To Bet or Not to Bet? The Error Negativity or Error-related Negativity Associated with Risk-taking Choices

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Abstract

■ The functional significance of error-related negativity (Ne/ERN), which occurs at approximately the same time as erroneous responses, has been investigated extensively using reaction time (RT) tasks. The error detection theory assumes that the Ne/ERN reflects the mismatch detected by comparing representations of the intended and the actually performed actions. The conflict monitoring theory asserts that the Ne/ERN reflects the detection of response conflict between intended and actually performed actions during response selection. In this study, we employed a gambling task in which participants were required to choose whether they would take part in betting in each trial and they were presented with gain or loss feedback in both the ''to bet'' and the ''not to bet'' trials. The response-locked ERP magnitudes were more negative for ''to bet'' than for ''not to bet'' choices for both large and small stakes and were more negative for choices involving large rather than small stakes. Dipole source analysis localized the ERP responses to the anterior cingulate cortex (ACC). These findings suggest that the ACC signals the riskiness of choices and may function as an early warning system that alerts the brain to prepare for the potential negative consequence associated with a risky action. ■

INTRODUCTION

Choices often involve risk and undesirable outcomes. Making a choice calls for appraisal of the expected outcomes related to different options. A critical function of the human brain is to assess options, monitor behavior, and prevent undesirable outcomes. Evidence suggests that the anterior cingulate cortex (ACC) is involved in action monitoring (Paus, 2001; Bush, Luu, & Posner, 2000; Luu, Flaisch, & Tucker, 2000), risk assessment (Mccoy & Platt, 2005; Ernst et al., 2004; Fukui, Murai, Fukuyama, Hayashi, & Hanakawa, 2004), and many other higher-order cognitive functions (see Botvinick, Cohen, & Carter, 2004; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004; Bush et al., 2000 for reviews). Studies of the error negativity (Ne; Falkenstein, Hohnsbein, & Hoormann, 1991; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990) or the error-related negativity (Ne/ERN; Gehring, Goss, Coles, Meyer, & Donchin, 1993), a medial frontal negative component of the event-related brain potential (ERP), have contributed to this evidence. The Ne/ERN is best identified in response-locked ERPs, in which it occurs at approximately the same time as erroneous button press in reaction time (RT) tasks and peaks around 50 to 100 msec after the response (Gehring et al., 1993; Falkenstein et al., 1990, 1991). Dipole source analysis of the Ne/ERN suggests that it is generated in the ACC (Herrmann, Rommler, Ehlis, Heidrich, & Fallgater, 2004; Miltner, Brauer, Hecht, Tippe, & Coles, 2004; van Schie, Mars, Coles, & Bekkering, 2004; Luu, Tucker, Derryberry, Reed, & Poulsen, 2003; Miltner et al., 2003; van Veen & Carter 2002; Gehring, Himle, & Nisenson, 2000; Holroyd, Dien, & Coles, 1998; Dehaene, 1996; Dehaene, Posner, & Tucker, 1994). The functional magnetic resonance imaging (fMRI) research also supports the role of the ACC in generating Ne/ERN and more generally in error processing (Holroyd, Larsen, & Cohen, 2004; Holroyd, Nieuwenhuis, et al., 2004; Ullsperger & von Cramon, 2001; Carter et al., 1998).

Several theories of the Ne/ERN have been suggested. The error detection theory assumes that the Ne/ERN is a neural correlate of mismatch detected by comparing representations of the intended and the actually performed actions (Coles, Scheffers, & Holroyd, 2001; Falkenstein, Hoorman, Christ, & Hohnsbein, 2000; Scheffers & Coles, 2000; Scheffers, Coles, Bernstern, Gehring, & Donchin, 1996; Gehring et al., 1993; Falkenstein et al., 1991). The Ne/ERN is usually found on action slips due to premature responding under time pressure—that is, the response is made before stimulus evaluation and task rule application are completed. The continuous building up of the representation of the intended action after the premature responding may provide basis for the correctness assessment of the action and the awareness of response error.

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A related theory assumes that the Ne/ERN does not reflect the error detection per se but rather the monitoring of response conflict during response selection (Holroyd, Yeung, Coles, & Cohen, 2005; Yeung & Sanfey, 2004; Botvinick, Braver, Barch, Carter, & Cohen, 2001). This conflict monitoring theory agrees with the error detection theory in that when an impulsive erroneous action is executed, stimulus evaluation can continue, leading to activation of the correct response. However, the conflict monitoring theory assumes that activation of the correct response gives rise to a transient period during which both the correct response tendency and the already executed incorrect response are activated. The conflict between the two active, incompatible response tendencies is detected by the ACC, which generates the Ne/ERN. This conflict monitoring theory of the Ne/ERN is consistent with a number of fMRI findings concerning conflict control (see Botvinick et al., 2001, 2004; Ridderinkhof et al., 2004 for reviews).

Currently, whether Ne/ERN (and the ACC) is sensitive mostly to response error or to response conflict is still under debate (Holroyd et al., 2005; Botvinick et al., 2001, 2004; Ridderinkhof et al., 2004; Ullsperger & von Cramon, 2001, 2004; Yeung & Sanfey, 2004; Holroyd & Coles, 2002; Bush et al., 2000). The difficulty in choosing between the two alternative theories comes mostly from the employment of RT tasks, such as the Eriksen flanker task or the go/no-go task, in which the computation of the Ne/ERN effects is intrinsically related to erroneous responses. To be specific, these tasks have the following characteristics. Firstly, the participant should respond according to well-learned stimulus–response (S–R) rules. In other words, the individual should perform according to the predefined appropriateness for his behavior. Secondly, these RT tasks have time pressure on the participant who should respond as soon as possible, often without full processing of the stimuli. Thirdly, the action is driven by the external stimulus and the S–R rule, rather than by the participant's free will. Fourthly, a given response can be evaluated immediately against the internal representation of the correct S–R mapping and, should the response be incorrect, the awareness of the error is often available from an internal error detection or monitoring process at the time of the response (Holroyd et al., 2005; Gehring et al., 1993).

In this study, however, we employed a gambling task in which the participant was free to decide whether he wanted to bet or not to bet for the current round of gamble with either a small or a large stake, followed by receiving feedback concerning the (potential) win or loss of money for the action adopted. Here, the participant could make free choices without time pressure or the predefined correctness for his decision. In other words, there was no error to be detected by the participant at the time of decision making. Moreover, given that the stimulus was the same in each trial, the participant could only make his decision based on his past experience and the current mental state. If we obtained an Ne/ERN effect between the response-locked ERPs in deciding ''to bet'' or ''not to bet,'' our data would then allow us to rule out the possibility of the error detection theory as a general theory for the Ne/ERN effect because our manipulations have excluded the error detection process in the choice phase and the potential effect could not be attributed to the neural process associated with error detection.

