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How an uncertain cue modulates subsequent monetary outcome evaluation: An ERP study

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ABSTRACT

People avert uncertain situations more than certain ones, and the neural correlates of such acts have gained increasing attention in past decade. However, the electrophysiological bases of how subjects respond to uncertain cues, and how such cues affect subsequent outcome evaluations have rarely been explored. In the present study, participants completed a gambling task while their neural activities were recorded through electroencephalography. The results indicated that subjects were sensitive to the uncertain cue as represented by feedback-related negativity (FRN). This uncertain cue further enhanced the neural response to outcome evaluation represented by P200, FRN, and P300 temporally. The enhanced P200 outcome may reflect the negative bias of the emotional reaction, which is a reflection of uncertain deviation at an early stage. The discrepancies of differentiated feedback-related negativity between uncertain and certain condition indicated increased motivation or prediction error toward the outcome. Finally, the increased P300 amplitude under uncertain outcome compared with certain one, as well as its sensitivity to the valence of the outcome under uncertain condition, embodies the increased arousal of the affective response. Therefore, uncertain cue effects observed in the current study suggest that uncertainty induces a larger motivational/affective and expectation response toward outcome revelation.

1. Introduction

Human beings have a natural inclination to avert outcomes lacking in probabilities [5,22], a situation referred to as ambiguous [7], as opposed to risk situation with informed probabilities. In actual situations, reactions vary from certainty, to risk, and ambiguity with different degrees of uncertainty.

Previous neuroimaging studies found that risk and ambiguity are processed separately in the brain. In a pioneering paper, Hsu et al. [10] found that ambiguity option activates the amygdala and the orbito-frontal cortex, while the risk option activates the striatal system. According to a follow-up study, the activation of the lateral prefrontal cortex is associated with ambiguity preference, whereas that of the posterior parietal cortex is predicted by risk preference [11]. Furthermore, Bach et al. [2] found that more brain areas (i.e., posterior inferior frontal gyrus and posterior parietal cortex) are activated under ambiguity option compared with risky ones. To explore the diversity of the different degrees of uncertainty, Sarinopoulos et al. [20] recently reported uncertain cue can affect human perception of subsequent aversive pictures, and found that subjects are inclined to overestimate the frequency of the aversive pictures after uncertain cues. Two negative emotion-related brain regions, the insula and amygdala, are also involved in neural responses toward emotional pictures following uncertain cues. The activation of both the insula and the amygdala negatively correlates with the anterior cingulated cortex (ACC) activity elicited by an uncertain cue during uncertain expectation.

Accordingly, uncertain cues affect subsequent monetary gain and loss perception. Although there are many works on ambiguity and risk, the temporal dynamics of such an issue is still an open question. Applying event-related brain potential (ERP), we designed a gambling task named "Wheel of Fortune" to explore how an uncertain cue is processed neurally, and how this cue modulates subsequent monetary outcome evaluation.

Past studies have demonstrated that ERP components, feedback-related negativity (FRN) and P300, are recruited in decision making under uncertainty. Previous electroencephalograph (EEG) research suggested that FRN is involved in the performance and error monitoring and monetary loss outcome processing. FRN is a negative reflection of ERP, approximately peaking between 200 and 300 ms after revelation of an erroneous or unfavorable

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stimulus; it is also generated from ACC and its adjacent cortical areas, as revealed by source localization techniques [8,16]. Miltner et al. [14] first reported that FRN reflects the neural response of error monitoring. It also reflects an evaluation of the motivational and affective significance of events [8,24]. Due to the motivational impact of the outcome, FRN is sensitive to the loss relative to the gain outcome. According to reinforcement learning theory, which is initially proposed by Holroyd and Coles [9], the FRN reflects the impact of the phasic change of dopaminergic signals in the basal ganglia on ACC. The phasic activation in the midbrain decreases when the outcome turns out to be worse than expected, thereby resulting in dis-inhibition of the ACC activation as reflected by FRN. Nieuwenhuis et al. [16] reported that the amplitude of the FRN is sensitive to the prediction errors and the distinction between expected and realized outcome; and it is largest under unexpected negative outcome. Therefore, we predicted that the uncertain cue and subsequent outcome can elicit a larger FRN as opposed to certain conditions.

