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Research Report

The P300 and reward valence, magnitude, and expectancy in outcome evaluation

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ABSTRACT

The P300 in event-related potentials (ERPs) has been implicated in outcome evaluation and reward processing, but it is controversial as to what aspects of reward processing it is sensitive. This study manipulated orthogonally reward valence, reward magnitude, and expectancy towards reward magnitude in a monetary gambling task and observed both the valence and the magnitude effects on the P300, but only when the amount of reward was expected on the basis of a previous cue. The FRN (feedback-related negativity), defined as the mean amplitudes of ERP responses to the loss or the gain outcome in the 250–350 ms time window post-onset of feedback, was found to be sensitive not only to reward valence, but also to expectancy towards reward magnitude and reward magnitude, with the violation of expectancy and the small magnitude eliciting more negative-going FRN. These findings demonstrate that while the FRN may function as a general mechanism that evaluates whether the outcome is consistent or inconsistent with expectation, the P300 is sensitive to a later, top-down controlled process of outcome evaluation, into which factors related to the allocation of attentional resources, including reward valence, reward magnitude, and magnitude expectancy, come to play.

1. Introduction

The P300 has been one of the most studied components of the event-related potentials (ERPs) since it was first reported in 1965 (Desmedt et al., 1965; Sutton et al., 1965). It is implicated in a large number of cognitive and affective processes and is traditionally associated with allocation of mental resources (Duncan-Johnson and Donchin, 1977; Polich, 2007; Polich and Kok, 1995; Squires et al., 1975). In recent years, differential effects on the P300 has also been observed in tasks involving decision making or outcome evaluation (Hajcak et al., 2005, 2007; Luu et al., 2009; Sato et al., 2005; Toyomaki and Murohashi, 2005; Yeung and Sanfey, 2004; Yeung et al., 2005; Yu et al., 2007), and these effects are thought to reflect the evaluation of the functional significance of feedback stimuli. However, it is controversial as to what aspects of the significance the P300 is sensitive.

In ERP studies on outcome evaluation or feedback processing, it has been found that two ERP components are particularly sensitive to the valence of reward or performance outcome. The first component is called FRN (i.e., feedback-related negativity)

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or MFN (i.e., medial-frontal negativity), which is a negative deflection at frontocentral recording sites that reaches maximum between 250 and 300 ms post-onset of feedback stimulus (Gehring and Willoughby, 2002; Heldmann et al., 2008; Holroyd and Coles, 2002; Holroyd, 2004; Nieuwenhuis et al., 2004; Miltner et al., 1997; Yu and Zhou, 2006a, 2006b). The FRN is more pronounced for negative feedback associated with unfavorable outcomes, such as incorrect responses or monetary losses, than for positive feedback. Another component is the P300, which is the most positive peak in the 200–600 ms period post-onset of feedback and which typically increases in magnitude from frontal to parietal sites.

