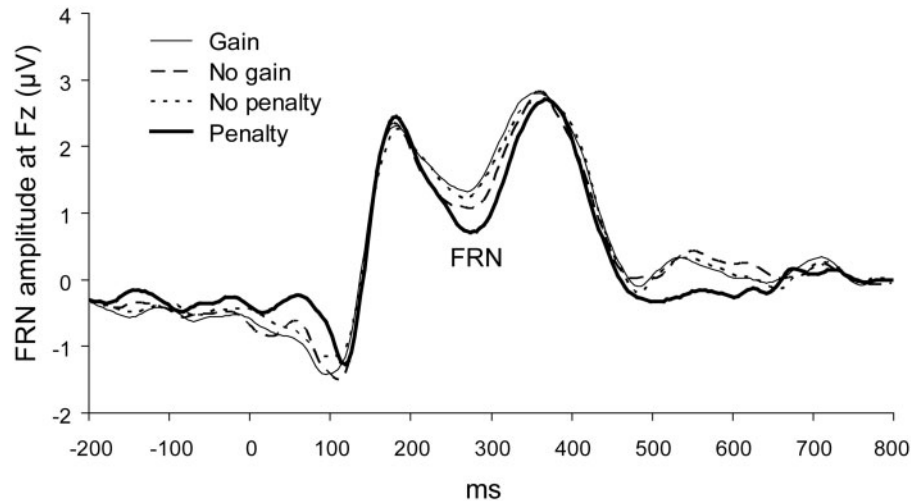
Fig. 2 Grand average FRN amplitudes (µV) at Fz for positive (gain, no penalty) and negative (penalty, no gain) feedback during the monetary incentive delay task.

emerged for the gain minus penalty condition, $r = 0.45$, $P < 0.013$ (Figure 3B), indicating that increasing negative emotionality was associated with greater differentiation between positive and negative feedback. No relation was found for negative emotionality and the gain minus no gain or the no penalty minus penalty feedback conditions (P's > 0.24). Finally, we also examined the correlation between negative emotionality and the penalty FRN after partialling out the variance due to the gain FRN. The significant correlation remained, $r = -0.45$, $P = 0.004$, indicating that the relation was not due to general attention to, or salience of receiving feedback.[1]

Finally, RTs to the incentive cues were unrelated to the FRN and, similar to prior findings in depression (Pizzagalli *et al.*, 2009), RTs were unrelated to negative emotionality (P's > 0.09). Analyses showed that loss cues were rated more negatively, $r = -0.41$, $P = 0.027$, and more arousing, $r = 0.36$, $P = 0.053$, by individuals with higher negative emotionality. Increasing levels of negative emotionality were also associated with higher arousal ratings of penalties, $r = 0.41$, $P < 0.029$. These affective ratings were unrelated to the amplitude of the FRN (P's > 0.15).

LORETA correlations

Given the significant relations between negative emotionality and the FRN, we extracted intracerebral current density for penalty and gain feedback conditions from structurally defined rostral, dorsal and subgenual ACC ROIs (Pizzagalli *et al.*, 2006). Increased activation in the rostral ACC, $r = 0.45$, $P < 0.012$ (Figure 3) in response to the penalty feedback was related to higher negative emotionality, whereas

dorsal and subgenual ACC activation was unrelated to negative emotionality ($P > 0.07$). Highlighting the specificity of these findings, current density in response to gain feedback was unrelated to negative emotionality (P's > 0.17). Moreover, a simultaneous regression to predict negative emotionality from the rostral ACC activity in response to gain and penalty outcomes indicated that only rostral ACC activation for penalties accounted for a significant amount of unique variance in negative emotionality (penalty semi-partial $r = -0.49$, $P = 0.008$, R^2 total = 0.26). Thus, individuals with higher negative emotionality showed enhanced FRN and rostral ACC activation specific to penalty feedback.