In addition to FRN, P300 represents different aspects of stimuli evaluation [24]. The P300 is a positive-polarity component most pronounced at the centro-parietal recording sites at about 300–600 ms after stimuli presentation. Nieuwenhuis et al. [15] assumed P300 originates from the locus coeruleus–noradrenergic system and its amplitude is sensitive to various aspects of stimuli, including the high-level motivational evaluation, attention allocation, and probability of occurrence. Furthermore, recent studies indicated that, in addition to motivational salience, the P300 is also sensitive to the valence of outcome and that gain elicits a larger P300 than that of corresponding loss [4]. Due to the effect of the uncertain cue as mentioned above, we predicted a larger P300 for outcomes after the unexpected cue.

2. Material and methods

2.1. Participants

A total of 22 participants (14 male, mean age = 22.2 years; SD = 1.72) from Zhejiang University in China were recruited for the experiment. All participants were right-handed, had normal or corrected-to-normal vision, and did not have any history of neurological or mental diseases. Informed consent was obtained from all participants in accordance with the guidelines of the Internal Review Board of Zhejiang University Neuromanagement Lab. Participants were given written instructions at the beginning of the experiment.

2.2. Experimental procedure

Placed in an electrically shielded room, the subjects sat in front of a 17-in. Philips CRT display at about a meter away. EEG was recorded throughout the experiment. Participants were required to play a game called "Wheel of Fortune" by pressing a button. Experimental stimuli were presented sequentially at the center of the CRT computer screen. The "wheel" with an arrow index in the center area was presented on the screen at the start of each trial. To improve subjects' involvement, subjects have 3 options to control the rotation speed: 1 for low speed, 2 for medium, and 3 for high. After the subjects pressed the button, the wheel immediately rotated at a speed chosen by the subjects for a variable duration of 1200–2600 ms. After a "blank" delay lasting from 400 to 600 ms, one of the three cues was presented after the rotation: "round" to indicate a certain gain, "triangle" to indicate a certain loss, and "?" to indicate uncertainty. One second after the cue presentation, the feedback was revealed for each cue, i.e., "+10" for a gain of 10 Yuan and "−5" for a loss of 5 Yuan. Outcome values of 10 and 5 Yuan were chosen for gain and loss, respectively, because past behavioral studies suggested that people are almost twice as sensitive to monetary losses as they are to gains [22]. Without the subjects' knowledge, the occurrence of the outcome after the uncertain cue was preprogrammed to have a 50/50 chance of gain or loss. The outcome results were counterbalanced throughout the experiment. To increase the sense of reality, we manipulated the program so that at the start of each trial, the arrow index on the rotating table always pointed to the result of the last trial. The inter-trial interval was 1 s (Fig. 1). The stimulus presentation, marker, and button response recording were controlled by E-prime2.0 software package. The experiment contained 4 blocks, each comprising 40 trials. Practice trials were administered before the formal experiment began. After the experiment, one trial from each block was selected. Subjects were informed in advance that they would be paid 30 RMB Yuan each as basic payment and an additional gain or loss based on the mean of outcome of the selected 4 trials, resulting in earnings approximately ranging from 25 to 40 Yuan (RMB) (mean = 32, SD = 4.0).

2.3. EEG data acquisition and analysis

EEG was recorded (band-pass 0.05–70 Hz, sampling rate 500 Hz) with Neuroscan Synamp2 Amplifier (Scan 4.3.1, Neurosoft Labs, Inc. Virginia, USA) using an elastic electrode cap with 64 Ag/AgCl electrodes in accordance with the international 10–20 system. All electrodes were referenced to the left mastoid first and digitally re-referenced to the linked mastoids reference later. Vertical and horizontal electrooculograms (EOGs) were recorded with two pairs of electrodes; one pair was placed above and below the left eye in parallel with the pupil and the other pair was placed 10 mm from the lateral canthi. Electrode impedance was maintained below 5 kΩ throughout the experiment.