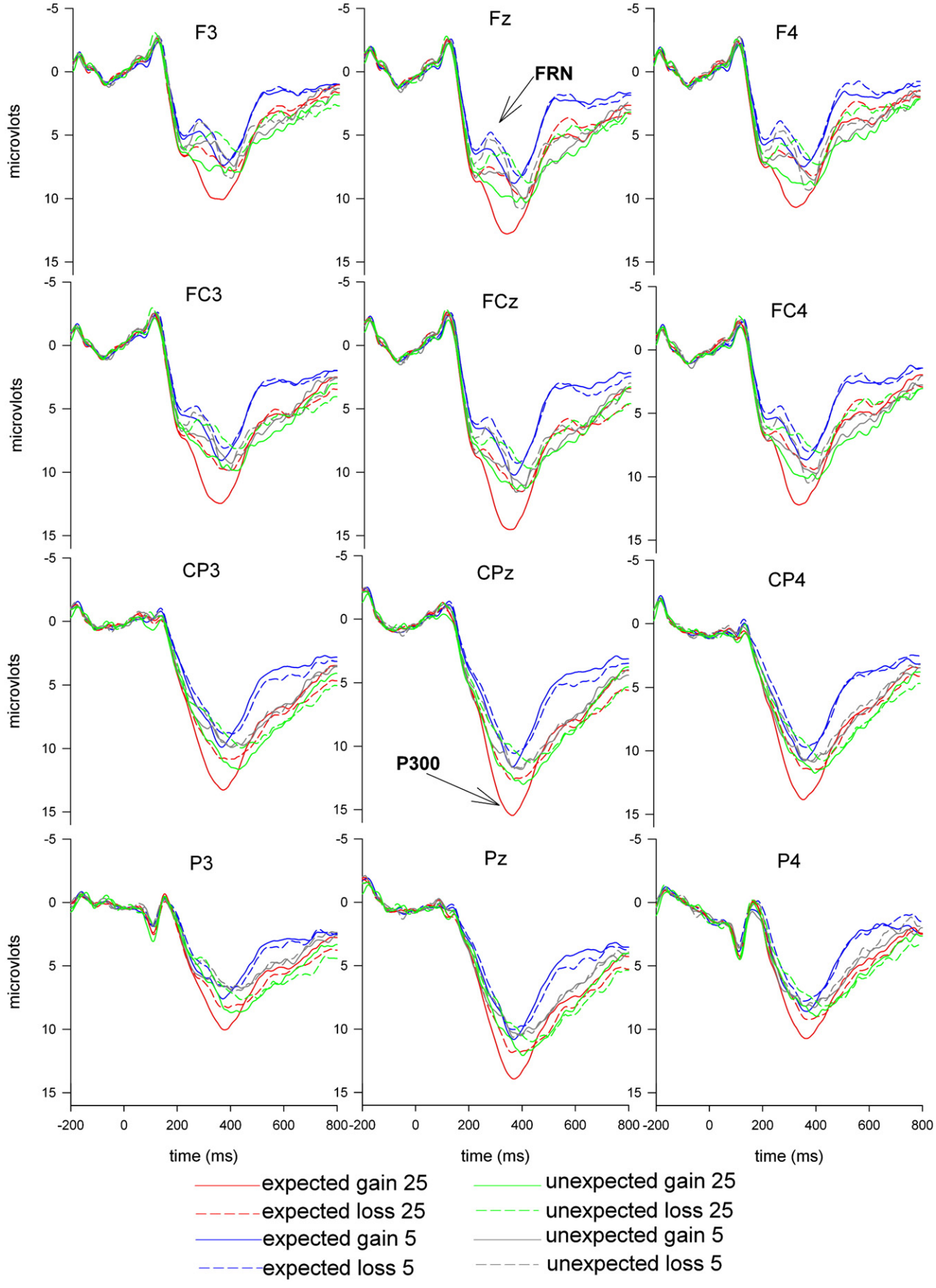
It has been claimed that the FRN and the P300 encode different aspects of outcome evaluation (Yeung and Sanfey, 2004). While the FRN is sensitive to feedback valence, the P300 is sensitive to the magnitude of reward, with a more positive response to a larger (whether positive or negative) than to a smaller reward (Sato et al., 2005; Yeung and Sanfey, 2004). In contrast, feedback valence has no impact upon the P300 (Sato et al., 2005; Yeung and Sanfey, 2004). Yeung and Sanfey (2004), for example, asked the participant to choose between cards that were unpredictably associated with monetary gains or losses of various magnitudes. After selection, a positive or a negative number appeared on the chosen card to indicate how much money the participant won or lost on that trial. After an additional interval, the participant was shown what he would have won or lost had he selected the alternative card. It was found that the P300 was insensitive to the valence of the actual outcome but was sensitive to the valence of the alternative outcome, with a larger P300 associated with a positive outcome. The authors concluded that the valence effect on the P300 is observed when valence is defined in terms of high-level motivational/affective evaluations, such as regret or disappointment, but not when valence is defined in terms of the straightforward reward value. However, other studies found that the P300 is sensitive to reward valence as well as to reward magnitude in monetary gambling tasks, with more positive amplitudes for positive feedback than for negative outcomes (e.g., Hajcak et al., 2005, 2007; Holroyd et al., 2006; Yeung et al., 2005).

Another aspect of the significance of feedback is the probability of the positive or negative outcome experienced by the participant. This probability, manipulated either on a trial-by-trial basis (Hajcak et al., 2005, 2007) or in a blocked manner (Cohen et al., 2007; Hajcak et al., 2005; Holroyd et al., 2003; Holroyd and Krigolson, 2007), would allow the participant to form expectancy towards a particular outcome and hence could affect brain responses to the upcoming feedback. Although these studies reported inconsistent results regarding whether the FRN effect is affected by this probability manipulation, they provided evidence that the P300 is modulated by the probability, with more positive amplitudes to unexpected feedback than to expected feedback (Hajcak et al., 2005, 2007). This pattern of the P300 effect is consistent with earlier studies employing the classic oddball paradigm and manipulating the probability of the appearance of a particular stimulus (Courchesne et al., 1977; Duncan-Johnson and Donchin, 1977; Johnson and Donchin, 1980).

