Contextual valence modulates the neural dynamics of risk processing

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Abstract

A well-known bias in risky decision making is that most people tend to be risk averse when gains are salient but risk seeking when losses are salient. The present study addressed the neural dynamics of this process by recording ERPs during a gambling task in a gain and a loss context. Behaviorally, participants were found to be risk averse in the gain context but risk neutral in the loss context. During the anticipation stage, an increased stimulus-preceding negativity was elicited by high- versus low-risk choices in the gain but not the loss context. During the outcome-appraisal stage, the feedback-related negativity was larger after high- versus low-risk choices in the gain instead of the loss context. For the P300, an outcome valence effect (a larger P300 for gain vs. loss outcomes) emerged following the high- versus low-risk decisions in the gain but not the loss context. Our findings suggest that risk processing can be modulated by the context of valence during the anticipation stage and by both the contextual valence and the outcome valence during the outcome-appraisal stage, which may be driven by the motivational salience imposed by the context of valence.

Descriptors: Risk taking, Contextual valence, Stimulus-preceding negativity, Feedback-related negativity, P300
FRN) and late (P300) stages. The FRN is a frontocentral negative deflection peaking between 250–350 ms following negative relative to positive feedback (Miltner, Braun, & Coles, 1997), and appears to be generated in the anterior cingulate cortex (Gehring & Willoughby, 2002) and in the ventral and dorsal striatum (Carlson, Foti, Mujica-Parodi, Harmon-Jones, & Hajcak, 2011; Foti, Weinberg, Dier, & Hajcak, 2011). The FRN component is thought to encode the quantitative reward prediction error (RPE; i.e., the difference between predicted and obtained outcomes, Holroyd & Coles, 2002), and to reflect a fast evaluation of the motivational significance of ongoing events (Gehring & Willoughby, 2002; Yeung, Holroyd, & Cohen, 2005). Following the FRN, the P300 is a positive deflection with a centroparietal distribution between 300–600 ms, which may reflect the motivational significance of the outcome information (Nieuwenhuis, Aston-Jones, & Cohen, 2005).

Despite numerous studies on these feedback-related ERPs, little research has focused on the electrophysiological signature of reward anticipation. The most likely candidate is the stimulus-preceding negativity (SPN; Damen & Brunia, 1987), a slow, negative, nonmotor wave that progressively increases as the motivational stimuli arrive (Brunia, Hackley, van Boxtel, Kotani, & Ohgami, 2011). Increasing evidence suggests that the SPN constitutes an index for anticipatory, dopaminergically mediated cortical activity (Foti & Hajcak, 2012; Mattos, Valle-Inclan, & Hackley, 2006; Stavropoulos & Carver, 2014) and that the anterior insular cortex is likely the main neural generator of the SPN (Bocker, Brunia, & van den Berg-Lenssen, 1994; Brunia, de Jong, van den Berg-Lenssen, & Paans, 2000; Kotani et al., 2009).

One important approach for unveiling the characteristics of risk taking during reward decision making is to assess the influences of its parameters (outcome valence, magnitude, and probability) on the ERP components described above. Previous studies have found that the FRN amplitude is only influenced by the outcome valence, as a binary distinction between gains and losses (Hajcak, Moser, Holroyd, & Simons, 2006; Yeung & Sanfey, 2004), but an increasing number of studies have demonstrated that the FRN amplitude scales with RPE, which depends on the probability and magnitude of the reward (Walsh & Anderson, 2012). For instance, the FRN amplitude is sensitive to both the outcome probability (Hajcak, Moser, Holroyd, & Simons, 2006; Holroyd, Krigolson, Baker, Lee, & Gibson, 2009; Holroyd, Nieuwenhuis, Yeung, & Cohen, 2003) and the outcome magnitude (Bellebaum, Polezzi, & Daum, 2010; Goyer, Woldorff, & Huettel, 2008; San Martin, Manes, Hurtado, Isla, & Ibáñez, 2010). Although it is well established that the P300 amplitude increases as the outcome probability decreases (Duncan-Johnson & Donchin, 1977) and increases as the outcome magnitude increases (Yeung & Sanfey, 2004), it is still not clear whether the P300 is larger for gains relative to losses (Cohen, Elger, & Ranganath, 2007; Frank, Worch, & Curran, 2005; Schuermann, Endrass, & Kathmann, 2012) or vice versa (Hajcak et al., 2007; Kreussel et al., 2012; Wu & Zhou, 2009).