To understand the potential cognitive processes that might be involved in the gambling task and to understand how the conflict monitoring theory could handle the potential Ne/ERN effect in this task, we give a simple outline of the purported decision processes based on previous behavioral decision research (see Mellers, Schwartz, & Cooke, 1998; Payne & Bettman, 1992 for reviews). To put it simply, decision making refers to the processes by which a person chooses a particular response based on his assessment of the potential costs and benefits associated with alternative actions. Risk taking, an essential component of much decision making, involves the selection of action with the potential for a relatively large beneficial or negative outcome over an alternative action that results in a relatively small beneficial or negative outcome. Risk-taking decision making can be broken down into a number of components, including the finding out of potential choices, the comparison between risk and reward associated with each option, the implementation of the action chosen, and the evaluation of the outcome obtained for the action. Importantly, for the purpose of this study, although the ''to bet'' choice would result in either winning or losing money for the trial in this gambling task, the ''not to bet'' choice would result in no monetary consequence, even though information about the potential gain or loss was given after the choice. Thus, choosing to bet was a risky action, whereas choosing not to bet was a cautious one avoiding risk. Here the riskiness of the choice can be formally defined as a spread from the mean in the objective values of possible outcomes (Lee, 2005).

With the above understanding, the conflict monitoring theory could predict an Ne/ERN effect for the ''to bet'' vs. the ''not to bet'' trials in the current gambling task (but see Discussion). When a participant makes decisions, there might be two conflicting internal desires: to take risk and win potential monetary reward and to give up and avoid potential loss. This conflict might induce differential ACC activities and the Ne/ERN responses (van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Indeed, a recent study examining ERPs associated with decisions to hit another card in the Blackjack gambling task (Hewig et al., 2007) observed that, compared with the condition in which the participant had cards with lower scores (<17) in hand, the hit decision elicited a more negative Ne/ERN for the condition in which the participant had cards with higher scores (>16).

[However, the authors interpreted this finding as suggesting that the observed Ne/ERN was the consequence of an ''erroneous'' decision as the higher risk choice (to hit above 16) was beyond the risk threshold (mean = 15.68, *SD* = 0.60, as computed according to models of item response theory) and might be classified as an error.] Moreover, the conflict between the desire to win and the desire to be safe should be more severe when the stake was large than when the stake was small, as the outcomes from the ''to bet'' and ''not to bet'' choices were more dispersing for the former than for the latter. The conflict monitoring theory could predict a main effect of the stake magnitude, with stronger Ne/ERN responses to big stake trials than to small stake trials. In computer stimulations of the conflict monitoring theory, it was shown that the Ne/ERN amplitude correlated positively with the degree of conflict (Yeung & Sanfey, 2004; but see Carbonnell & Falkenstein, 2006).

To check whether the participant was mentally devoted to the task, we also analyzed the ERPs locked to the feedback stimuli concerning his monetary gain or loss. The win and loss feedback in the ''to bet'' trials would elicit the classic feedback-related negativity (FRN), an ERP component thought to be of the same origin as the Ne/ERN (Nieuwenhuis, Holroyd, Mol, & Coles, 2004; Holroyd & Coles, 2002; Miltner, Braun, & Coles, 1997). Holroyd and Coles (2002) suggested that the FRN is generated in the ACC and by information about changes in reward prediction. The ACC uses external information about rewards to learn about the consequences of recent actions and to select more appropriate responses in the future. In the ''not to bet'' trials, the win or loss feedback was irrelevant to the participant's interest, hence, should not elicit an FRN effect. However, by counterfactually thinking, the participant would know that they could win or lose if he had chosen to bet. In this situation, the win feedback could actually be a negative feedback as the participant lost a chance to win, and the loss feedback could actually be a positive feedback as he successfully avoided the potential loss (see Yu & Zhou, 2006a; Holroyd, Larsen, et al., 2004).

METHODS

Participants

Fourteen undergraduate students (7 men; mean age = 21.4 ± 1.5 years) participated in the experiment. They were first told that they would get paid 40 yuan (about US$6) for their participation and their performance in the experiment would determine how much they would be awarded or penalized on top of this basic payment. Informed consent was obtained from each participant, and the experiment was approved by the Academic Committee of the Department of Psychology, Peking University.

Task and Procedures

The participant sat comfortably about 1 m in front of a computer screen in an electrically shielded room. On each trial, the participant was presented with a stake (either 20 or 150 cents) in the center of the screen (4° high, 4° wide in visual angle, white against a black background). One line of words ''bet or not'' in Chinese were presented below the number. The participant pressed one of the buttons on a keyboard to indicate whether he would like to take part in this trial (left ctrl button) or not (right ctrl button). The mappings between button press and betting were counterbalanced over participants. After 500 msec, the outcome was presented on a gray card (4° high, 4° wide). For example, ''+150'' in red or ''−150'' in green indicated that the participant had won or lost 150 cents, respectively, after they decided to bet; and ''+150'' or ''−150'' in white indicated that the participant would had won or lost 150 cents, respectively, if they had decided to bet. The mappings between the color and win/loss status in the ''to bet'' trials were counterbalanced over participants. The outcome was also highlighted by thickening of the white outlines of the card if the participant had chosen ''to bet.'' Participants were told that they would gain or lose the amount of money shown on the card if they had chosen to gamble and they would receive nothing if they had chosen not to gamble. The intertrial interval was 1000 msec.

Before the formal test, the participant was given detailed task instructions and a practice block consisting of 20 trials. The formal test consisted of six blocks of 40 trials each. Participants were told the exact number of trials they would take in this experiment and they were also told that the stakes would be randomly chosen for them by the computer. The gain/loss outcomes were determined according to a prespecified pseudorandom sequence, with half of the times gaining and another half of the times losing when the participant chose to gamble. A similar pseudorandom sequence was applied to outcomes when the participant chose not to gamble. However, the participants were not told about these manipulations. They were simply encouraged to use whatever strategy to maximize his gains. They were also told that if the experiment resulted in a net loss, it would be taken as zero and the participant would receive no reward or penalty.

ERP Recording

The EEG was recorded from 64 scalp sites using tin electrodes mounted in an elastic cap (NeuroScan, Herndon, VA, USA) according to the International 10–20 system. Eye blinks were recorded from left supraorbital and infraorbital electrodes. The horizontal electrooculogram (EOG) was recorded from electrodes placed 1.5 cm lateral to the left and right external canthi. All electrode recordings were referenced to an electrode placed on the left mastoid, and the impedance was maintained below 5 kΩ. The EEG and EOG were amplified using a 0.05–70 Hz band-pass and were continuously sampled at 500 Hz/channel for off-line analysis. Ocular artifacts were corrected with an eye-movement correction algorithm. All trials in which EEG voltages exceeded a threshold of ±60 μV during the recording epoch were excluded from analysis. The EEG data were re-referenced off-line to linked mastoid electrodes by subtracting from each sample of data recorded at each channel one-half the activity recorded at the right mastoid. The data were filtered using a 1–20 Hz band-pass to remove low-frequency waves from the EEG, and were baseline corrected by subtracting from each sample the average activity of that channel during the baseline period. EEG epochs of 800 msec (with 400 to 300 msec preresponse baseline) were extracted off-line for response-locked ERPs when the participant decided to bet or not to bet and EEG epochs of 800 msec (with 200 msec prestimulus baseline) were extracted off-line for stimulus-locked ERPs when the feedback was presented.