The main purpose of this study is to provide further evidence for the impacts of reward valence, reward magnitude, and a previously unexamined form of expectancy, magnitude expectancy, upon the P300 in outcome evaluation. Importantly, we investigate to what extent these aspects of feedback would interact to determine the pattern of the P300 effect (and also the pattern of the FRN effect). To achieve this aim, we used a cued gambling task in which a cue about the amount of monetary reward in the current trial (e.g., the number “25”, standing for 2.5 Chinese yuan) was first presented, followed by the participant’s selection of a choice card. Finally, a feedback stimulus (e.g., “+25” or “+5”) was presented, which encoded information concerning the valence of reward (gain or loss), the magnitude of reward (a small or a larger amount of money), and magnitude expectancy (whether the amount of reward was consistent or inconsistent with expectation built upon the magnitude of the cue number). Note that, most previous studies manipulated reward expectancy by presenting a particular, valenced outcome with a specific probability in a testing block or in the whole experiment. Here the magnitude expectancy was built upon whether the magnitude of reward (the gain or loss outcome) was consistent with the magnitude of the cue presented at the beginning of a trial. Although this cue was valid in 80% of the trials (i.e., the cue “25” was followed by the reward “25” or the cue “5” was followed by the reward “5”), the valence of feedback was still unpredictable (i.e., gain or loss in 50% of the trials). By measuring ERP responses to the feedback stimuli, we would be able to examine the main effects of reward valence, magnitude and expectancy, as well as interactions between them on the P300.

We hypothesized that outcome evaluation can be roughly divided into two related processes: an early evaluation of the cognitive or motivational significance of the feedback stimuli, followed by more elaborative evaluation, in which factors that affect the allocation of attentional resources, such as intentionality or expectancy, come into play in a top-down controlled manner (Goyer et al., 2008; Leng and Zhou, in revision). On this view, reward valence, reward magnitude, and magnitude expectancy may modulate the amplitude of the P300, which represents the controlled process in outcome evaluation. It is not clear, however, whether these factors would interact in modulating the amplitude of the P300. Previous studies found that the impacts of reward valence and reward expectancy on the P300 are generally non-interactive (e.g., Hajcak et al., 2005, 2007). On the other hand, it is not clear either whether reward magnitude or magnitude expectancy would affect the early process represented by the FRN given that evidence concerning this issue is either contradictory or lacking. While some studies found that the FRN is insensitive to the reward magnitude (Hajcak et al., 2006; Holroyd et al., 2006; Sato et al., 2005; Polezzi et al., 2008; Toyomaki and Murohashi, 2005; Yeung and Sanfey, 2004), other studies obtained a magnitude effect on the FRN (Goyer et al., 2008; Marco-Pallares et al., 2008). The inconsistency may partly be caused by different parameterization of the FRN in those studies.

There are essentially three ways to measure the FRN or the FRN effect. The first way is to measure the base-to-peak or peak-to-peak difference, defining the FRN as the difference between the most positive point (P2) and the most negative point (N2) in the 150–350 ms time window post-onset of


F3
Fz
F4
FRN
FC3
FCz
FC4
CP3
CPz
CP4
P300
P3
Pz
P4
microvlots
-5
0
5
10
15
-200
0
200
400
600
800
time (ms)
expected gain 25
expected loss 25
expected gain 5
expected loss 5
unexpected gain 25
unexpected loss 25
unexpected gain 5
unexpected loss 5

feedback (Holroyd et al., 2003; Holroyd, 2004; Holroyd et al., 2006; Hajcak et al., 2006; Nittono et al., 2008; Sato et al., 2005). If there is no negative deflection in the 150–350 ms time window, as in many cases of positive feedback, the FRN is scored as zero. A problem with this measurement is that the positive feedback itself elicits a positive response and by setting its FRN as zero, the FRN effect (i.e., the differential ERP responses to negative and positive feedback) would be underestimated (Holroyd et al., 2008; Potts et al., 2006). The second way of measurement is to compute the mean amplitude in a time window (say, 200–300 ms) post-onset of feedback for gain and loss trials respectively and to enter mean amplitudes into statistical analyses (Gehring and Willoughby, 2002; Marco-Pallares et al., 2008; Yeung et al., 2005; Yeung and Sanfey, 2004). The third way of measurement, essentially the same as the second, is to compute the loss-minus-gain difference and use either the mean amplitude or the peak value of the difference wave in a time window as the FRN effect (Cohen and Ranganath, 2007; Hajcak et al., 2005, 2007). A problem with the second and the third methods is that the computation of mean amplitudes or the loss-minus-gain differences may be affected by the following P300, which could respond differentially to experimental conditions. One way to minimize this confound is to remove slow wave ERP responses, with which the P300 is associated, through bandpass filtering (Donkers et al., 2005; Heldmann et al., 2008; Luu et al., 2003). In this study we analyzed the FRN effects by using the mean amplitudes of ERP responses to different trials after bandpass filtering.