The data of 2 male subjects were excluded because of excessive recording artifacts, leaving 20 subjects for final analysis. In off-line analysis, EOGs artifacts with ocular movements were corrected using the method proposed by Semlitsch et al. [21]. EEG recordings were segmented for the epoch from 200 ms before the onset of stimuli to 800 ms after this onset, with the pre-stimulus period as the baseline. Each set of raw EEG data was inspected visually for artifacts. Trials contaminated by amplifier clipping, bursts of electromyographic activity, or peak-to-peak deflection exceeding ±80 μV were excluded from averaging. The data were digitally low-pass filtered below 30 Hz (24 dB/Octave). The EEG epochs were averaged separately for outcome of certain, uncertain condition (uncertain_gain,

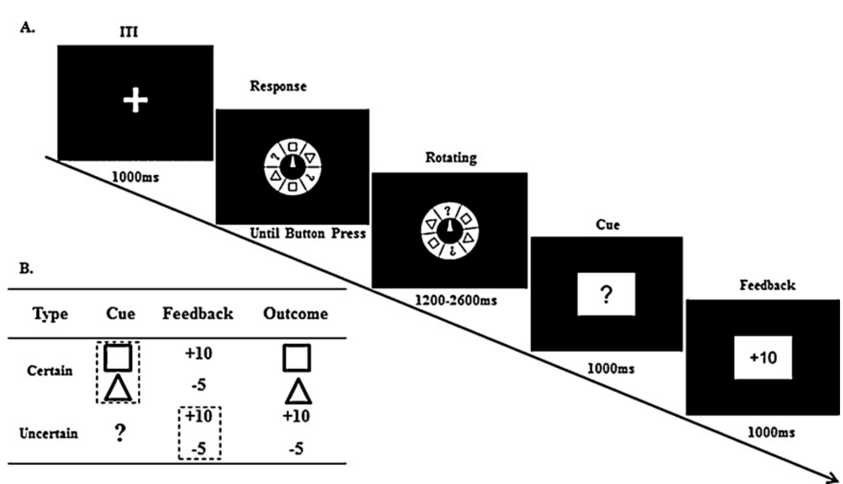

Fig. 1. Experimental schematic diagram. (A) Experimental paradigm. Subjects made decision with button press to select the preferred rotating speed of the wheel presented at the center of the screen. Then, they were informed the cue and feedback successively after a varied time of rotation. (B) Experimental conditions. At the cue stage, it consists of 2 conditions, one is certain which includes a sure win (indexed by a rectangle) and a sure loss (indexed by a triangle), the other is uncertain (indexed by a question mark). At the subsequent feedback stage, the corresponding results are revealed (column 3). In the EEG analysis, the different outcomes, i.e., the certain cues under the certain condition and uncertain feedbacks under the uncertain one (highlighted in dashed frame) are compared directly (column 4).

uncertain_loss, certain_gain, and certain_loss), as well as cue of uncertainty (uncertain_cue).