ERP responses to cues

We performed ANOVA analyses on the ERP components elicited by reward (+\$) and loss (−\$) cues; specifically, we considered the N1, N2 and P2 at sites Fz and the P3 at Pz, where these components were maximal. The amplitude of the N1 did not differ by *cue type* ($P > 0.10$; reward: $-1.44 \pm 1.18 \, \mu V$ *vs* loss: $-1.08 \pm 1.02 \, \mu V$). The P2 was higher for the loss ($2.85 \pm 2.12 \, \mu V$) relative to reward ($2.35 \pm 1.81 \, \mu V$) cue, $F(1, 28) = 4.98$, $P < 0.035$, and there was a trend for a difference in the P2–N2 complex by *cue type*, $F(1, 28) = 2.78$, $P = 0.059$ (gain: $-4.08 \pm 1.72 \, \mu V$ *vs* loss: $-4.53 \pm 2.21 \, \mu V$). Finally, the P3 amplitude was higher for the reward ($6.34 \pm 2.98 \, \mu V$) than loss ($5.72 \pm 2.76 \, \mu V$) cue, $F(1, 28) = 5.88$, $P < 0.025$ (Figure 4). The amplitude of these ERP components were unrelated to the FRN or to negative emotionality (all P's > 0.07), suggesting that the relations found between the FRN and negative emotionality scores were specific to feedback processing.

DISCUSSION

Negative affect and depressive mood are highly interrelated, share common etiological influences, and both predict the

[1]Both higher total scores on the BDI-II ($r = -0.39$, $P < 0.045$) and higher PANAS negative affect ($r = -0.40$, $P = 0.034$) were related to the penalty FRN, but not the gain FRN ($P > 0.57$). A simultaneous regression analysis to predict the amplitude of the penalty FRN from total BDI-II scores and negative affect indicated overlapping variance among these measures (semi-partial $rs < 0.19$, $P > 0.29$), further justifying the use of a composite score.
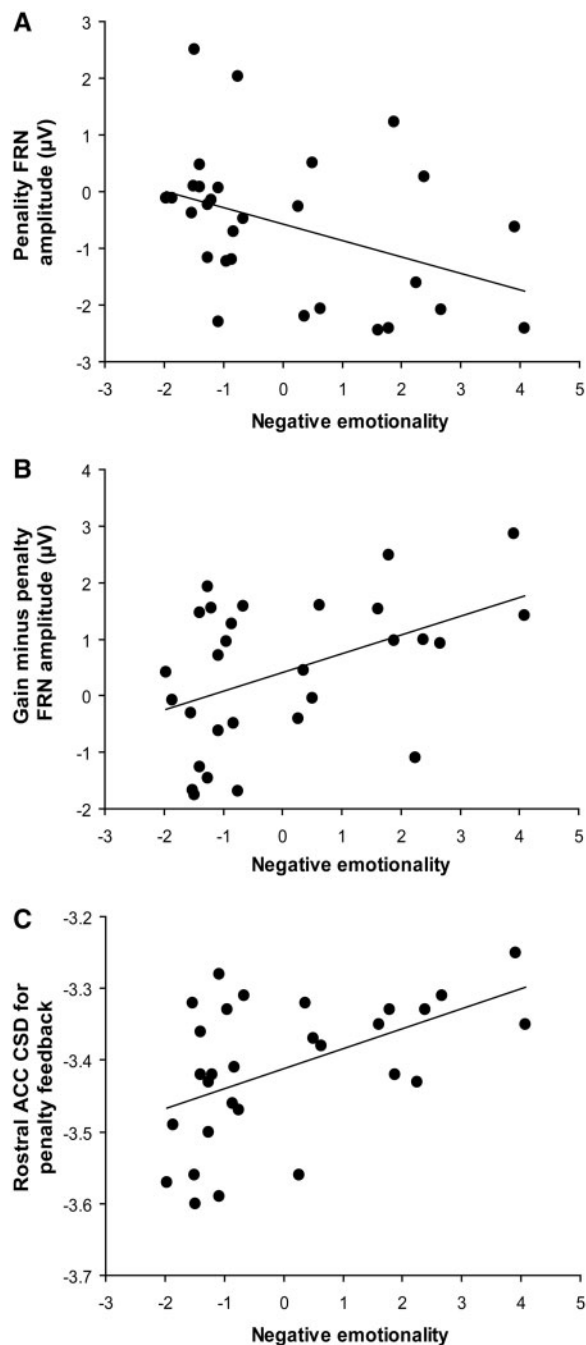
Fig. 3 Scatterplots and Pearson correlations between negative emotionality and the FRN amplitude (μV) at Fz for (A) penalty feedback, (B) gain minus penalty feedback and (C) current source density (CSD; log A/m²) in the rostral ACC in response to penalty feedback.