ERP Analysis

The response-locked ERP amplitudes were measured as the peak amplitudes of the waveforms in a window of −50 to 200 msec after responses. These ERP amplitudes were calculated for the three midline electrode locations (Fz, Cz, Pz). The FRN amplitudes were measured as the average amplitudes of the waveforms in a window of 200 to 300 msec after the onset of feedback. The average amplitudes of the waveforms in a later window of 300 to 500 msec postfeedback were also measured because we observed a negative ERP component differing between win and loss trials for the ‘‘not to bet’’ trials in this time window (see Figure 3). The ERP amplitudes following feedback were calculated also for the three midline electrodes (Fz, Cz, Pz). We chose these midline electrodes because the Ne/ERN and the FRN effects were the strongest on them.

The Ne/ERN data were entered into ANOVAs, with stake magnitude (high vs. low), choice (to bet vs. not to bet), and electrode location (Fz vs. Cz vs. Pz) as three within-participant factors. For the ‘‘to bet’’ and ‘‘not to bet’’ trials, the FRN data were entered into ANOVAs separately, with stake magnitude (high vs. low), reward valence (win vs. loss), and electrode location (Fz vs. Cz vs. Pz) as three within-participant factors. The Greenhouse–Geisser correction for repeated measures was applied where appropriate.

Dipole Analysis

An attempt was made to localize the dipole sources of the four ERP components at the response phase and the feedback-locked difference waves (loss minus win in the ‘‘to bet’’ condition and win minus loss in the ‘‘not to bet’’ condition). For each ERP component, source localization was carried out with the Brain Electrical Source Analysis program (BESA, Version 5.0) using a four-shell ellipsoidal head model. As suggested by Scherg and Berg (1990), data were high-pass filtered (1 Hz) before dipole fitting in order to remove slow drifts which could bias the resulting solution. For the response-locked ERP component, a time window of −50 to 50 msec postresponse, covering the period of significant ERP activities for all four conditions, especially at frontal electrodes, was chosen for the localization analysis of the ERP waveforms. A time window of 200 to 300 msec was chosen for the loss-minus-win difference wave in the ‘‘to bet’’ condition and a time window of 300 to 500 msec was chosen for the win-minus-loss difference wave in the ‘‘not to bet’’ condition. Principal component analysis (PCA) was employed in this interval for the ERP components in order to estimate the minimum number of dipoles. The dipoles were fitted with no restriction to their direction or location.

RESULTS

Behavior Results

Participants gained, on average, an extra 10.94 Chinese yuan (about US$2.44) on top of the basic payment (40 yuan) at the end of the experiment. For large stakes, the proportion of choosing to bet ranged from 49.6% to 78.4%, with a mean of 64.7% (SD = 7.2%). For small stakes, the proportion of choosing to bet ranged from 30.8% to 75.9%, with a mean of 49.9% (SD = 13.6%). Although there was no difference between the ‘‘to bet’’ and the ‘‘not to bet’’ choices when the stake was small [$t(13) < 1$], the difference between the two types of choices was significant when the stake was large [$t(13) = 7.6$, $p < .05$], indicating that participants tended to take risks and to bet when the potential win (or loss) was large. This choice bias effect differed significantly between the small and the large stake conditions [$t(13) = 3.08$, $p < .01$].

For RTs associated with the decisions ‘‘to bet’’ and ‘‘not to bet,’’ an ANOVA with stake magnitude and choice as two within-participant factors showed a significant main effect of stake magnitude [$F(1, 13) = 7.27$, $p < .05$] and a significant interaction between the two factors [$F(1, 13) = 11.19$, $p < .01$]. Further tests suggested that the difference between RTs for the ‘‘to bet’’ decision (959 msec, SD = 275) and the ‘‘not to bet’’ decision (835 msec, SD = 304) was not significant for the small stake [$t(13) < 1$], but it was significant for the larger stake [886 msec (SD = 247) vs. 1083 msec (SD = 275), $t(13) = 3.4$, $p < .05$]. Participants were generally faster in their decision when the stake was small than when the stake was large. They were also faster in deciding to bet than in deciding not to bet when the stake was large, whereas the reverse trend was true when the stake was small.

Previous studies on decision making have shown that recent outcomes can alter the preference order for the current options (Kahneman & Tversky, 1979). To examine whether the current choice of "to bet" or "not to bet" was affected by the win or loss in the previous trial, we computed the mean probabilities of the two choices as a function of the choice and outcome in the previous trial, collapsing over the small and large stakes. When choices in previous trials were "to bet," an ANOVA with factors of the previous outcome (win vs. loss) and the current choice (to bet vs. not to bet) revealed a significant interaction between the two factors [$F(1, 13) = 23.74$, $p < .001$]. Further tests showed that participants were more likely to bet (62.3%) than not to bet (37.7%) if they made bets and lost in previous trials [$t(13) = 5.98$, $p < .001$], a finding replicated in previous studies (e.g., Gehring & Willoughby, 2002; Kahneman & Tversky, 1979). However, their choices in current trials were at chance level if they made bets and won in previous trials [$t(13) = 1.11$, $p > .1$].When choices in previous trials were "not to bet," there was no significant main effect of choice for current trials and no interaction between previous (potential) outcome and current choice ($F < 1$). These findings indicated that participants were sensitive to the outcomes of their gambles and tried to use the knowledge to guide their current performance (cf. Yeung & Sanfey, 2004; Gehring & Willoughby, 2002). Indeed, debriefing revealed that most participants believed that they detected some transient patterns in the feedback and they could predict to some extent whether betting on the current trial would win or lose.

ERP Results

Response-locked ERPs

The response-locked ERPs for the three midline electrodes are shown in Figure 1. ANOVA on the peak amplitudes with factors of choice (to bet vs. not to bet), stake magnitude (large vs. small), and electrode location (Fz vs. Cz vs. Pz) revealed a main effect of choice [$F(1, 13) = 5.55$, $p < 05$], a main effect of stake magnitude [$F(1, 13) = 30.49$, $p < .001$], and a main effect of location [$F(2, 26) = 21.78$, $p < .001$]. The interaction between magnitude, choice, and location was also significant [$F(2,26) = 3.72$, $p < .05$]. Further tests showed that the main effects of choice and stake magnitude were significant at Fz and Cz ($p < .05$), but not at Pz ($p > .1$). The average ERP amplitudes were significantly more negative for the "to bet" choices (−3.41 μV) than for the "not to bet" choices (−2.84 μV), and were significantly more negative for the larger stakes (−3.55 μV) than for the small stakes (−2.70 μV).