2. Results

2.1. *Behavioral results*

There are few meaningful behavioral measures in this task. The selection of the left card varied between 38% and 58% (mean=47%) of the total trials. The participants were sensitive to the outcome of their previous choices: the percentage of selecting the same card as the previous trial was 51.2%, 51.0%, 44.8% and 43.6% respectively following feedback of '+25', '+5', '−25' or '−5'. Compared to the cases in which they were penalized on the previous trial, the participants were more likely to select the same card if they had gained in the previous trial, $F(1, 15)=5.49$, $p<0.05$. But the magnitude of gain or loss did not affect the subsequent choice, $F(1, 15)<1$.

2.2. *The P300 results*

The peak amplitudes of the P300 were entered into a 2 (magnitude expectancy: expected vs. unexpected)×2 (reward magnitude: 25 vs. 5)×2 (valence: gain vs. loss)×3 (scalp side: left vs. middle vs. right)×2 (row of electrodes: CP row vs. P row) repeated-measures ANOVA. The main effect of reward magnitude was significant, $F(1, 15)=25.95$, $p<0.001$, with more positive P300 responses to feedback with the large magnitude (13.11 μV) than to feedback with the small magnitude (11.60 μV). This effect interacted with expectancy, $F(1, 15)=11.91$, $p<0.005$, with the P300 being more positive for the large magnitude than for the small magnitude in the expected conditions (13.40 vs. 10.76 μV, $p<0.001$), but not in the unexpected conditions (12.44 vs. 12.82 μV, $p>0.1$). The main effect of valence was significant, $F(1, 15)=9.12$, $p<0.01$, with more positive P300 responses to positive feedback (12.94 μV) than to negative feedback (11.77 μV). This effect interacted also with expectancy $F(1, 15)=8.95$, $p<0.01$, with a larger valence effect in the expected conditions (12.85 vs. 11.31 μV, $p<0.005$) than in the unexpected conditions (13.04 vs. 12.22 μV, $p=0.085$). The valence effect also interacted with reward magnitude, $F(1, 15)=9.75$, $p<0.01$, with a larger valence effect in conditions with the large magnitude (13.90 vs. 12.32 μV, $p<0.005$) than in conditions with the small magnitude (11.99 vs. 11.21 μV, $p=0.061$). The main effect of magnitude expectancy (12.08 μV for the expected conditions vs. 12.61 μV for the unexpected conditions) approached significance, $F(1, 15)=3.30$, $p=0.089$.

The main effect of scalp side was significant, $F(2, 30)=8.08$, $p<0.05$, with the P300 being larger in the midline (13.63 μV) than at the left (11.22 μV) or the right (12.22 μV) side. The main effect of the row of electrodes was also significant, $F(1, 15)=9.18$, $p<0.01$, with more positive P300 responses at the CP row (13.49 μV) than at the P row (11.21 μV). Analyses of the P300 amplitudes on CPz, on which the amplitudes and effects were the maximal (see Fig. 1), obtained the same pattern of effects as the above electrode group analyses.

2.3. *The FRN results*

To remove the potential influence of the P300 upon the measurement of the FRN, the ERPs were filtered with 2–20 Hz bandpass. Mean amplitudes in the 250–350 ms time window post-onset of feedback, defined through visual inspection, were entered into a 2 (magnitude expectancy)×2 (reward magnitude)×2 (valence)×3 (scalp side)×2 (row of electrode) repeated-measures ANOVA. There was a small but significant main effect of magnitude expectancy (Fig. 2), $F(1, 15)=9.45$, $p<0.01$, with more negative-going ERP responses when the reward magnitude was unexpected (0.35 μV) than when it was expected (0.78 μV). This effect interacted with scalp side, $F(2, 30)=5.96$, $p<0.01$, with the effect being larger in the midline than on the left or right hemisphere. A significant main effect of reward magnitude was also observed, $F(1, 15)=12.56$, $p<0.01$, with more negative-going ERP responses when the reward magnitude was small (0.30 μV) than when it was large (0.82 μV). This effect interacted with row of electrode, $F(1, 15)=8.15$, $p<0.05$, with the effect being larger at the Fz row than at the FCz row.