Fig. 4 Grand averaged ERPs for reward and loss cues during the monetary incentive delay task.

onset and course of depression and other emotional disorders (Klein *et al.*, 2011). The present study is the first to use ERP source localization study in order to examine ACC-mediated feedback responses (i.e. the FRN) in relation to negative emotionality (a composite measure including negative affect and subclinical depressive symptoms) using a well-established monetary incentive delay task. Healthy adults performed a monetary incentive delay task, which
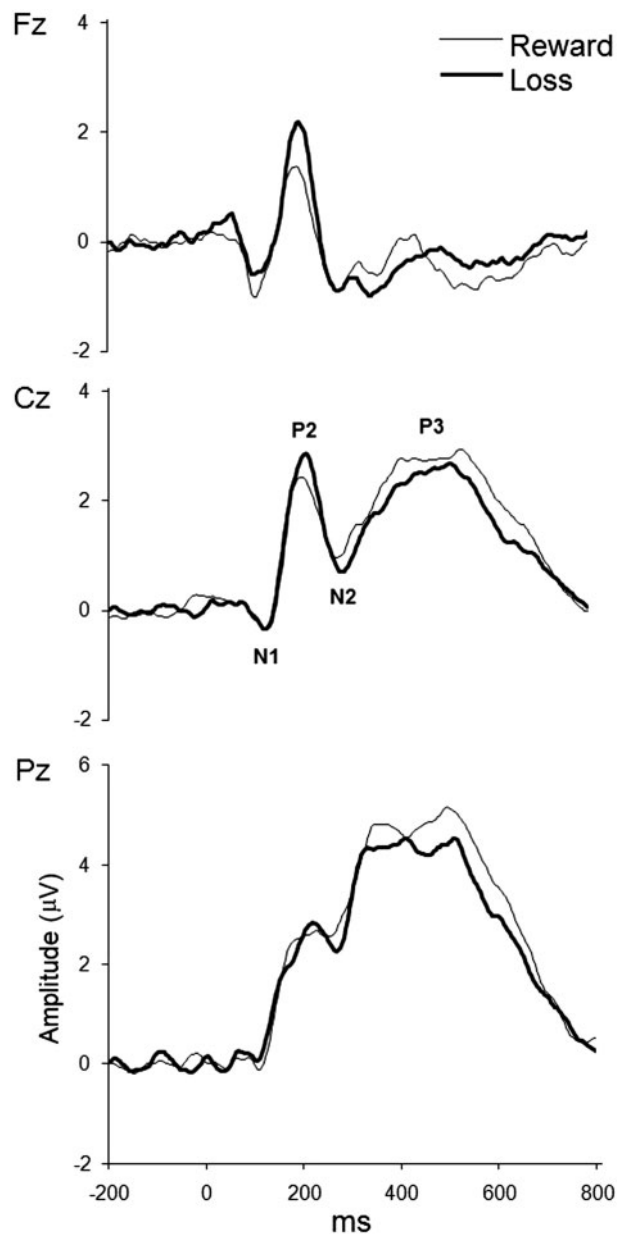
elicited positive (gain, no penalty) and negative (penalty, no gain) feedback. Consistent with previous studies, we found that the FRN was larger following presentation of negative compared to positive feedback (penalty versus gain and no gain versus gain feedback; Gehring and Willoughby, 2002; Yeung and Sanfey, 2004; Holroyd *et al.*, 2006). We did not, however, find a difference in the FRN amplitude for penalty versus no penalty feedback. These results are partially consistent with the notion that the worst possible outcomes elicit the most negative FRN (Holroyd *et al.*, 2004a; Potts *et al.*, 2006) and that negative valence predicts more negative FRN amplitudes (Gehring and Willoughby, 2002; Yeung and Sanfey, 2004; Pfabigan,

et al., 2011). Of primary relevance to study hypotheses, higher negative emotionality was specifically related to larger FRNs and greater activation in the rostral region of the ACC for penalty (monetary loss) feedback.