Note that here we reported data with the 400 to 300 msec preresponse baseline. The same pattern of effects was obtained when the 400 to 0 msec or the 200 to 0 msec preresponse baseline was used, suggesting that the current results were not biased by the baseline we chose.

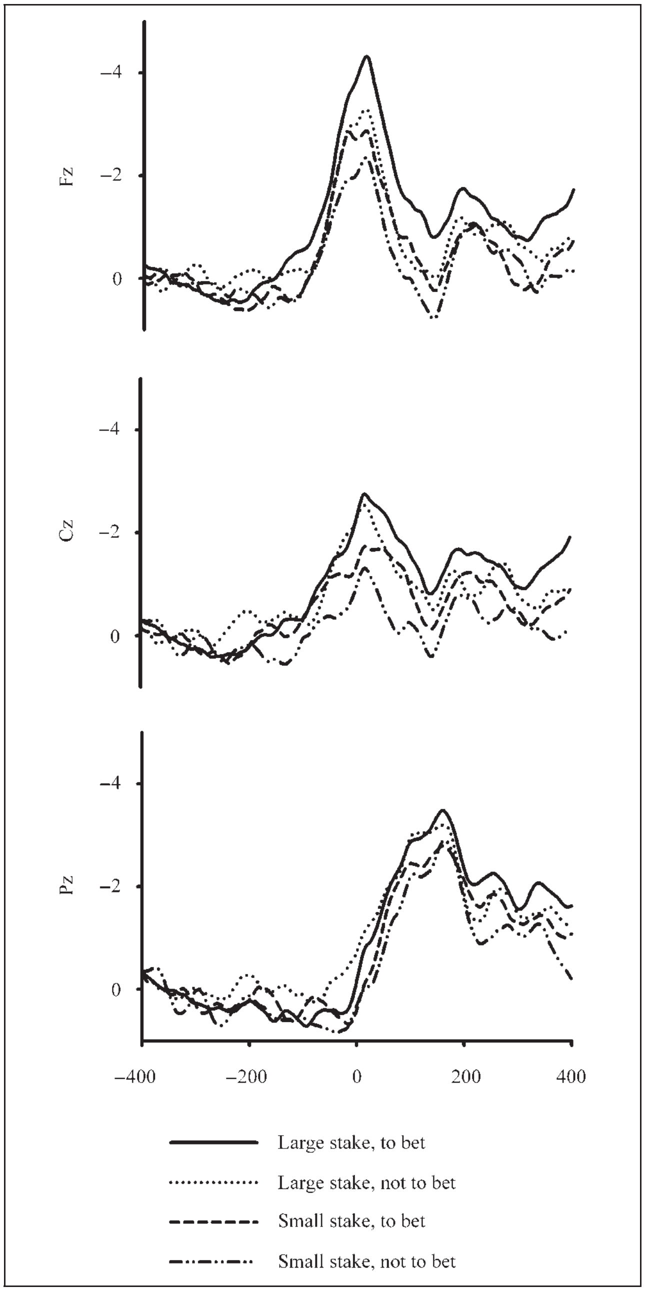


Figure 1. Grand-average ERP waveforms from channel Fz, Cz, and Pz, separately for the "to bet" and "not to bet" choices. Ordinate is in microvolts and abscissa is in milliseconds. Response onset was presented at 0 msec.

Dipole Source Analysis of the Response-locked ERPs

The initial PCA indicated that one principal component was able to explain more than 98% of the variance in the data for each condition. Thus one dipole was fitted with no restriction to the direction and location of the dipole for each condition. The locations of the dipole model for the ERP components were: $x = -0.1, y = 12.8; z = 76.1$ (Talairach coordinates), with residual variance (RV) of 4.6% for the large and ‘‘to bet’’ condition; $x = 6.5, y = 5.3; z = 58.7$, with RV of 6.4% for the large and ‘‘not to bet’’ condition; $x = -2.9, y = 9.4; z = 77.9$, with RV of 4.7% for the small and ‘‘to bet’’ condition; and $x = 6.2, y = 8.2; z = 76.8$, with RV of 7.0% for the small and ‘‘not to bet’’ condition (see Figure 2). All these locations were at the dorsal ACC. The ERP difference waves (e.g., ‘‘to bet’’ minus ‘‘not to bet’’), which were markedly reduced in magnitude compared with previous Ne/ERN studies using RT tasks, provided no stable and satisfactory dipole models.

Feedback-locked ERPs

The grand averages for electrodes Fz, Cz, and Pz are shown in Figure 3. The difference waveforms between the win and the loss trials, collapsed over the magnitude of stakes, are also presented in Figure 4. For the ‘‘to bet’’ condition, we can see that feedback-related negativity appeared to peak at approximately 250 msec after the feedback stimulus for both win and loss trials. An ANOVA on the average amplitudes, with factors of reward valence (win vs. loss), stake magnitude (large vs. small), and electrode location (Fz vs. Cz vs. Pz), found a main effect of valence [$F(1, 13) = 25.27, p < .001$], a main effect of magnitude [$F(1, 13) = 23.92, p < .001$], and a main effect of electrode location [$F(2, 26) = 12.31, p < .01$]. The overall FRN magnitudes were more negative-going in the loss trials (3.38 μV) than in the win trials (5.66 μV), more negative-going when the stakes were small (3.73 μV) than when the stakes were large (5.31 μV), and more negative-going at Pz (2.31 μV) than at Cz (5.24 μV) and Fz (6.02 μV). The interaction between reward valence and stake magnitude was not significant [$F(1, 13) = 1.69, p > .1$], nor the three-way interaction between reward valence, stake magnitude, and electrode location [$F(2, 26) < 1$]. In the time window of 300 to 500 msec after feedback presentation, the main effect of valence was not significant [$F(1, 13) = 1.21, p > .1$], suggesting that the valence effect of FRN in the ‘‘to bet’’ condition did not extend into this time window.

