

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

Rongjun Yu^{1,2}, Wu Zhou³, Xiaolin Zhou^{2,4*}

1 Department of Psychology, South China Normal University, Guangzhou, China, **2** Department of Psychology and Center for Brain and Cognitive Sciences, Peking University, Beijing, China, **3** Departments of Otolaryngology and Communicative Sciences, Neurology and Anatomy, University of Mississippi Medical Center, Jackson, Mississippi, United States of America, **4** Key Laboratory of Machine Perception, Ministry of Education, Peking University, Beijing, China

Abstract

Reward probability and uncertainty are two fundamental parameters of decision making. Whereas reward probability indicates the prospect of winning, reward uncertainty, measured as the variance of probability, indicates the degree of risk. Several lines of evidence have suggested that the anterior cingulate cortex (ACC) plays an important role in reward processing. What is lacking is a quantitative analysis of the encoding of reward probability and uncertainty in the human ACC. In this study, we addressed this issue by analyzing the feedback-related negativity (FRN), an event-related potential (ERP) component that reflects the ACC activity, in a simple gambling task in which reward probability and uncertainty were parametrically manipulated through predicting cues. Results showed that at the outcome evaluation phase, while both win and loss-related FRN amplitudes increased as the probability of win or loss decreased, only the win-related FRN was modulated by reward uncertainty. This study demonstrates the rapid encoding of reward probability and uncertainty in the human ACC and offers new insights into the functions of the ACC.

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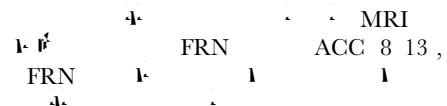
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* E-mail: xz104@pku.edu.cn

Introduction

Reward probability and uncertainty are two fundamental parameters of decision making. Whereas reward probability indicates the prospect of winning, reward uncertainty, measured as the variance of probability, indicates the degree of risk. Several lines of evidence have suggested that the anterior cingulate cortex (ACC) plays an important role in reward processing. What is lacking is a quantitative analysis of the encoding of reward probability and uncertainty in the human ACC. In this study, we addressed this issue by analyzing the feedback-related negativity (FRN), an event-related potential (ERP) component that reflects the ACC activity, in a simple gambling task in which reward probability and uncertainty were parametrically manipulated through predicting cues. Results showed that at the outcome evaluation phase, while both win and loss-related FRN amplitudes increased as the probability of win or loss decreased, only the win-related FRN was modulated by reward uncertainty. This study demonstrates the rapid encoding of reward probability and uncertainty in the human ACC and offers new insights into the functions of the ACC.



Materials and Methods

Participants

S = 16 (8 female); T = 22 ± 2.5 years; 40 (US \$6). A = C, D, P, T, P. U.

Experimental design

16 (F, 1). I = 1, 2, 10. T = 3000 ms, A = 0.5, A = 0.5, A = 700 ms, 1000 ms, T = 2, 10, 0, 0.125, 0.25, 0.375,