Although depression (particularly anhedonia) has been associated with blunted processing of positive stimuli, including insensitivity to rewards (e.g. Henriques and Davidson, 2000; Pizzagalli *et al.*, 2009), we found no relation between negative emotionality and the FRN for positive feedback, replicating prior null findings in clinical depression (Tucker *et al.*, 2003). Our findings may be due to the use of a composite measure, which might have tapped into elevated negative affect as opposed to anhedonia. Higher negative emotionality was related to the FRN difference wave (gain minus penalty feedback) and underlying ACC activation, but separate analyses indicated that the findings were driven by heightened responses to negative feedback. The lack of relation between negative emotionality and the FRN elicited by positive feedback in the present study is consistent with prior data highlighting emotional processing deficits in depression specific to negative stimuli (Yoshimura *et al.*, 2010) and/or negative emotions (Mak *et al.*, 2009). Taken together, the results of the present study support the hypothesis that even mildly elevated levels of depressive symptoms/negative affect are associated with hypersensitivity to negative feedback (e.g. Beck, 1976; Elliott *et al.*, 1998). Additionally, these findings underscore how individual differences in affective states (specifically, negative emotionality) relate to ACC responses to negative outcomes. Accordingly, purely cognitive models of performance monitoring may not adequately explain variation in responses to feedback, necessitating the inclusion of state and/or trait affective measures in FRN research.

FRN results emerging from the current non-clinical sample fit prior findings. Sato *et al.* (2005) found that individuals reporting high negative affectivity (as assessed by the PANAS) assigned a negative value to unfavorable outcomes, as indexed by a larger FRN response to negative (but not positive) outcomes. Given documented relations between negative affect/depression and punishment sensitivity (e.g. Depue and Iacono, 1989; Gray, 1994; Pinto-Metza *et al.*, 2006), results are in line with studies demonstrating that the FRN to negative feedback is enhanced in individuals highly sensitive to punishment (Balconi and Crivelli, 2010; Santesso *et al.*, 2011). Results are also consistent with some depression studies. In particular, Tucker *et al.* (2003) reported that the FRN was larger for moderately depressed individuals (although the opposite effect was found for more severe depression) when given negative performance feedback dependent on their response speed to a target. These authors also demonstrated that depressed subjects exhibited larger FRNs to negative but not positive feedback (but see Foti and Hajcak, 2009). We recently extended these findings by showing that, relative to controls, remitted depressed individuals were characterized by larger FRN to

negative feedback in a reinforcement learning task (Santesso *et al.* 2008a). Furthermore, studies have demonstrated a link between (i) enhanced error-related negativity (ERN), a closely related negative component elicited by response errors (Holroyd *et al.*, 2004b; Ridderinkhof *et al.*, 2004; Ullsperger *et al.*, 2007) and (ii) depression (e.g. Chiu and Deldin, 2007; Holmes and Pizzagalli, 2008, 2010; but see Schrijvers *et al.*, 2008, 2009), negative affect as indexed by the PANAS (Luu *et al.*, 2000; Hajcak *et al.*, 2004), negative mood induction (Wiswede *et al.*, 2009) and sensitivity to punishment (Boksem *et al.*, 2006). Collectively, these findings indicate that depression and negative affect are characterized by potentiated responses to both internal (ERN) and external (FRN) representations of performance failures (and/or punishment cues), which might contribute to the maintenance of negative processing biases.

The present LORETA results highlighting a link between increased rostral ACC activation and negative emotionality mirror prior findings (e.g. Elliott *et al.*, 2002; Engels *et al.*, 2010), most notably those by Holmes and Pizzagalli (2008), who found that enhanced error-related response monitoring was associated with rostral ACC hyperactivation in unmedicated, clinically depressed individuals. Overall, these results suggest that the rostral ACC might play an important role in regulating responses to negative performance outcomes, particularly in those experiencing negative affect. Whereas our results provide additional support that neural responses to negative feedback are related to individual differences in negative affect, further research is warranted to determine whether ACC hyperactivation is linked to processing and/or regulating responses to negative environmental feedback as opposed to other negative stimuli.