For the ‘‘not to bet’’ trials, it is clear from Figure 4 that although the feedback concerning the potential win and loss did not elicit different ERP responses in the time

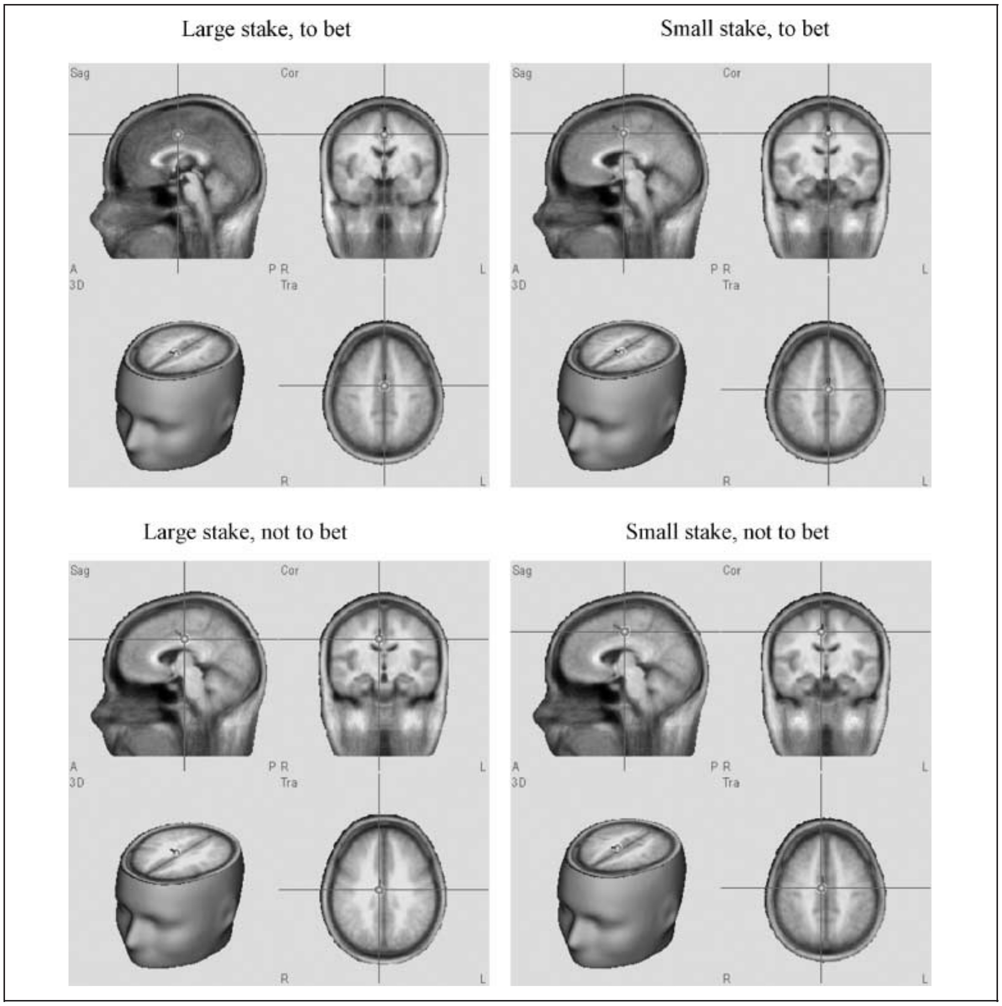
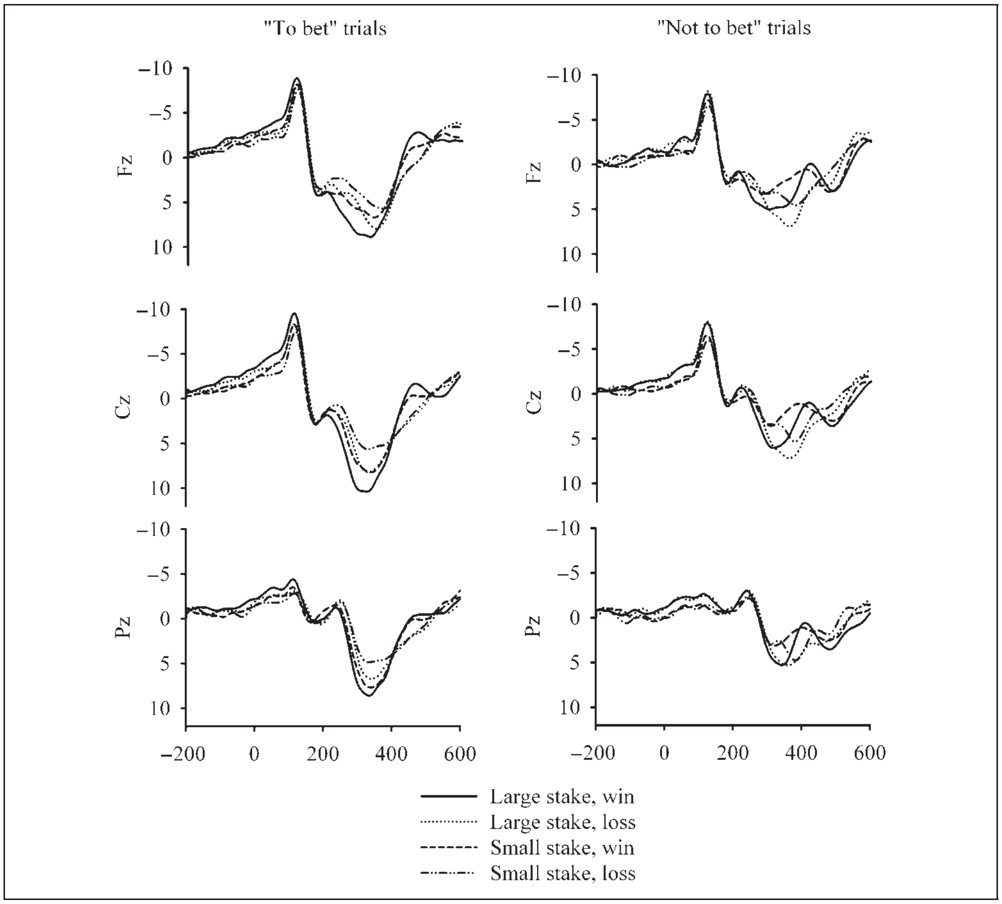


Figure 2. Dipole source localization for ERNs. Dipolar stereotaxic coordinates are transferred on a magnetic resonance imaging brain atlas.

Figure 3. Grand-average ERP waveforms from channel Fz, Cz, and Pz, separately for the "to bet" and "not to bet" choices. Ordinate is in microvolts and abscissa is in milliseconds. Feedback stimuli onset was presented at 0 msec.



window of 200 to 300 msec, they did produce a differential effect in the time window of 300 to 500 msec. Statistical analyses confirmed this observation. An ANOVA with factors of reward valence (win vs. loss), stake magnitude (large vs. small), and electrode location (Fz vs. Cz vs. Pz) found that the main effect of valence was not significant in the time window of 200 to 300 msec [$F(1, 13) = 3.48$, $p > .1$], but it was significant in the time window of 300 to 500 msec [$F(1, 13) = 5.70$, $p < .05$]. The overall ERP responses in the latter time window were more negative-going for the potential (but missed) win trials (3.55 μV) than for the potential loss trials (4.42 μV). Moreover, in the latter time window, the main effect of magnitude was significant [$F(1, 13) = 32.77$, $p < .001$], with small stake trials eliciting more negative-going ERP responses (3.00 μV) than large stake trials (4.97 μV).