Few studies have systematically assessed the impact of risk parameters on the SPN. Two studies reported an inverted U-shaped relationship between probability and the SPN amplitude, such that the SPN was larger during unpredictable trials than during predictable trials (Catena et al., 2012; Foti & Hajcak, 2012). However, a more recent study found that the SPN amplitude varied as an inverse function of outcome probability (Fuentemilla et al., 2013). As for reward magnitude, one study employing a simple gambling paradigm found no magnitude effect on the SPN, but the sequential analysis suggested that the effect of the prior outcome was larger for large magnitude choices relative to small magnitude choices (Masaki, Takeuchi, Gehring, Takasawa, & Yamazaki, 2006). Similarly, the SPN amplitude was significantly enhanced for high-arousal pictures compared to low-arousal pictures, irrespective of valence (Poli, Sarlo, Bortolotto, Buodo, & Palomba, 2007). The valence effect on the SPN remains unclear, with only one study showing that the typical SPN right hemisphere dominance appeared during punishment conditions but disappeared during reward conditions (Ohgami et al., 2006).

A limitation of previous ERP studies is that most have focused on risk processing during the outcome-appraisal stage and have ignored risk processing during the anticipation stage. Using a simple gambling task, Masaki and colleagues (2006) examined the affective-motivational influences on both the reward anticipation stage as indexed by the SPN and the outcome-appraisal stage as indexed by the FRN. The authors found that participants tended to make more risky decisions after monetary losses. Importantly, both the SPN and the FRN were larger following a larger gain, indicating incentive or motivational influences during both the reward anticipation and outcome-appraisal stages. However, as in previous ERP studies, Masaki et al. focused on a neutral context with zero expected value; that is, a choice was made between a low-risk option (either winning or losing a small amount of money) and a high-risk option (either winning or losing a large amount of money) on each trial.

As outlined above, the risk-taking behavior seems to be modulated by context (Kahneman & Tversky, 1979). However, to the best of our knowledge, no previous ERP study has investigated the time course of risk taking across different contexts. Therefore, the purpose of the present study was to tap into how risk processing is modulated by the context of valence during the anticipation and outcome-appraisal stages. To this end, we designed a probabilistic two-choice gambling task during which the expected value and the expected risk were manipulated orthogonally. Participants made a choice between a low-risk option and a high-risk option across contexts with different valences. We defined the contextual valence as a gain context versus a loss context. In the gain context, options yielded either larger gains or smaller losses and thus participants would eventually win money, whereas in the loss context, the magnitudes of the gain and loss were reversed and thus participants would ultimately lose money. By manipulating the context of valence, we hypothesized that participants would be risk averse in the gain context but risk seeking in the loss context, despite the same expected value between the low-risk and high-risk options (Kahneman & Tversky, 1979). Critically, the behavioral pattern should be reflected in the anticipation stage as indexed by the SPN and in the outcome-appraisal stage as indexed by the FRN and P300, as all of these components are associated with motivational significance (Brunia et al., 2011; Gehring & Willoughby, 2002; Nieuwenhuis et al., 2005).

Method

Participants

Eighteen healthy undergraduate students participated in the experiment. Two participants’ data were discarded due to an inadequate number of trials available for the ERP analysis. The remaining 16 participants (8 females and 8 males) between the ages of 19 and 26 years (mean = 23 years) were right-handed and had normal or correct-to-normal visual acuity. Each received a base payment of 30 renminbi (yuan) for participating, plus a bonus of up to 30 yuan...
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Based on the points earned during the task. Written informed consent was obtained from each participant. The study was carried out according to the 1964 Declaration of Helsinki and was approved by the Institute Review Board of the Institute of Psychology, Chinese Academy of Sciences.

Procedure

The participants were seated comfortably approximately 80 cm away from a computer screen in a dimly lit and sound-attenuating chamber. On each trial (see Figure 1 for an example), they were presented with two options displayed on either side of a fixation cross and asked to make a choice between them. This pair of options remained on the screen until the participants selected one of them by pressing a button with either their left or right index finger, corresponding to the location of the chosen option. Following their responses, a fixation cross was presented in the center of the screen for 2,500 ms and, thereafter, a number (either positive or negative) appeared for 1,000 ms to indicate how many points they won or lost on the trial. The outcome of each option was determined randomly (50% probability). Every trial finished with an intertrial interval that varied randomly from 900 to 1,100 ms.

In the present experiment, we applied context manipulation to create a gain and a loss context. For the gain context, the low-risk option yielded either a gain of 10 points or a loss of 5 points, whereas the high-risk option yielded either a gain of 25 points or a loss of 20 points. In the loss context, the magnitudes of the gains and losses were reversed: the low-risk option yielded either a gain of 5 points or a loss of 10 points, whereas the high-risk option yielded either a gain of 20 points or a loss of 25 points. The difference in the expected values between the contexts ensured that participants tended to accumulate winnings steadily throughout the gain context (at an average rate of 2.5 points per trial) but dissipate winnings steadily throughout the loss context (at an average rate of −2.5 points per trial). As a variable that is interpretable in terms of the mean squared deviation from the expected outcome (Markowitz, 1952), the expected risk was defined as the product of the loss probability and the loss consequence magnitude [i.e., loss probability × (gains − losses)] (Brown & Braver, 2007). Therefore, the expected value and the expected risk of the current study were manipulated orthogonally: in the gain context, the expected values of the low- and high-risk options were equal (+2.5) and their expected risk values were different (low-risk option = 7.5; high-risk option = 22.5); in the loss context, the expected values of the low- and high-risk options were equal (+2.5) and their expected risk values were different (low-risk option = 7.5; high-risk option = 22.5). The expected risk and expected value of each option are shown in Figure 1.