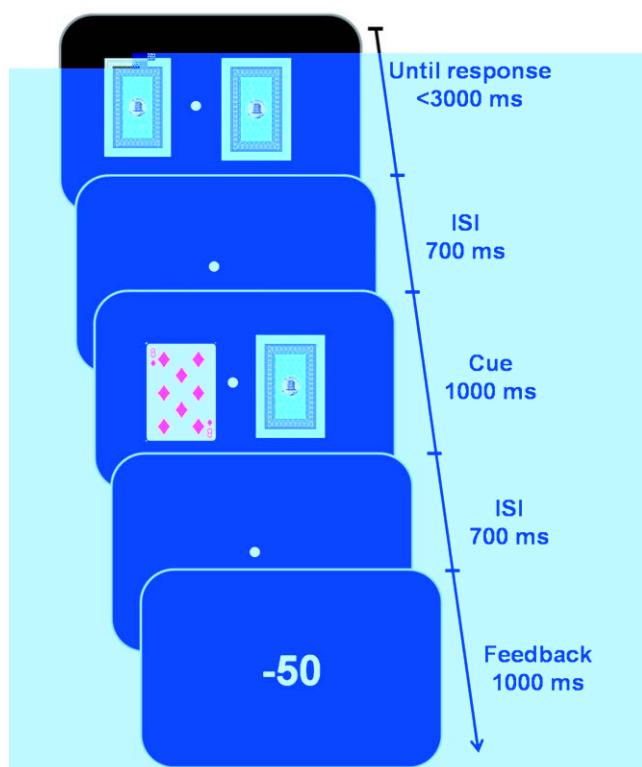
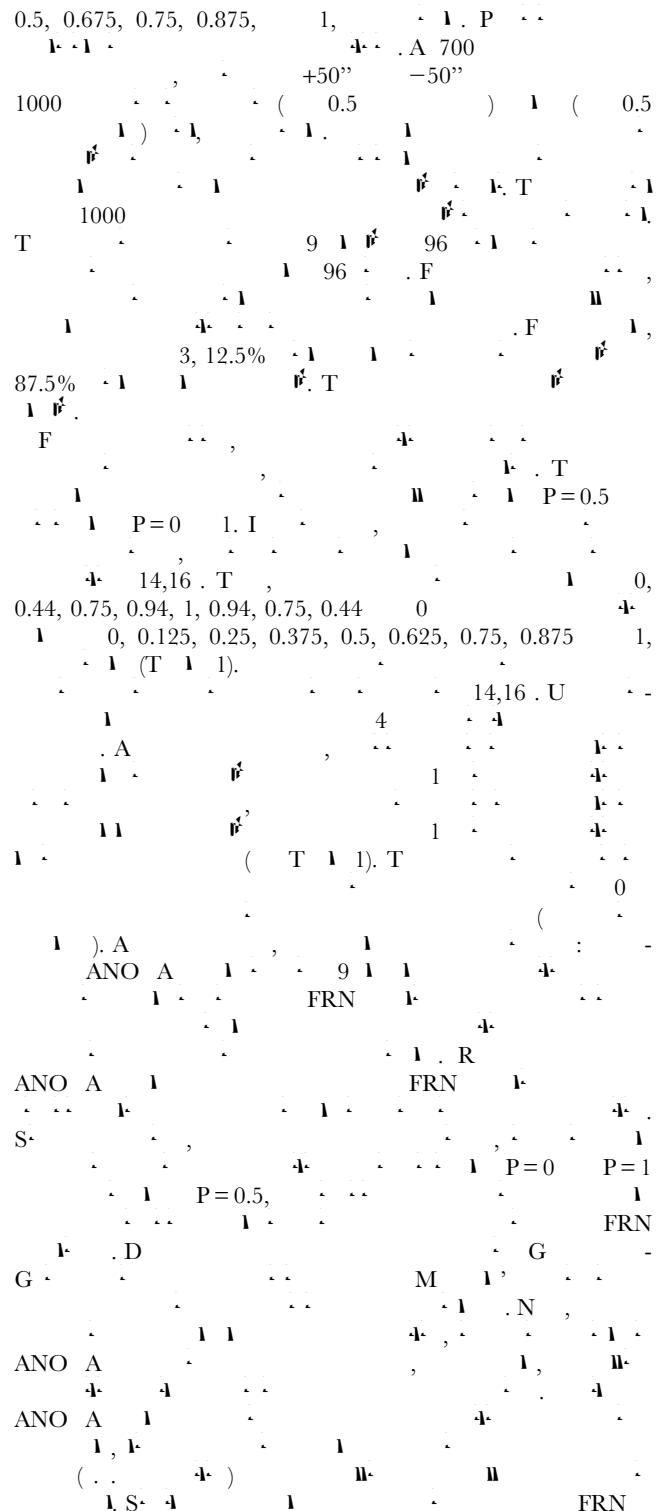


Figure 1. Illustration of events and timing in a single trial.
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ERP recording and analysis