Not surprisingly, the main effect of reward valence was significant as well, $F(1, 15)=22.49$, $p<0.001$, with more negative-going ERP responses to negative outcomes (0.18 μV) than to positive outcomes (0.94 μV). This effect also interacted with scalp side, $F(2, 30)=6.66$, $p<0.01$, and with row of electrode, F

Fig. 1 – Grand-average event-related potential (ERP) waveforms on the anterior (F3, FC3, Fz, FCz, F4, and FC4) and posterior (CP3, P3, CPz, Pz, CP4, and P4) electrodes as a function of reward valence, magnitude and expectancy. Feedback stimulus onset occurred at 0 ms. The analyses of the FRN and the P300 effects were conducted using ERPs on the anterior and posterior electrodes, respectively.

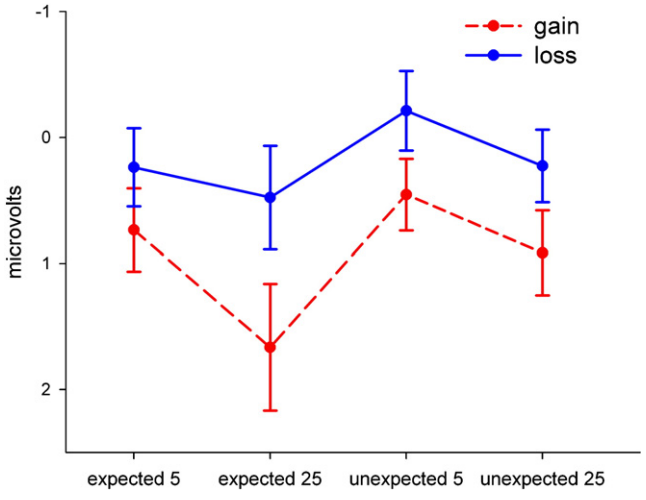


Fig. 2 – The mean FRN amplitudes in the 250–350 ms time window post-onset of feedback after the 2–20 Hz bandpass filtering. The values reported are collapsed over ERP responses on the 6 anterior electrodes (F3, FC3, Fz, FCz, F4, and FC4). Standard errors are also depicted.

(1, 15)=8.85, $p<0.01$, with the FRN effect being larger in the midline than on the left or right hemisphere and being larger at the Fz row than at the FCz row. There was a three-way interaction between magnitude expectancy, reward magnitude and valence, $F(1, 15)=6.72$, $p<0.05$, but no two-way interactions between these variables. This three-way interaction was mainly caused by the surprisingly more positive ERP responses to the expected large gain (see Fig. 2). Separate analyses of ERP responses to loss feedback found a significant main effect of magnitude expectancy, $F(1, 15)=10.45$, $p<0.01$, and a main effect of reward magnitude, $F(1, 15)=5.37$, $p<0.05$. Importantly, the interaction between magnitude expectancy and reward magnitude was not significant, $F(1, 15)<1$, indicating that the three-way interaction in the overall analysis was not caused by the variation of ERP responses in loss trials. Analyses of ERP responses to positive feedback obtained also a significant main effect of magnitude expectancy, $F(1, 15)=6.44$, $p<0.05$, and a main effect of reward magnitude, $F(1, 15)=13.29$. $p<0.005$. But unlike the loss trials, the interaction between magnitude expectancy and reward magnitude approached significance, $F(1, 15)=4.35$, $p=0.055$. It is clear from Fig. 2 that this interaction was caused by the more positive ERP responses to the expected large gain. Detailed analyses confirmed this observation. While the difference between the expected and the unexpected small gains was not significant, $F(1, 15)=2, 07$, $p>0.1$, the difference between the expected and the unexpected large gains was significant, $F(1, 15)=8.05$, $p<0.05$. Analyses of the FRN effects on Fz, on which the amplitudes and effects were the maximal, obtained the same pattern of effects as the above electrode group analyses.

3. Discussion

The ERP patterns of both the P300 and the FRN effects are very clear. The P300 peak amplitude was sensitive to both reward valence and reward magnitude. Moreover, this sensitivity was modulated by expectancy towards the reward magnitude, with the reward magnitude effect and the valence effect being either eliminated or reduced when the amount of reward was inconsistent with expectation built upon a preceding cue. The FRN amplitude, after bandpass filtering to reduce the influence of the P300, was modulated not only by reward valence, but also by reward magnitude and magnitude expectancy. In the following paragraphs, we discuss the functional significances of the P300 and the FRN in outcome evaluation, respectively.