2.4. EEG data analysis

First, we compared the ERP of the four outcome results: uncertain_gain, uncertain_loss, certain_gain, and certain_loss. In the debriefing stage, participants regarded the symbol of certain cue as the exact outcome of gain or loss. Therefore, we defined the certain cue as certain outcome titled certain_gain/certain_loss. Three components P200, FRN, and P300 were analyzed. The P200 was the first positive component peaked at around 200 ms after the onset of the outcome, which defined as the mean value between the time window of 200–240 ms. The FRN was the negative deflection between 2 positive components, with the mean value between the time window of 280–320 ms. To further minimize the effects of the overlap of the FRN with positive ERP components, different waves were computed separately for each outcome condition by subtracting the ERPs elicited by the gain trials from ones by loss trials. This component was defined as differentiated feedback-related negativity (d-FRN). P300 was detected as the most positive value at 250–600 ms after outcome onset (base-to-peak). Based on previous studies and topographic distribution for corresponding components, we chose six electrodes (F1, Fz, F2, FC1, FCz, FC2) in frontal area for P200, FRN and d-FRN measurements, C1, Cz, C2, CP1, CPz, CP2 for P300 in the statistical analysis. Within-subject repeated measures ANOVA was performed for P200, FRN, and P300 with three factors: condition (certain, uncertain), valence (gain, loss), and electrodes. Repeated measures ANOVA was also applied for d-FRN with two factors: condition (certain, uncertain) and electrodes.

Second, we compared the ERPs between the uncertain_cue and uncertain_gain and uncertain_loss. The same electrodes and time windows mentioned above were adopted for FRN and P300, respectively, in the statistical analysis. Within-subject

