Rapid Processing of Both Reward Probability and Reward Uncertainty in the Human Anterior Cingulate Cortex

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1 D l P , S C N l U , G , C , **2** D l P C B C S , P U , B , C , **3** D l O C l l S , N A l , U M M C J , M , U S Al , **4** K L M P , M E , P U , B , C

Abstract

R l l . W S (ACC) l ACC. l (FRN), (ERP), ACC R FRN FRN l . T ACC. l ACC.

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Introduction

Reward probability and uncertainty are essential parameters in the computation of the utility function of a behavior choice [1,2]. Whereas reward probability crucially determines the expected reward value associated with a behavior choice, reward uncertainty, i.e., the variance of the probability distribution, provides an estimate of the risk associated with the same choice. In non-human primates, substantial evidence indicates that the midbrain dopamine neurons encode the reward prediction signal that is based on reward probability, as well as the reward prediction error signal that is the difference between the actual and expected reward [3–5]. The cues that predict higher reward probabilities evoke larger phasic activations in the midbrain dopamine neurons. Whereas the outcomes that are better than predicted (positive prediction errors) evoke phasic activations in the dopamine neurons, the outcomes that are worse than predicted (negative prediction errors) evoke phasic inhibitions. In a seminal study, Fiorillo et al. (2003) further showed that the midbrain dopamine neurons encode reward uncertainty in their tonic discharges. Recent fMRI studies reported similar encoding of reward probability and uncertainty in the human midbrain regions [6,7].

The anterior cingulate cortex (ACC) receives projections from the midbrain dopaminergic regions and has been proposed to play

reward probability and uncertainty in fMRI and the evidence for the link between the FRN and the ACC [8–13], we predicted that the FRN amplitude would be modulated by both reward probability and uncertainty.

aterials and ethods

P

Sixteen undergraduate students (8 male; mean age 22±2.5 years) participated in the gambling experiment. They were told that their performance in the gambling task determined how much they would be awarded or penalized on the top of a base payment of 40 yuan (about US $6). Written, informed consent was obtained from each participant, and the study was approved by the Academic Committee of the Department of Psychology at Peking University.

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We used a modified version of a gambling task in which reward probability and uncertainty were manipulated parametrically [14–16] (Fig. 1). In each trial, participants were first presented with the back side of two cards that were drawn without replacement randomly from a deck of nine cards numbered between 2 to 10. They were asked to guess within 3000 ms which card had a larger number in order to win 0.5 yuan. A 0.5 yuan penalty was imposed for late response. Participants were explicitly informed about this rule and a visual feedback ''too late, lose 0.5 yuan'' was presented to participants if they failed to respond within 3000 ms. At 700 ms after participants' response, the chosen card (called cue card) was presented for 1000 ms. The winning probability was indicated by the number of the cue card ranging from 2 to 10, which corresponded to the winning probability of 0, 0.125, 0.25, 0.375, 0.5, 0.675, 0.75, 0.875, and 1, respectively. Participants were explicitly informed of these probabilities. At 700 ms after the offset of the cue card, a sign of ''+50'' or ''−50'' was presented for 1000 ms to indicate a win (and 0.5 yuan reward) or loss (and 0.5 yuan penalty) trial, respectively. We only presented the numeric feedback without showing the original two cards in order to control for the visual property of feedback stimuli. The next trial began 1000 ms after the offset of the feedback in the previous trial. The experiment consisted of 9 blocks of 96 trials with each cue card being presented a total of 96 times. For each cue condition, the proportion of trials for the win or loss outcome followed exactly the probability indicated by the cue number. For example, for the cue card 3, 12.5% trials would give the win feedback and 87.5% trials the loss feedback. There was a short break between blocks.

For each condition, reward probability was indicated by the number in the cue card, as we pointed out earlier. There are

electrode recordings were referenced to an electrode placed on the left mastoid. The EEG and EOG were band-pass filtered (0.05∼70 Hz), sampled at 500 Hz and stored in hard disks for off-line analysis.