3.1. *The role of P300 in differentiating good from bad outcomes*

The finding of a magnitude effect on the P300 replicated previous studies (e.g. Sato et al., 2005; Yeung and Sanfey, 2004). Importantly, we found a valence effect on the P300, with more positive amplitudes for positive outcomes than for negative outcomes. This finding is inconsistent with some of the previous studies (e.g. Sato et al., 2005; Yeung and Sanfey, 2004), but consistent with several other studies (Holroyd, 2004; Hajcak et al., 2005, 2007). It is possible that the failure of Yeung and Sanfey (2004) in observing the valence effect on the P300 was due to their use of a particular paradigm, in which the participant was first presented with the outcome of his choice and then the alternative outcome of the unselected action. They obtained a valence effect on the P300 for the latter, not for the former. In this design the participant could not judge whether he had made the best decision on the presentation of the choice outcome since the alternative outcome could even be better. For the present paradigm, the outcome was deterministic and there could be no comparison between this outcome and an alternative one. Although Sato et al. (2005) did provide the deterministic information concerning gain or loss in the feedback stage in their monetary gambling task, they did not provide information concerning the amount of gain or loss directly. The information of reward magnitude, which was provided as a cue at the beginning of the trial, had to be retrieved from working memory. It is possible that, in this case, the gain or loss information was encoded efficiently by the FRN and the attentional resources, represented by the P300, were devoted to retrieve and encode information of the amount of reward, rather than the valence of reward. In the present experiment, the valence and the magnitude information was provided simultaneously by the feedback stimulus. It is thus easy for the P300 to encode this information in an integrated manner, showing both the magnitude and the valence effects.

The P300 effect has been reported in some previous studies for the processing of affective pictures, with a more positive P300 for affective stimuli than for neutral stimuli over the parietal sites (Briggs and Martin, 2009; Dolcos and Cabeza, 2002; Ito et al., 1998; Junghöfer et al., 2001; see Olofsson and Nordin, 2008 for a review). One may be inclined to relate the role of P300 in reward processing to that in affective information processing, since both types of stimuli are of affective significance. However, the P300 amplitude in outcome evaluation is stronger for positive than for negative feedback while the P300 is often reported to be stronger for

both negative and positive than for neutral information in affective picture processing (Briggs and Martin, 2009; Olofsson and Nordin, 2008), with little difference between the valenced information even after the arouse level of stimuli is controlled (Briggs and Martin, 2009; but see Conroy and Polich, 2007 for a slightly different pattern of the P300 effect). Moreover, studies on decision making have shown that losses loom larger than gains (Tversky and Khaneman, 1981), indicating that the arousal for a loss of a certain magnitude should be greater than the arousal for a gain of the same magnitude. If the P300 responds simply to the arousal level elicited by feedback stimuli in a monetary gambling task, we should have observed stronger P300 responses to negative outcomes than to positive outcomes.

Earlier studies using the oddball paradigm (Courchesne et al., 1977; Duncan-Johnson and Donchin, 1977; Johnson and Donchin, 1980) have consistently found that unexpected stimuli elicit stronger P300 responses. Studies employing gambling tasks also found that unexpected outcomes elicit stronger P300 responses than expected outcomes (e.g. Hajcak et al., 2005, 2007). However, in the present study, we failed to observe this sensitivity to the manipulation of expectancy towards reward magnitude even though the unexpected feedback was infrequently presented (20% of the total trials). There could be two reasons for this absence of probability effect on the P300. First, information concerning expectancy violation has already been coded by the preceding FRN (see below) and hence the neural system does not need to code it again on the P300. Second, the expectancy here was manipulated by inducing expectation towards the amount of reward, rather than towards the valence of reward. It is possible that the P300 encodes only the most significant properties of feedback when these properties are at different levels of relevance to one's self-interest.

Although expectancy towards the reward magnitude did not elicit a P300 effect, it did modulate the valence and the magnitude effects, with the absence of these effects when the magnitude of reward was inconsistent with expectation built upon a cue. This may indicate that the inconsistency captures attention such that the attentional resources allocated to other aspects of feedback, i.e., the valence and the magnitude, are reduced in this situation, resulting in the non-significant effect of valence or magnitude on the P300.

These findings suggest a role of the P300 in coding the motivational significance of reward (Nieuwenhuis et al., 2005). This coding enables the system to differentiate good from bad outcomes of decision making and to potentiate and optimize further actions. Our behavioral results showed that the participants were more likely to stay on the previous choice following positive as compared to negative feedback (see also Gehring and Willoughby, 2002; Yeung and Sanfey, 2004). However, the present study failed to find a statistical relation between the participants' P300 response to the current trial and the choice behavior in the next trial (the analysis of data was not reported here). The failure of finding this relationship was perhaps due to the totally random presentation of feedback, whose valence, magnitude, and the congruency with the cue were predetermined by the experimenter and were performance-independent. It is interesting to investigate in the future the relationship between the P300 amplitude and the subsequent choice behavior by employing intelligent programming, such as the reinforcement learning algorithm (e.g., Cohen and Ranganath, 2007).