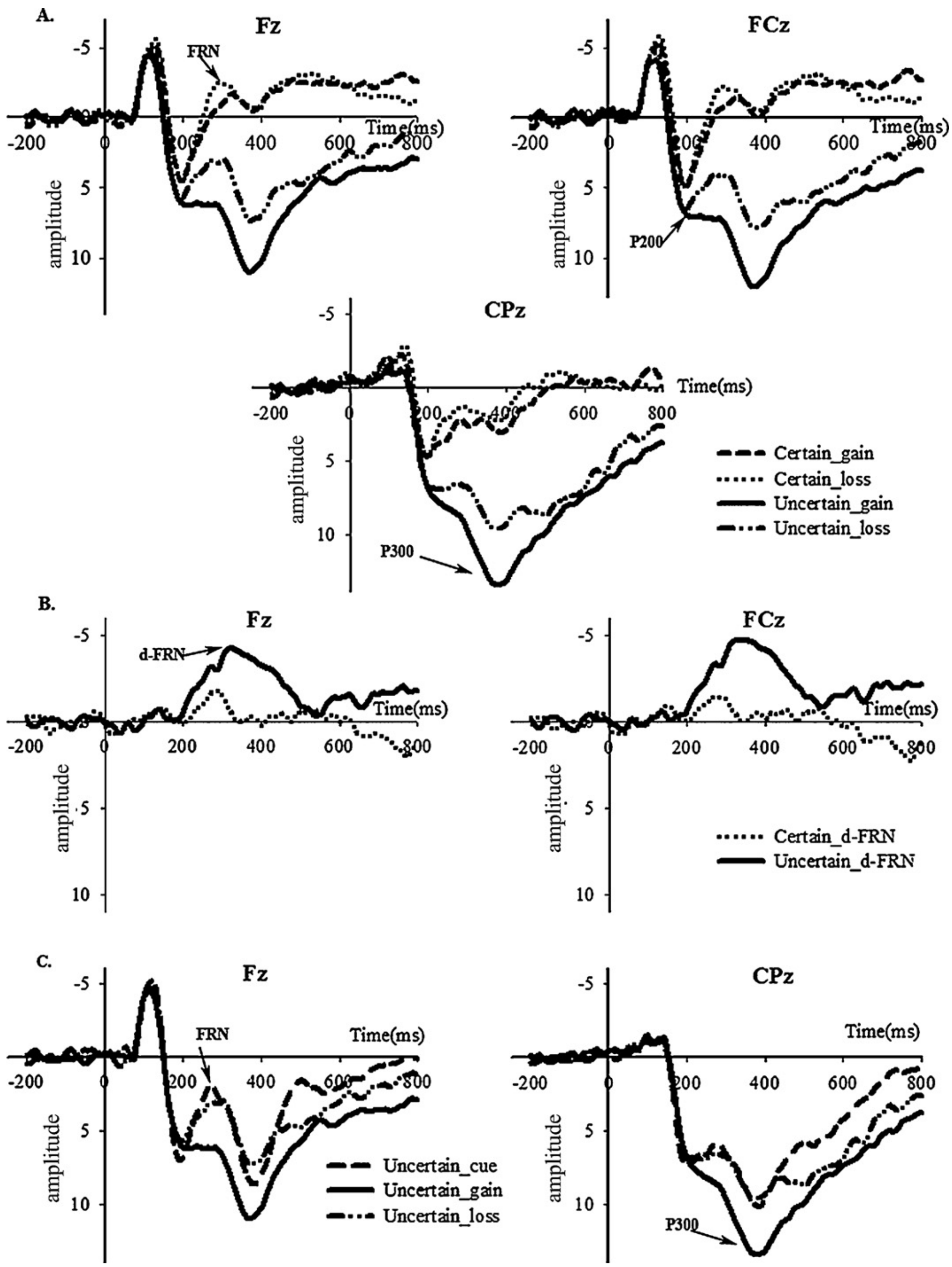

Fig. 2. ERP results. (A) Grand-averaged ERPs at Fz, FCz and CPz electrodes for FRN, d-FRN, P200 and P300 with comparison of the outcome under certain condition and uncertain one as presented in Fig. 1B. (B) Comparison of d-FRN between certain and uncertain outcome at electrodes of Fz and FCz. Generally, the uncertain condition elicits a larger negative deflection than that of certain ones ($p = 0.006$). (C) Grand-averaged ERPs at Fz and CPz electrodes for FRN and P300 with comparison of the cue and outcome (including gain and loss) under uncertain condition.

repeated measures ANOVA was applied with three factors: condition (uncertain_cue, uncertain_gain, certain_loss) and electrodes. The Greenhouse–Geisser correction was adopted for the violation of sphericity assumption in ANOVA where appropriate. Bonferroni correction was used for post hoc multiple comparisons.

2.5. ERP results

Fig. 2A illustrates the grand-averaged ERP elicited by the outcome stimuli of uncertain and certain conditions both for gains and losses. Within-subject ANOVAs of P200 for three factors (context, valence, electrode) over frontal-central region exhibited a significant main effect for context [$F(1, 19) = 23.481$, $p < 0.001$], indicating that the mean amplitude of P200 was larger for an uncertain condition (5.789 μV) than a certain one (3.025 μV). Both the main effect of valence [$F(1,19) = 10.047$, $p < 0.01$]and electrodes [$F(5,15) = 6.433$, $p < 0.01$]were significant. However, the interaction effect between context and valence was not significant [$F(1,19) = 1.344$, $p = 0.261$]. As indicated in Fig. 2A, P200 was more positive for gain trials than for loss trials in an uncertain condition but not in a certain condition. The further analysis confirmed such a result in gain loss comparison under different contexts, $F(1,19) = 5.317$, $p = 0.033$ in the uncertain outcome, and $F(1, 19) = 0.737$, $p = 0.401$in the certain outcome.

The statistical result for FRN with three factors (context, valence, electrode) across frontal area revealed a main effect for context [$F(1,19) = 42.901$, $p < 0.001$]. A significant main effect of valence [$F(1, 19) = 28.032$, $p < 0.001$] indicated that the mean amplitude of FRN across loss trials (−1.193 μV) was smaller than that across gain trials (5.804 μV). The main effect of electrode was significant [$F(5,15) = 4.172$, $p = 0.014$]. Furthermore, the interaction effect between context and valence was also significant [$F(1,19) = 10.821$, $p = 0.004$]. Further analysis indicated that the difference between uncertain_gain and uncertain_loss was significant [$F(1,19) = 28.362$, $p < 0.001$]; and the gain loss discrepancy under certainty reached a significance [$F(1,19) = 4.962$, $p = 0.038$], the loss (−1.721 μV) had a more negative deflection compared with gain (−0.664 μV).