Ocular artifacts were corrected with an eye-movement

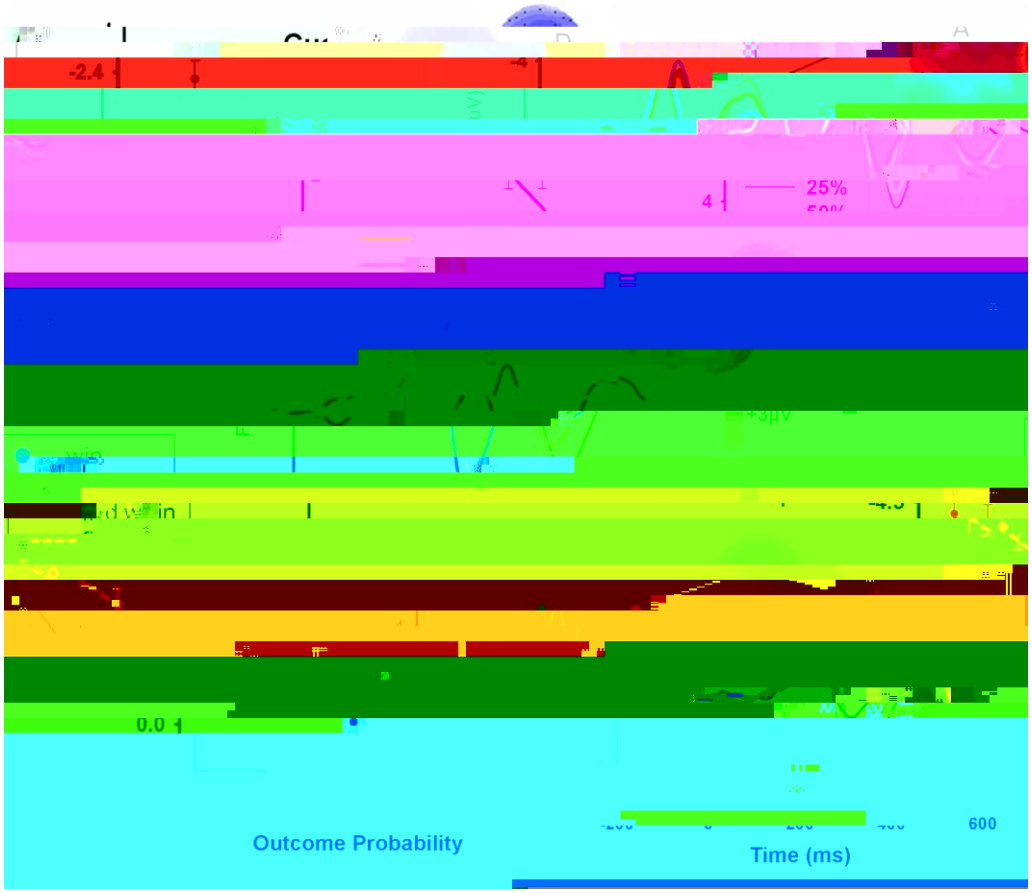

Figure 2. Grand-average ERP waveforms from channel *Fz*. ERPS were time locked to (A) the cue phase, (B) win outcome condition, and (C) loss outcome condition. P . . . . . I . . . . . T . . . . . I . . . . . F. . . I . , 25% . . . . . 25% . . . . . 25% . . . . . 75% . . . . . F. . . . . I . . . . . 25%, 50%, 75%, . , 100% . . . . . T. . . . . I . . I . . FRN 300I . . . . . (D) C . . . . . FRN, . , (E) . . I . . . . FRN. T. . . . . I . . . . . :10.1371/. 0029633. 002

high uncertainties (Fig. 2D). The proportion of the variance explained by the model was high, with $R^2 = 0.73$, $p = 0.019$. Note, the uncertainty effect might be interpreted with caution, as the effect may predominately driven by the P = 1 condition. After taking out the P = 1 condition, there was no significant correlation between FRN amplitude and reward probability or uncertainty (P values >0.05).

For the interval 250–325 ms post-cue (Table 2), regression analysis revealed that both probability coefficient (0.565 ± 0.26) and uncertainty coefficient (-0.789 ± 0.23) were significantly different from zero ($t = 2.17$, $p = 0.073$ for probability, and $t = -3.33$, $p = 0.014$ for uncertainty). The explanation power was the same as the model on FRN data in the interval of 275–325 ms post-cue.