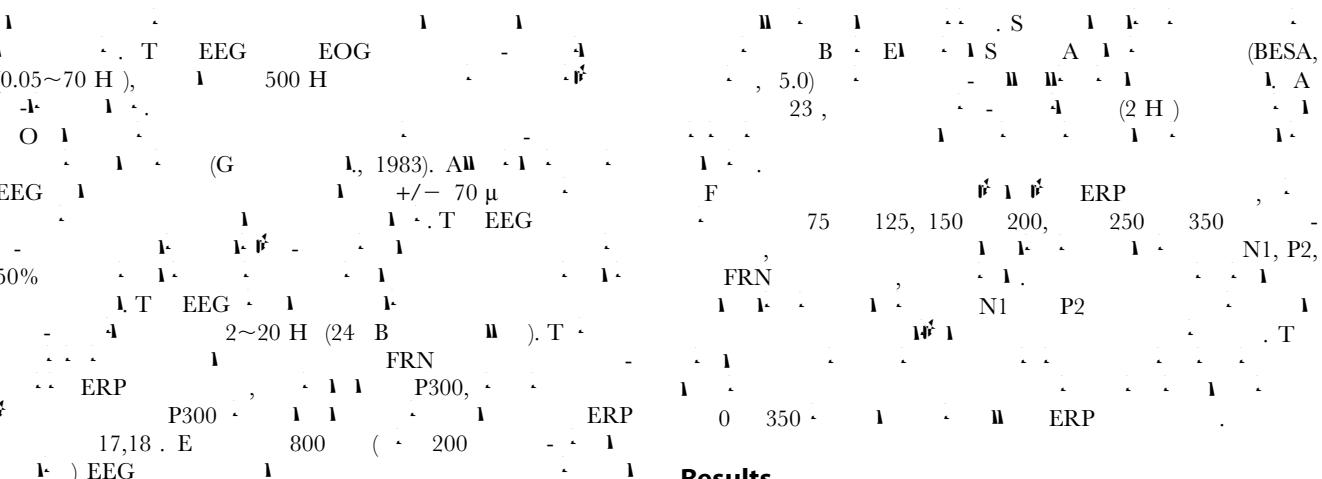
EEG: 64 channels, 10/20 system, (Neurosoft Inc., USA). T = 5 KΩ. EOG: (EOG) 1.5 ms. All

Table 1. The win probability and uncertainty for each of the nine conditions at the cue phase and the reward prediction error and uncertainty prediction error associated with win and loss outcomes.

Cue phase				Actual wins in the outcome phase			Actual losses in the outcome phase		
Cue number	Win probability	Uncertainty	FRN amplitude	Positive PE	Uncertainty PE	FRN amplitude	Negative PE	Uncertainty PE	FRN amplitude
2	0	0	-1.859	N/A	N/A	N/A	0	0	-1.252
3	0.125	0.438	-1.785	0.875	0.438	-2.696	0.125	0.438	-0.854
4	0.25	0.75	-2.346	0.75	0.75	-1.907	0.25	0.75	-0.743
5	0.375	0.938	-1.749	0.625	0.938	-0.807	0.375	0.938	-1.487
6	0.5	1	-1.985	0.5	1	-0.532	0.5	1	-2.617
7	0.625	0.938	-1.876	0.375	0.938	-0.044	0.625	0.938	-3.27
8	0.75	0.75	-1.641	0.25	0.75	-0.743	0.75	0.75	-3.943
9	0.875	0.438	-1.667	0.125	0.438	-0.838	0.875	0.438	-4.232
10	1	0	-0.889	0	0	-1.338	N/A	N/A	N/A

Grand mean FRN amplitudes (μ V) during the interval 275–325 ms post-cue across participants are also presented. PE = prediction error.

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Results

Cue-evoked FRN

FRN amplitude (T = 275, 325 ms) was analyzed using a two-way ANOVA (cue condition: Win, Loss; electrode: Fz, T7, T8, A1, A2, 2A). The main effect of cue condition was significant, $F(1,120) = 3.57, p = 0.016$, $F(1,120) = 5.33, p = 0.036$, $F(1,15) = 3.28, P = 0.09$. The main effect of electrode was significant, $F(4,120) = 2.25, p = 0.049$, $F(4,120) = 2.25, p = 0.049$. The interaction between cue condition and electrode was significant, $F(4,120) = 5.874, p = 0.001$, $F(4,120) = 3.977, p = 0.065$, $F(4,120) = 10.657, p = 0.005$. The main effect of electrode was significant, $F(4,120) = 2.25, p = 0.049$, $F(4,120) = 2.25, p = 0.049$.