Dipole Source Analysis of the Feedback-locked ERPs

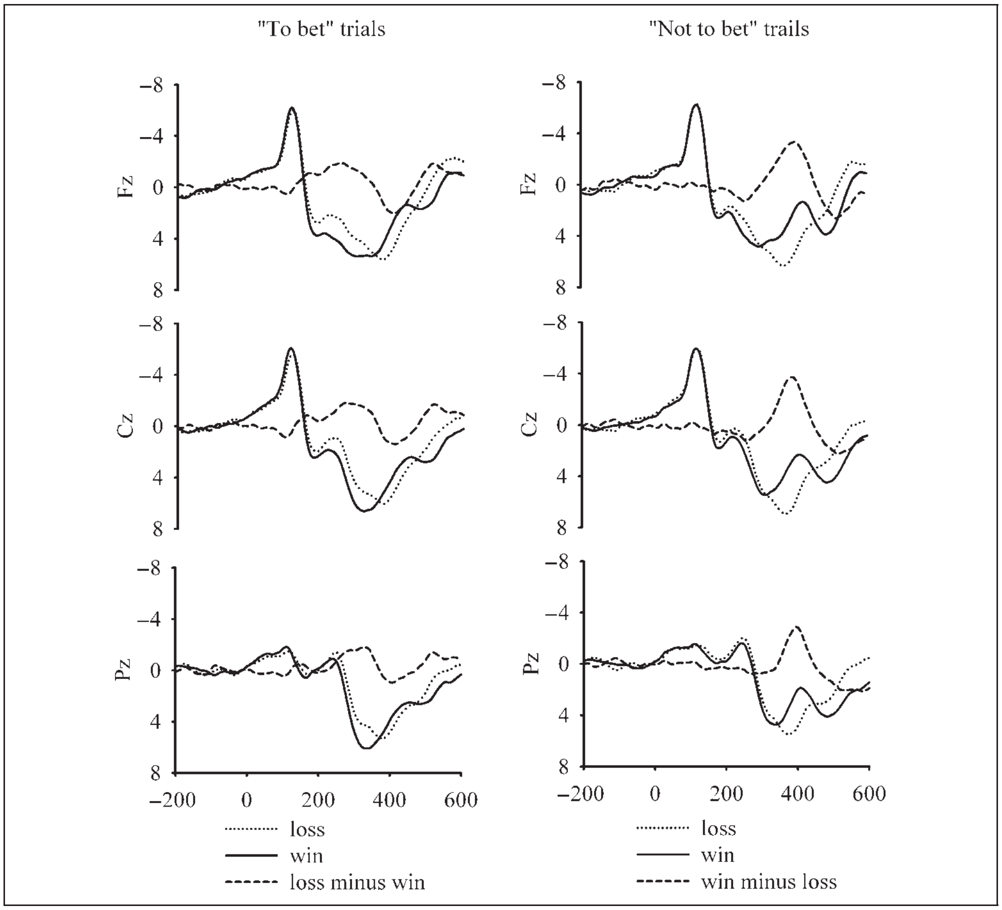
Source analysis was applied to the FRN difference waves in the time window of 200 to 300 msec after feedback presentation for the "to bet" condition. The initial PCA indicated that two principal components were able to explain more than 99% of the variance in the data (one for 79.8% and the other for 19.2%). Thus, two dipoles were fitted with no restriction to the direction and location of the dipoles. The location of the first dipole for the ERP component was: $x = 4.4, y = 15.5, z = 23.9$, and the location of the second dipole was: $x = -11.9$, $y = -33.6$, $z = -1.1$ (Figure 5, left). The residual variance was 7.9%. Thus, the FRN effect in this study could be related to the activity in the ACC.

Similarly, the source analysis on the difference waves in the latter time window of 300 to 500 msec for the "not to bet" condition found two dipoles, one at $x = -1.2$, $y = 14.5$, $z = 28.7$, and the second at $x = -5.4, y = -41.5, z = -13.0$ (Figure 5, right). The residual variance was 10.59%. Thus, the negativity for the win-minus-loss in the "not to bet" condition could also be related to the activity in the ACC.

DISCUSSION

In this gambling task, we observed that the response-locked ERP components were more negative for the "to bet" choices than for the "not to bet" choices and were more negative for choices with large stakes than for choices with small stakes. Moreover, the Ne/ERN effect (i.e., "to bet" minus "not to bet") did not vary according to the magnitude of stake. Source localization analysis showed that these ERP components could be

Figure 4. Grand-average ERP waveforms from channel Fz, Cz, and Pz, separately for the win and loss trials (collapsed over trials with small or large stakes). The difference between the grand-average ERP waveforms for the loss and win trials is also plotted separately for the "to bet" and the "not to bet" conditions. Ordinate is in microvolts and abscissa is in milliseconds. Feedback stimuli onset was presented at 0 msec.

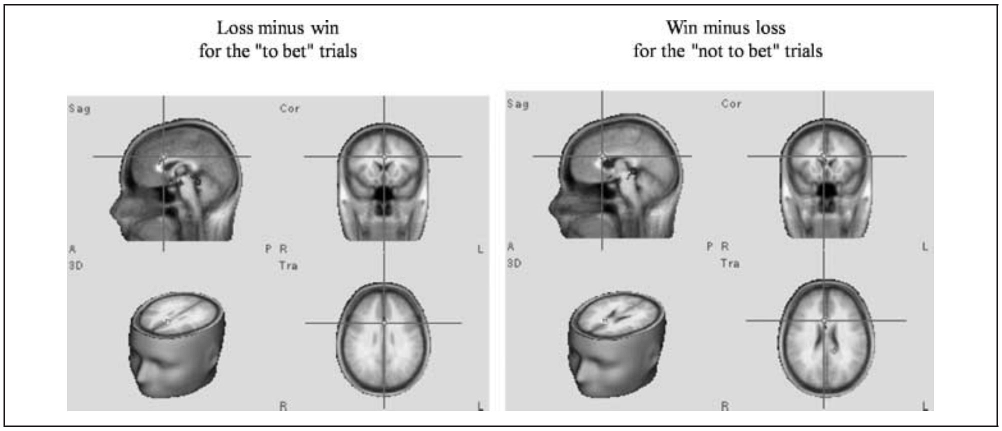


explained by the dipole activity at the dorsal ACC. Furthermore, we obtained the typical FRN effect (i.e., loss minus win) for feedback after participants decided to bet, but a delayed, reversed (i.e., win minus loss) FRN effect for feedback concerning the potential (but missed) win and loss after participants decided not to bet. The FRN effect was also related to the activity in the dorsal ACC. The finding of the Ne/ERN effect in the gambling choice suggests that the ACC, which generates the Ne/ERN, is sensitive to the on-line evaluation of the riskiness of choices and it may act as an alerting system to prepare the brain for the potential negative consequences of risky actions.