The statistical analysis of d-FRN produced a significant main effect of context [$F(1,19) = 9.566$, $p = 0.006$], and the d-FRN under the uncertain context (−3.556 μV) was negatively larger than that under certain one (−1.240 μV).

The grand-averaged ERP of the P300 was larger for the uncertain conditions than for certain ones (Fig. 2A). Within-subject ANOVA for P300 in three factors (context, valence, electrode) over centro-parietal area revealed a significant main effect for context [$F(1,19) = 55.370$, $p < 0.001$], thus confirming that the mean amplitude of P300 was larger for the uncertainty (12.904 μV) than for certainty (5.598 μV). The main effect of valence [$F(1,19) = 22.922$, $p < 0.001$] was significant, the main effect of electrode was not significant [$F(5,15) = 1.121$, $p < 0.391$]. The interaction between context and valence was also significant [$F(1,19) = 9.734$, $p = 0.006$]. Further analysis revealed that uncertain_gain induced a larger positive deflection than uncertain_loss [$F(1,19) = 27.190$, $p < 0.001$], but certain_gain (5.990 μV) only had a larger trend than certain_loss [5.206 μV, $p = 0.171$].

In order to compare the cue and outcome stage under uncertainty, we compared the FRN and P300 between the uncertain cue and the subsequent outcome. Fig. 2B illustrates the grand-averaged ERP elicited by the stimuli for cue and outcomes under uncertain trials. Within-subject ANOVAs of FRN for situation (uncertain_cue, uncertain_gain, uncertain_loss) over frontal region exhibited a significant main effect for situation [$F(2,18) = 27.630$, $p < 0.001$]. Post hoc pairwise comparison with Bonferroni correction showed that the uncertain_cue (3.775 μV) evoked an equal amplitude of negativity with uncertian_loss (4.016 μV, $p = 1.00$) and both of them were obviously smaller than that of the gains (FRN_gain = 7.592 μV, $p < 0.001$). Within-subject ANOVAs over centro-parietal area for P300 resulted in a significant main effect for situation [$F(2,18) = 31.961$, $p < 0.001$], indicating that the mean amplitude of the P300 elicited by gain outcome (14.593 μV) was larger than that of loss (11.215 μV) and uncertain (10.881 μV).

3. Discussion

The neural correlates underlying uncertainty have gained increasing research attention for the past several years [2,10,11]. The current study investigated how the cue of uncertainty would affect subsequent outcome evaluation. The ERP results demonstrated that the uncertain cue evokes an increased neural response and further enhances the neural sensitivity to gain and loss outcome evaluation.

At the cue stage, uncertain cue elicited FRN, which is equivalent to the loss outcome (Fig. 2B). This is an interesting point that deserves attention because subsequent outcomes have two possibilities, one is a gain and another is a loss. From the theory of expected utility [23], the uncertain cue can be understood as a cue with positive value, which is inconsistent with the FRN results. However, such a result is in accordance with recent functional magnetic resonance imaging (fMRI) results demonstrating that the ACC is activated under the uncertain cue in the face of negatively valenced pictures [20]. Hence, in the financial context, the neural response represented by FRN is also sensitive to the uncertain information.

From the difference waveforms, the results reveal that the FRN at the outcome stage after the uncertain cue is more sensitive to the loss–gain differentiation as compared with certain ones. One interpretation for such a discrepancy is that, as discussed above, subjects may view the uncertain cue as more threatening than others, including loss, thereby heightening neural response at the following outcome stage [20]. In addition, as suggested in the introduction, the FRN is sensitive to the reinforcement learning and motivational significance of the outcome [8,16]. The uncertain cue may enhance the strength of the expectancy toward the outcome after the uncertain cue, which change the degree of desire for gain and avoidance for loss, leading to a stronger prediction error. For instance, in a recent paper, Zhou and his colleagues found that action/inaction decision could modulate outcome evaluation through changing the anticipation of the subsequent outcome, the unfavorable outcome after the action elicits a larger d-FRN than inaction choice [25]. Therefore, the uncertain cue may alter the expectation toward the following outcome, resulting in an increased differential FRN effect under uncertain outcome.