Dipole Analysis

A dipole analysis was conducted to examine the source of the FRN. The results showed a significant dipole source located in the right anterior region, $R = 0.745 \pm 0.24$, $T = -0.556 \pm 0.21$, $t = 3.08, p = 0.038$. The dipole source was located in the right anterior region, $R = 0.745 \pm 0.24$, $T = -0.556 \pm 0.21$, $t = 3.08, p = 0.038$.



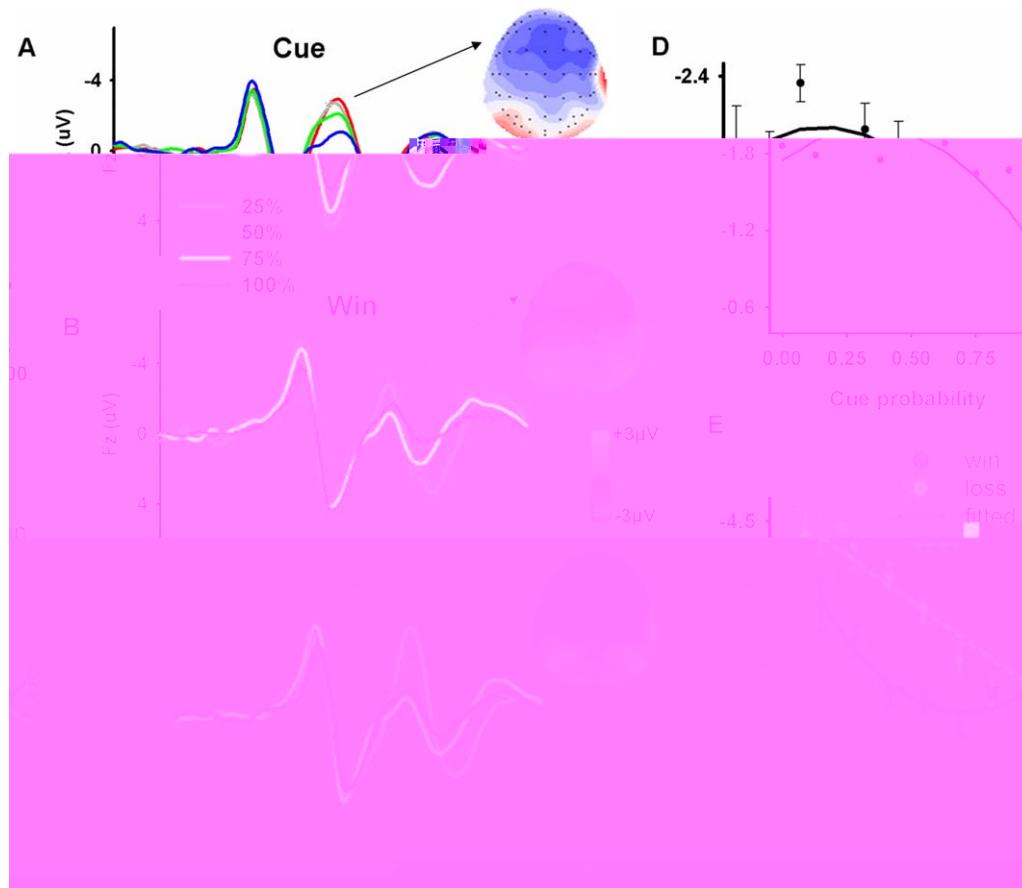


Figure 2. Grand-average ERP waveforms from channel Fz. ERPS were time locked to (A) the cue phase, (B) win outcome condition, and (C) loss outcome condition. Please note, the outcome probability used in this figure refers to the actual outcome frequency. Thus low probability indicates that the outcome is infrequent. For example, 25% probability in win condition refers to 'actual win after the prediction of 25% winning probability', whereas 25% probability in loss condition refers to 'actual loss after the prediction of 75% winning probability'. For clarity, only waveforms for probabilities of 25%, 50%, 75%, and 100% are presented. The topographic map of mean FRN at 300ms in the cue, win, and loss conditions were also shown. (D) Coding of reward probability and reward uncertainty in cue-evoked FRN, and (E) outcome-evoked FRN. The regression lines were computed based on the regression equations for each condition.

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Table 2. The win probability and uncertainty for each of the nine conditions at the cue phrase.