The Response-locked Ne/ERN Effect

As we argued in the Introduction, our experimental manipulations precluded the possibility of error detection as the cognitive process responsible for the Ne/ERN effect. Because our participants were free, and without time pressure, to decide whether they would like to bet

Figure 5. Dipole source localization of the difference wave in "to bet" and "not to bet" condition separately. Dipolar stereotaxic coordinates are transferred on a magnetic resonance imaging brain atlas.



in the current round of gambling and there was no predefined appropriateness for their choices (i.e., both types of choices were permitted and they would not know which choice was better until they received feedback), there should be no explicit ''errors'' to detect. Moreover, participants were more likely to chose ''to bet'' than to chose ''not to bet,'' suggesting that the ''to bet'' decisions were unlikely to be classified (implicitly) as errors (c.f., Hewig et al., 2007). Nevertheless, we observed an Ne/ERN or Ne/ERN-like effect between the choices ''to bet'' and the choices ''not to bet''; and this effect corresponded in many aspects, including the peak latency of the waveform, the scalp distribution, and the anatomical generator, to the classical Ne/ERN effect observed in RT tasks. Therefore, our data unambiguously demonstrate that the error detection theory cannot be a general theory of the Ne/ERN.

The conflict monitoring theory fares much better with the present findings. According to an extended version of this theory (e.g., van Veen et al., 2001), the ACC may monitor not only conflicts occurring between different S–R mappings in response selection but also conflicts between different internal desires or plans. The conflict between taking risk and winning potential monetary reward and giving up and avoiding potential loss when a participant faces a stake may well be detected by the ACC and the Ne/ERN effect is thus ensured.

It is interesting to note, however, that it was the ''to bet'' choices, rather than the ''not to bet'' choices, that elicited more negative response-locked ERPs. The conflict monitoring theory may have difficulties to account for this finding. Participants made their decisions based on the same task rule and the same visual stimuli. The strength of the response conflict should then be symmetric to the two types of choices across the whole set of trials, although one might assume that the safe choice (i.e., winning or losing nothing) is the default choice a person usually takes and any deviation from this choice would incur a response conflict that must be overcome. However, this default assumption was not supported by the behavioral data in this study. In the large-stake condition, the ''to bet'' decisions were associated with significantly shorter RTs and higher frequencies of the choice than the ''not to bet'' decisions. In the small-stake condition, although the ''to bet'' decisions were associated with (nonsignificant) longer RTs than the ''not to bet'' decision, the choice frequencies for the ''to bet'' and ''not to bet'' decisions did not differ significantly. Thus, choosing to bet was no more effortful than choosing not to bet. It is not clear how the finding of more negative ERPs for the ''to bet'' choices than for the ''not to bet'' choices could fit with the default assumption that would be required by the conflict monitoring theory. On the other hand, this pattern of responses was likely to be associated with the fact that the participants would receive a certain amount of reward regardless of their performance, as indicated in the instructions. This could encourage them to seek higher reward by taking risky choices, especially when the stakes were large.

One possible escape route for the conflict monitoring theory is to assume that the ACC and the associated the Ne/ERN are responding not to the conflict between choices themselves but to the conflict between outcome predictions (i.e., possible loss vs. possible win). Participants might have competing outcome predictions when they made choices and this conflict has different strengths in the ''to bet'' and the ''not to bet'' conditions. Moreover, the outcome predictions could change dynamically as the performance is progressed. Although it is hard to calculate the degree of prediction conflict precisely, our finding that RTs were faster for the ''to bet'' decisions than the ''not to bet'' decisions when the stake was large suggests that the outcome prediction conflict should be smaller for the former than for the latter. Thus, the conflict monitoring theory would again predict larger Ne/ERN amplitudes for the ''not to bet'' than for the ''to bet'' trials, inconsistent with our actual findings.

Furthermore, the conflict monitoring theory may predict a bigger ERP difference (i.e., the Ne/ERN effect) between the two types of choices for the large stake than for the small stake because the outcomes from the two choices are more dispersing for the large stake than for the small stake and the conflict between the internal desire to bet and win and the desire not to bet and to be safe should be more intensive for the former than for the latter. However, consistent with Carbonnell and Falkenstein (2006), who used an RT task but measured the degree of conflict, we obtained equal Ne/ERN effects between the two types of choices for the large and small stakes. The absence of interaction between the size of Ne/ERN effect and the magnitude of stake is difficult for the conflict monitoring theory.

We propose a new function for the ACC and the Ne/ERN, as complementary to the conflict monitoring theory. We believe that apart from the many previously proposed functions (see Botvinick et al., 2004; Ridderinkhof et al., 2004; Bush et al., 2000), the ACC is also involved in the on-line evaluation of the riskiness of options and decisions. By the definition of behavioral economics, choosing to bet is a risky choice and may incur loss. The on-line assessment of this choice would result in higher ACC activity and a more negative ERP component than a safe choice (i.e., not to bet). Moreover, given that the overall riskiness was also higher for trials with large stakes than for trials with small stakes, we observed stronger Ne/ERN responses for the former than for the latter.

Specifically, as the ACC is involved in assessing the motivational impact of the outcome events (Yu, Luo, Ye, & Zhou, 2007; Gehring & Willoughby, 2002; Bush et al., 2000), the ACC might be able to link the decision with its outcomes. The ACC may weigh the motivational impacts of all possible outcomes associated with a choice and integrate these affective information to assess the riskiness of the choice. Lesions of the ACC in monkeys impair the ability to integrate risk and payoff in a dynamic foraging task, suggesting that the ACC is essential for learning the value of actions (Kennerley, Walton, Behrens, & Rushworth, 2006). Findings that compared with positive outcomes, negative outcomes elicit enhanced FRNs, which are generated in the ACC, demonstrate that the ACC is particularly involved in evaluating the negative outcomes. The ability to process aversive outcomes places the ACC in an ideal position to evaluate riskiness of actions. Thus, the ACC might learn that risky choices have a greater deal of potentials to lead to negative outcomes. This riskiness assessment account of ACC function is consistent with the fMRI findings that the ACC is associated with risky decisions in gambling tasks (Cohen, Heller, & Ranganath, 2005; Fishbein et al., 2005; Ernst et al., 2004; Fukui et al., 2004).