An alternative account for the differential FRN discrepancies is the motivational or affective evaluation of the ongoing events. Recent literature indicates that the outcome of self-execution elicited a larger d-FRN differentiation than that of other's response. For example, our recent work found that compared with other's performed results, the self's outcome elicited a relatively larger FRN effect [13], indicating that connection of the outcome with performer self could raise the motivational significance of the outcome. The uncertain cue may augment the motivation of the outcome, leading to a more prominent loss–gain divergence at the outcome stage.

P200 is a positive-polarity ERP component associated with the attention processing of perceptual stimuli, such as faces [6]. The outcome after an uncertain cue induced a larger, rather than a smaller, positive deflection of P200 under the certain cue, whether it is a gain or loss. This is consistent with the results that the early potential P200 is related to the negativity of the stimuli [1]. Amodio found that the outgroup face induces a larger P200 than that of the ingroup one in racial stereotyping task. Therefore, larger P200 amplitude for uncertain outcome is in line with the negative deviation of the emotion toward uncertain cue. On the other hand, the P200 can also be the result of the predictability of the stimuli. Due to the modulation of uncertain cue, the outcomes after the uncertain cue raise a larger P200, which is in accordance with recent result stating that the risk choice before the outcome induces a larger P200 [18].

A valence effect of the P200 is also observed under uncertain cues, but not in certain ones. Polezzi et al. reported the P200 is not sensitive to the gain and loss of the outcome [18], which is consistent with the current results of certainty condition. The valence effect observed in the present study is rarely discussed in past studies. However, Bellebuam et al. [3] revealed that P200 is larger under a reward outcome than a non-reward outcome both in active and observational gambling tasks. Additionally, the active execution induces a larger discrepancy of P200 between reward and non-reward than that of passive observation. Taken together, the P200 results suggest that, compared with the outcome of certain situation, the outcome after the uncertain cue is treated as the negative sign. Moreover, this uncertain cue further enhances the sensitivity of the P200 to the gain- and loss-outcome differences at a very early stage, which is approximately 200 ms after the presentation of the stimuli.

P300 is generally related to processes of the occurrence of the stimuli. The P300 is more prominent after uncertain cue, irrespective of the valence. This is in line with a recent paper, which suggests that the unexpected low probability stimuli induced the largest P300 regardless of gain or loss outcome [17]. Therefore, the uncertain cue bias affects subjects' expectation about subsequent outcomes, which is consistent with the context-updating hypothesis stating that the unexpected outcome required increases updating representations in one's working memory [19]. In addition, due to the high-level motivational salience as above mentioned, the negative bias of the uncertain cue may induce the arousal of the stimuli after the uncertain cues, which is consistent with the behavioral decision-making theory stating that the negative bias may evoke a more intense emotional reaction [12].

Moreover, the P300 difference is not presented between gain and loss under certain condition, which is consistent with the results of previous reports regarding the role of P300 in valence differentiation [24]. However, we observed an obvious differential effect between gain and loss following uncertain cues, where gain elicits larger amplitude than that of loss. This result is in line with a very recent observation stating that P300 is also sensitive to the valence of the stimuli [4]. Furthermore, a recent paper found that the P300 difference between gain and loss after action choice is larger than that after an inaction one [25]. Therefore, the modulation effect of the valence difference suggests that the uncertain condition increased the affective significance of the uncertain outcome, which is consistent with the FRN results mentioned above.

In summary, by adopting a gambling task, the current electrophysiological study indicated the uncertain cue induced a negative affective response, as represented by the increased amplitude of FRN. This heightened reaction, in turn, induces a larger subsequent reward expectation and motivational/affective response, widening the neural disparity between gain and loss at the outcome stage in P200, FRN and P300 under uncertainty.

Conflicts of interest

There are no conflicts of interest.

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