Cue number	Winning probability	Uncertainty	FRN amplitude
2	0	0	-1.859
3	0.125	0.438	-1.785
4	0.25	0.75	-2.346
5	0.375	0.938	-1.749
6	0.5	1	-1.985
7	0.625	0.938	-1.876
8	0.75	0.75	-1.641
9	0.875	0.438	-1.667
10	1	0	-0.889

Grand mean FRN amplitudes (μ V) during the interval 250–325 ms post-cue across participants are also presented.

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Source analysis of the FRN

Discussion

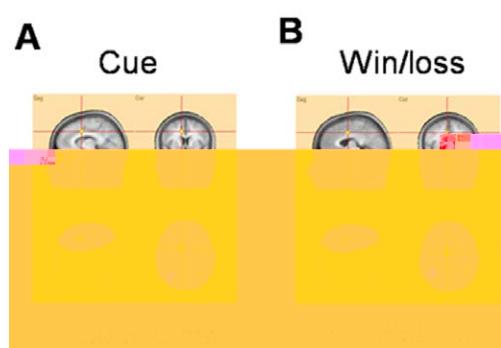
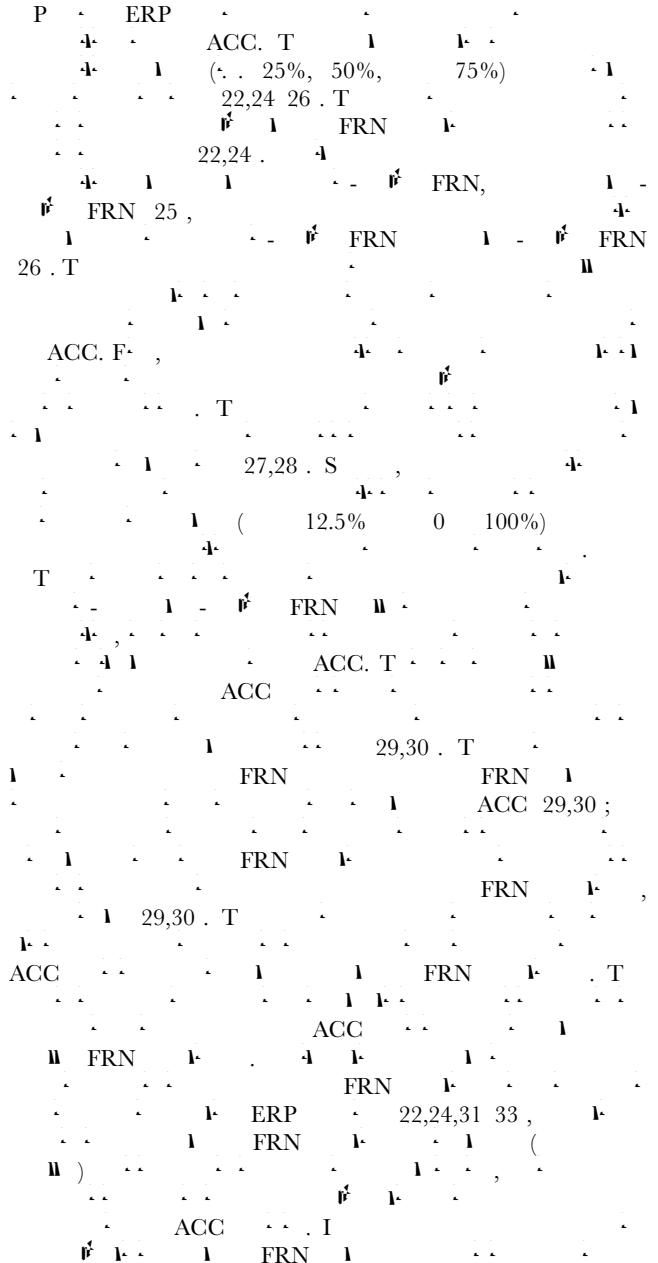


Figure 3. Sagittal, transversal, and coronal views of dipoles. Dipoles were superimposed on MRI-based head models for grand-average ERP waveforms in (A) cue phase and (B) outcome (win/loss) phase.
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References

Author Contributions

$$C \quad : \quad R \quad A \quad I \quad : \quad R \quad C \quad P$$

$\downarrow A / \quad \downarrow A \quad \downarrow A : R \quad \quad \quad \downarrow R$