Some ERP evidence suggests that cognitive impairments in depression/negative affect include altered attention to positive and negative stimuli at both early and late stages of processing (e.g. Krompinger and Simons, 2009; Yang *et al.*, 2011). In our study, negative emotionality was unrelated to incentive cues signaling potential reward or penalty as indexed by stimulus-locked N1, P2, N2–P2 and P3 components, which reflect early sensory processing and low-level attention allocation (Hillyard *et al.*, 1994) and later stage stimulus evaluation or categorization (Johnson, 1988; Kok, 1997). These results suggest that, at least in our modified MID task, elevated negative emotionality may be more detrimental to feedback processing than to cues predicting possible incentives. This pattern mirrors recent data highlighting blunted neural responses to reward feedback, but largely preserved responses to reward-predicting cues, in depressed patients tested with the same MID task (Pizzagalli *et al.*, 2009).

We used a composite measure of negative affect and depression, and it is important to emphasize that participants did not exhibit clinical levels of depression. The mean BDI-II total score in this sample was 5.7—well below the cutoff of 14 for mild depression. Severity of depressive symptoms has

been found to influence FRN findings (Tucker *et al.*, 2003). Given prior evidence of increased FRNs in individuals with current (Tucker *et al.*, 2003) and past (Santesso *et al.*, 2008a) depression, we speculate that the present findings would extend to clinical samples. Moreover, potentiated ERN and error-related rostral ACC activation have been described in healthy controls with variants of the serotonin transporter gene (Fallgatter *et al.*, 2004; Beste *et al.*, 2010; Holmes *et al.*, 2010) previously linked to increased vulnerability to depression (e.g. Caspi *et al.*, 2003). Altogether, these findings raise the possibility that enhanced ERN/FRN and associated ACC hyperactivation might be a trait marker for vulnerability to more severe forms of negative mood states, including depression.

The present study has limitations. First, prior data suggest that depressed individuals do not respond as fast as non-depressed individuals to monetary reward (Henriques and Davidson, 2000; Pizzagalli *et al.*, 2005). It is unclear whether the lack of findings for response speed was due to the nature of the task (although participants were informed that their RT to the target affected trial outcomes, feedback was pre-determined) or the use of a composite measure of negative affect and subclinical depression scores. More research is needed to determine how negative affect might influence behavioral responses to reward and punishment cues. Second, the ecological validity of the monetary feedback is limited, and cognitive biases might be particularly robust for self-relevant stimuli (e.g. Krompinger and Simons, 2009; Poulsen *et al.*, 2009). Future studies should use personally relevant or social feedback (e.g. Spreckelmeyer *et al.*, 2009) to determine whether the current FRN effects can be generalized to a broader set of negative outcomes. Third, depression is often comorbid with anxiety, with some researchers arguing they represent a single underlying dimension (Feldman, 1993; Mineka *et al.*, 1998), so we cannot rule out the possibility that the results reported here are due, at least in part, to anxiety experienced by the participants. Further still, we do not know if the participants can be characterized more generally as highly sensitive to punishment. Future studies should try to disentangle the unique contribution of negative affect, depression, anxiety and punishment sensitivity to feedback processing.

In summary, the present study adds to the extant literature by demonstrating a correlation between negative emotionality and enhanced negative feedback processing which may be associated with abnormal rostral ACC activation. Consistent with prior studies with individuals experiencing negative affect (Luu *et al.*, 2000; Hajcak *et al.*, 2004; Sato *et al.*, 2005) and clinical depression (Tucker *et al.*, 2003; Holmes and Pizzagalli, 2008), elevated negative emotionality predicted exaggerated FRN amplitudes and activity in the rostral ACC region in response to a negative—but not positive—outcomes. Although further research is needed to determine whether the FRN and related rostral ACC hyperactivation is context-specific, these results suggest that the

FRN is a useful measure for studying how healthy individuals rapidly assess environmental feedback and the ERN/FRN might be a potential biological marker for identifying individuals at increased vulnerability to depression.

Conflict of Interest

None declared.

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