O . . I . -. . . FRN

ANOVA with two types of outcomes (win/loss) and 8 levels of probabilities revealed a significant main effect of valence, $F(1,15) = 16.39$, $P = 0.001$, a significant main effect of probability, $F(7,105) = 12.91$, $P < 0.001$, and a significant interaction between valence and probability, $F(7,105) = 5.37$, $P = 0.002$, suggesting that the effects of outcome probability on FRN amplitude differ in win and loss domain.

Table 2. T. . . . . (2.)TJ 428.3.865.8(. .)-27495.949128.38.31

For win outcomes, tests of within-subjects contrasts revealed a significant linear main effect, $F(1,15) = 32.90$, $P<0.001$, and a significant quadratic, $F(1,15) = 7.56$, $P = 0.015$, suggesting that win-evoked FRN encode both reward probability and uncertainty, when examined separately. Consistent with the ANOVA analysis, regression analysis revealed that the win-evoked FRN (Fig. 2B) was significantly modulated by positive prediction error, $t(7) = -8.20$, $p<0.001$, and uncertainty prediction error, $t(7) = 7.89$, $p = 0.001$, with a coefficient of -2.596 ± 0.32 and 2.234 ± 0.28 for positive prediction error and uncertainty prediction error, respectively (Fig. 2E, in blue. Note, the outcome probability in this figure refers to the actual outcome frequency, as explained in the figure caption). The regression coefficient associated with positive prediction error indicated that the FRN had larger amplitudes for infrequent win feedback, whereas the regression coefficient associated with uncertainty prediction error indicated FRN amplitudes were larger for the win outcome with lower reward uncertainty. The proportion of the variance explained by the model was very high, with $R^2 = 0.947$, $p = 0.001$.

In the loss condition, tests of within-subjects contrasts revealed a significant linear main effect, $F(1,15) = 9.71$, $P = 0.007$, and a non-significant quadratic, $F(1,15) = 2.94$, $P = 0.107$, suggesting that loss associated FRN encode reward probability but not uncertainty. In consistent with the ANOVA analysis, regression analysis revealed that the loss-evoked FRN (Fig. 2C) was significantly modulated by negative prediction error, $t(7) = 7.70$, $p = 0.001$, with a coefficient of -4.795 ± 0.62, but not by uncertainty prediction error (the coefficient was 1.011 ± 0.56, $t(7) = 1.81$, $p = 0.130$). The proportion of the variance explained by the model was high, with $R^2 = 0.93$, $p = 0.001$ (Fig. 2E, in red). Note, the regression coefficients associated with reward prediction error were negative for both win-evoked FRN and loss-evoked FRN, suggesting that infrequent outcome evoked stronger negative-going FRN in both win and loss domains.

S[illegible] FRN

In the cue condition, the resulting five-source model accounts for the data with a residual variance of 4.86% (Fig. 3A) and the source of the cue-evoked FRN was located in the site of ACC ($x = 10$, $y = 5$, $z = 37$). In the win outcome condition, the resulting five-source model accounts for the data in the period 0 to 350 ms post onset of win feedback with a residual variance of 4.85% and the source of the win-evoked FRN was also located in the site of ACC ($x = 5$, $y = -2$, $z = 37$). The same model for the win condition also accounts for the ERP data in the loss condition with a residual variance of 4.74%, suggesting that win and loss ERPs have the same sources (Fig. 3B). Thus the dipole source analysis further indicated an involvement of the ACC in the rapid processing of reward probability and uncertainty signals.

Discussion

In this study, the FRN, as an indicator of the ACC activity, was measured in a simple gambling task in which reward probability and uncertainty could be dissociated. We provided, for the first time to our knowledge, a quantitative analysis of the encoding of reward probability and uncertainty in the human ACC. Our results suggest that the cue-evoked FRN may encode reward probability and uncertainty. While both win and loss-related FRN amplitudes decreased as a function of outcome probability, only the win-related FRN but not the loss-related FRN was modulated by reward uncertainty. These results provide new insights into the functions of the ACC in reward decision making.

Previous ERP studies have examined the encoding of reward probability in the ACC. They only used limited number of probability values (i.e. 25%, 50%, and 75%) and yielded inconsistent findings [22,24–26]. Two studies found that negative