3.2. *The FRN codes violation of expectancy*

The FRN results obtained in this study are generally consistent with those observed in previous studies on outcome evaluation. We found that feedback concerning monetary loss elicited a negative deflection at the frontocentral regions compared with feedback concerning monetary gain (Gehring and Willoughby, 2002; Holroyd and Coles, 2002; Holroyd, 2004; Nieuwenhuis et al., 2004; Miltner et al., 1997; Yu and Zhou, 2006a, 2006b), irrespective of magnitude expectancy or reward magnitude. We found that the FRN effect (i.e., the difference between ERP responses to loss and gain trials in the 250–350 ms time window) was in general not modulated by reward magnitude (see also Sato et al., 2005; Yeung and Sanfey, 2004), nor by expectancy towards the magnitude of reward, although there was a three-way interaction between reward valence, magnitude expectancy and reward magnitude due to the surprisingly more positive ERP responses to the expected large gain (see Fig. 2).

Interestingly, however, we found that violation of expectancy towards the magnitude of reward elicited an FRN effect. This novel finding extended the reinforcement learning theory of the FRN (Hajcak et al., 2007; Holroyd and Coles, 2002), which is built upon work done by Schultz et al. (1997) and which suggests that the FRN reflects the coding of prediction error. According to this theory, the FRN reflects the impact of the midbrain dopamine signals on the anterior cingulate cortex (ACC). The phasic decreases in dopamine inputs elicited by negative prediction errors (i.e., "the result is worse than expected") give rise to the increased ACC activity that is reflected as larger FRN amplitudes. The phasic increases in dopamine signals elicited by positive prediction errors (i.e., "the result is better than expected") give rise to decreased ACC activity that is reflected as smaller FRN amplitudes (Holroyd and Coles, 2002; Nieuwenhuis et al., 2004). The FRN effect for reward expectancy could be taken as evidence that the prediction error can be defined not only in terms of the valence of the outcome but also in terms of whether the outcome fits the pre-established, non-valenced expectancy. This more abstract definition of prediction error may open a new way to think of the functional significance of the FRN, suggesting that the FRN may reflect the detection of conflict between expectancy and the actual outcome, irrespective of on what attribute the expectancy is built. Indeed, in a previous study we demonstrated that the FRN is sensitive to the conflict between perceptual representations in working memory (Jia et al., 2007). Using a "guessing-confirmation" task in which the participant guessed whether the first stimulus (S1) would have the same color as the subsequently presented second stimulus (S2), this study showed that the FRN to S2, which served as feedback to the guessing, was affected not only by whether the guessing was correct, but also by whether S1 and S2 had the same color. The incongruency between perceptual properties of the stimuli

would reduce the size of the FRN effect for the correctness of guessing.

Previous studies using the base-to-peak measurement of the FRN suggest that the FRN is insensitive to reward magnitude (Hajcak et al., 2006; Holroyd et al., 2006; Sato et al., 2005; Toyomaki and Murohashi, 2005; Yeung and Sanfey, 2004). However, another study using the loss-minus-gain difference parameterization of the FRN found that the FRN effect is greater for monetary outcomes with large magnitude than for outcomes with small magnitude (Goyer et al., 2008). Using the mean amplitude of ERP responses in a time window together with the 2–20 Hz bandpass filtering, the present study also observed an effect of reward magnitude on the FRN. It is possible that different measurements have different sensitivities to the magnitude effect in the FRN. It is also possible that the manipulation of expectancy towards reward magnitude in this study highlighted the magnitude dimension, making it easier being encoded into the FRN.

An unresolved issue is why we observed a three-way interaction between reward valence, magnitude expectancy and reward magnitude. As can be seen in Fig. 2, this interaction was caused mainly by the most positive ERP responses to the expected large gain. Clearly, the finding of more positive responses to the expected large gain than to the unexpected large gain is inconsistent with the reinforcement learning theory of FRN, which would predict otherwise. Further studies are needed to replicate this finding and to manipulate expectancy based on properties other than the valence of reward.

4. Conclusion

Overall, this study provides further insights into the role of the P300 in outcome evaluation and reward processing. In particular, the P300 is sensitive to both feedback valence and reward magnitude. Moreover, this sensitivity can be modulated by expectancy towards reward magnitude, with the magnitude effect and the valence effect being either eliminated or reduced when the amount of reward is inconsistent with expectation. Furthermore, the FRN effect can be observed for the valence of reward, expectancy towards the magnitude of reward, and the magnitude of reward, suggesting that the FRN may function as a general mechanism that evaluates whether the outcome is consistent or inconsistent with expectancy, irrespective of on what attribute the expectancy is built.