The on-line signaling of the riskiness of choices may be highly adaptive, serving as an early warning system that alerts the brain to get ready for the potential negative consequences of actions (Yu & Zhou, 2006a; Brown & Braver, 2005). The ultimate outcomes of our choices may not be apparent until some time after we make the choices. Depending on the nature of choices, individuals may need to adjust the distribution of their attention resources, such that risky choices are associated with more resources. A real-life example is that a person bets $10,000 with trembling hands in a casino. In this scenario, this person realizes how risky his decision is and he is kept being alert. The subjective impact of losses is roughly twice that of gains (Tversky & Kahneman, 1981), suggesting that negative outcomes are of greater biological significance than positive outcomes. Moreover, the anatomical connections of the ACC would also allow this function. The ACC is interconnected with higher-level structures (e.g., the prefrontal cortex) and the limbic structures (e.g., amygdala) as well as with cortical areas with motor functions (Paus, 2001). The alerting signals could be sent from the ACC to these regions, mobilizing the executive, emotional, and motor systems to get ready for any potential negative consequences associated with risky actions.

Our riskiness account of the Ne/ERN also fits with the somatic marker hypothesis of decision making (Bechara, Damasio, Tranel, & Damasio, 1997; Bechara, Tranel, Damasio, & Damasio, 1996; Damasio, 1995), which postulates that external or internal stimulus initiates a state associated with pleasurable or aversive somatic markers. These markers function to guide the person's behavior by biasing the selection of actions resulting in an increase in pleasurable somatic markers and by biasing the avoidance of actions resulting in aversive somatic markers. The neural system underlying the somatic marker hypothesis involves several brain regions, including the ACC. The ACC is activated in the processing of somatic states associated with risk-taking decision making (Bechara, 2001). Indeed, the normal participants begin to generate anticipatory skin conductance responses (SCRs, or galvanic skin responses) that are more pronounced before picking a card from a risky deck (also the disadvantageous deck), compared to a safe deck (also the advantageous deck) (Bechara et al., 1996, 1997), whereas there is a correlation between SCR and ACC activity (Critchley, Mathias, & Dolan, 2001; Fredrikson et al., 1998) and ACC lesions could be followed by the impairment of SCR (Zahn, Grafman, & Tranel, 1996; Tranel & Damasio, 1994). In our study, the participants used, on average, less than 1000 msec to make their choices, indicating that their decisions were more likely to be based on hunch rather than on deliberate reasoning. The riskiness assessment function of the ACC may contribute to such gut feeling, allowing the participants to ''feel'' the risk of their decisions rather than just to ''know'' the existence of risk. When an action is being chosen, the ACC might simulate the emotion that this particular course of action would produce. The impairment of this function can lead to behavioral and emotional disorders such as drug abuse, pathological gambling, or anxiety. Attenuated activation of the ACC was found to correlate with increased risky choices in drug abusers (Fishbein et al., 2005). On the other hand, hyperactivation in the ACC during a low error rate decision task was found in high trait anxiety participants, reflecting the propensity to be more engaged in anticipating aversive outcomes (Paulus, Feinstein, Simmons, & Stein, 2004). Taken together, we propose that the ACC can function as a preemptive early warning system, which actively assesses the riskiness of actions to help us anticipate the potential danger and adjust behavior accordingly.

One might ask why the Ne/ERN should be stronger for trials with large stakes than for trials with small stakes when the participants had already chosen not to bet. Both types of trials had the objective value of zero and did not incur any loss on the participants. However, a large number of behavioral studies have demonstrated that the outcome of a risky decision is not judged by its objective value but rather by the subjective value that the decision maker harbors (e.g., Kahneman & Tversky, 1979). In the present study, participants could perceive the averted win as a loss and the averted loss as a win because of counterfactual comparison (Roese, 1997). The ''not to bet'' decision for a large stake could be riskier than for a small stake because it averted a potentially large win. This argument was supported by several lines of evidence. Firstly, RTs to decide not to bet was longer for trials with large stakes than for trials with small stakes (1083 msec vs. 835 msec), indicating that it was more effortful for the former type than for the latter type of decision. Secondly, ERP responses to feedback concerning the potential (but missed) win were more negative-going, in the time window of 300 to 500 msec, than ERP responses to feedback concerning the potential (but averted) loss, suggesting that participants did engage in counterfactual comparison. Thirdly, debriefing after the experiment showed that participants were more regretful when they received a win feedback but had chosen not to bet for trials with large stake than for trials with small stakes.

Feedback-related Negativity

ERP results in the feedback stage when participants decided to bet replicated many previous studies on FRN (e.g., Yu & Zhou, 2006a, 2006b; Gehring & Willoughby, 2002; Miltner et al., 1997; see Nieuwenhuis et al., 2004 for a review) and confirmed the sensitivity of the present experimental manipulations. The classic FRN effect was evident in the ''to bet'' condition, with a more negative component when betting was lost. Our source analysis revealed that this component was generated mainly by a region located near the ACC (see also Müller, Möller, Rodriguex-Fornells, & Münte, 2005; Gehring & Willoughby, 2002; Miltner et al., 1997).

In the ''not to bet'' condition, however, participants did not show differential ERP responses to feedback concerning the potential win and loss in the classical 200 to 300 msec time window. This null effect of the FRN is consistent with a previous finding that the FRN is not sensitive to the outcome of an alternative, not selected option (Yeung & Sanfey, 2004; Gehring & Willoughby, 2002). However, in a later time window of 300 to 500 msec after the feedback presentation, ERP responses were more negative for the ''missed win'' than for the ''missed loss.'' Moreover, the win-minus-loss difference wave of this effect could also be localized to the ACC. Although this negativity fell into the P300 time range, we believe it was not a P300 effect. The source analysis of the effect suggested that it was generated mainly by the ACC. It is possible that the system engaged in a counterfactual comparison process that treated the missed win as a negative feedback and the missed loss as a positive feedback to the ''not to bet'' action. This process could delay the appearance of the FRN effect. Indeed, an fMRI study on regret in monetary feedback processing suggested that the dorsal ACC contributes to the experience of regret (Coricelli et al., 2005). The ACC is activated when the alternative outcome of a nonselected option (winning 200 cents) is better than the actual outcome (e.g., winning 50 cents) and is relatively deactivated when the alternative outcome (losing 200 cents) is worse than the actual outcome (e.g., winning 50 cents). Although the functional significance of the FRN effect was not the focus of this study, our results, by showing that this component is enhanced for missed win than for missed loss, did suggest that the FRN component might reflect the high-level evaluation of the valence of outcomes.

Conclusion

By using a simple gambling task in which the participant can chose, under free will, to bet or not to bet for the current round, we demonstrate that the response-locked ERPs are more negative for risky choices compared with safe choices. This Ne/ERN effect, generated by the ACC, allows us to rule out the error detection theory as a general theory of the Ne/ERN and to question the appropriateness of the conflict monitoring theory for the ERP responses associated with freewill, risky choices. Instead, it may suggest that the ACC signals the riskiness of choices and may function as an early warning system that alerts the brain to prepare for the potential negative consequences associated with risky actions.

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