5. Experimental procedures

5.1. *Participants*

Nineteen graduate students (6 females, aged between 22 and 26 years) at the Southeast University in China participated in the experiment. All the participants were right-handed and had no history of neurological or psychiatric orders. Each person received a basic pay of 30 yuan (about $4.5) for his/her participation, plus a bonus of about 10 yuan based on his/her performance in the task. Data from 3 participants were excluded due to excessive artifacts in EEG recording. The study was approved by the local research ethics committee.

5.2. *Design and procedure*

The experiment used a 2 (valence)×2 (reward magnitude)×2 (expectancy towards reward magnitude) factorial design, with the outcome being either positive (i.e., winning money) or negative (i.e., losing money), either a large amount of money (i.e., 2.5 yuan) or a small amount of money (0.5 yuan), either expected (i.e., reward being consistent with the cue) or unexpected (inconsistent with the cue). The expected trials were 80% of the total 1000 trials while the unexpected trials were 20%. Half of the trials had positive feedback, half negative; and half of the trials had the large reward feedback (i.e., 2.5 yuan), half the small reward feedback (i.e., 0.5 yuan).

Each trial began with the presentation of a cue (“25” or “5”), representing, in most cases, the amount of the money involved in the current round of gamble. Then two cards were presented for 800 ms at the center of the screen, side by side. The participant was informed that one card represented “winning” and the another “losing”, and his/her task was to chose the winning card using whatever strategies he/she could appeal to. The participant was instructed to press the left or the right key of a joystick with his/her left or right index finger to indicate the card he/she selected, which would then flash for 500 ms, by thickening the frames of the card, to confirm the selection. Finally, a feedback stimulus appeared at the center of the screen for 1000 ms that informed the participant of the outcome of the current gamble. This stimulus could be either “+25” or “+5”, indicating “winning”, or “−25” or “−5”, indicating “losing”. The participant was told that he/she would be rewarded or penalized the amount of money indicated by the feedback.

Unknown to the participant, different types of trials were pseudo-randomized in the sequence and the feedback were predetermined, with the restrictions that no more than 4 consecutive trials were winning or losing and no more than 4 consecutive trials were from the same experimental condition. The total 1000 trials were divided into 10 blocks. Different orders of the blocks were created with a Latin square design and each participant received one particular order. The presentation of stimuli and recording of the participant’s responses were controlled by Presentation software (Neurobehavioral Systems, Inc.).

5.3. *EEG recording*

EEGs were recorded from 64 scalp sites using tin electrodes mounted in an elastic cap (NeuroScan Inc. Herndon, Virginia, USA) according to the International 10/20 system. Eye blinks were recorded from left supraorbital and infraorbital electrodes. The horizontal electro-oculogram (EOG) was recorded from electrodes placed 1.5 cm lateral to the left and right external canthi. The linked bilateral mastoids served as the reference point and the GND electrode on the cap served as ground. During recording, all activities were referenced to the averaged mastoids. Electrode impedance was kept below 5 kΩ. The biosignals were amplified with a bandpass from 0.05 Hz to 70 Hz and digitized at 500 Hz for offline analysis. Ocular

artifacts were corrected with an eye-movement correction algorithm. Separate EEG epochs of 800 ms (together with 200 ms pre-stimulus baseline) were extracted offline, time-locked to the onset of feedback. Epochs were baseline-corrected by subtracting from each sample the average activity of that channel during the baseline period. All trials in which EEG voltages exceeded a threshold of ±60 μv during recording were excluded from further analysis. The EEG data were low-pass filtered below 30 Hz.

5.4. *ERP analysis*

The P300 was defined as the most positive peak in the 250–600 ms time window following the feedback onset. To minimize overlap between the FRN and other ERP components, we offline filtered the EEG data through a zero phase shift with 2–20 Hz bandpass. The FRN was then defined as the mean amplitude in the 250–350 ms time window post-onset of feedback. The P300 and the FRN were statistically evaluated, with reward valence, magnitude expectancy, and reward magnitude as three critical factors and electrodes as topographic factors. For the P300, the electrodes CP3, P3, CPz, Pz, CP4, and P4 were included. For the FRN, the electrodes of F3, FC3, Fz, FCz, F4, and FC4 were included. Data were analyzed with repeated-measures analysis of variance (ANOVA). The Greenhouse–Geisser adjustment for non-sphericity was used where appropriate. Bonferroni correction was used for multiple comparisons.

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