Each context consisted of 240 trials divided into four blocks (60 trials each), and a rest break was given between blocks. Participants were informed about their current cumulative winnings at the end of each block. The participants completed six practice trials prior to each context. They completed all of the blocks of one context before advancing to the other context. Half of the participants performed the gain context first, followed by the loss context, and the remainder completed the experiment in the reverse order. Prior to the experiment, the participants were told explicitly that, on each trial, the probability of each outcome was 50% to rule out influence due to ambiguity (Knight, 1921) and that the results of each option on each trial were independent to reduce the effects of counterfactual comparison. They were encouraged to respond in such a way as to maximize their total points (ensuring gains and avoiding losses) as much as possible. The higher the points a participant earned, the more bonus money she/he would receive. However, no information regarding the conversion from points to money was provided until the end of the experiment.

Recording and Analysis

The EEG was recorded continuously using an elastic cap with a set of sintered Ag/AgCl electrodes (FP1, FP2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T3, C3, Cz, C4, T4, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, O1, Oz, O2, and left mastoid) mounted according to the extended 10-20 system. The signals were recorded using a right mastoid reference electrode and then rereferenced offline to the average of the left and right mastoids (Luck, 2005). The horizontal electrooculogram (EOG) was recorded as the voltage between electrodes placed bilateral to the external canthi to monitor horizontal eye movements. The vertical EOG was recorded via a pair of electrodes placed on the left infraorbital and supraorbital areas to detect blinks and vertical eye movements. Electrode impedance was kept below 5 kΩ. The EEG and EOG were amplified and digitalized using a Neuroscan NuAmps amplifier with filter settings of 0–100 Hz in DC acquisition mode and a sampling rate of 500 Hz.

The EOG artifacts were removed from the EEG signals offline with an eye-movement correction algorithm (Semlitsch, Anderer, Schuster, & Presslich, 1986). Given that we were interested in the FRN and P300 as well as slow waves, such as the SPN, the original EEG data were filtered using different parameters (Brunia, van Boxtel, & Böcker, 2012): for the SPN analysis, the original EEG data were low-pass filtered at 20 Hz; for the FRN and P300 analyses, the original EEG data were band-pass filtered with cutoffs of 0.1 and 20 Hz to remove low-frequency waves from the EEG. Both of the filtered EEG data were then segmented into epochs that were time-locked to the feedback onset. For the SPN, epochs were extracted from −2,500 ms to 500 ms, with the activity from −2,500 to −2,300 ms serving as the baseline (Masaki et al., 2006; Masaki, Yamazaki, & Hackley, 2010). For the FRN and P300, epochs were extracted from −200 ms to 1,000 ms, with the activity from −200 to 0 ms serving as the baseline. Although the baseline
period for the FRN and P300 overlapped with the SPN, the EEG data for the FRN and P300 had been filtered with a band pass of 0.1 and 20 Hz and, hence, the SPN differences would not contribute to differences in the FRN and P300 amplitudes. Trials contaminated with artifacts exceeding $\pm 100 \mu V$ were excluded from averaging. For figures, SPN waveforms were filtered with a low-pass cutoff at 7 Hz (24 dB/Octave).

Based on the grand-average waveforms and topographic maps, the SPN amplitude was extracted as the mean voltage from 2200 to 0 ms (i.e., the 200-ms window immediately prior to the feedback onset) at bilateral electrode sites (FT7/8, FC3/4, C3/4, and T3/T4). The data were subjected to an analysis of variance (ANOVA) using within-subjects factors of context (gain vs. loss), risk (low vs. high), hemisphere (left vs. right), and site (FT7/8 vs. FC3/4 vs. C3/4 vs. T3/T4). To isolate the FRN (Holroyd et al., 2009; Walsh & Anderson, 2011), we created a low-risk outcome difference wave (losses after low-risk choices minus gains after low-risk choices) and a high-risk outcome difference wave (losses after high-risk choices minus gains after high-risk choices) separately for the gain and loss contexts. We measured the FRN as the mean voltage of the difference waves from 290 to 350 ms after the feedback onset from two frontocentral sites (Fz and FCz), where the difference waves were maximal across the entire sample. The FRN data were analyzed using a Context $\times$ Risk $\times$ Site (Fz vs. FCz) ANOVA.

The P300 amplitude was calculated as the mean voltage of the 350 to 450 ms time window following the feedback onset at CPz and Pz given a posterior distribution of the P300 component. The P300 data were analyzed using a Context $\times$ Risk $\times$ Valence (gain vs. loss) $\times$ Site (CPz vs. Pz) ANOVA. For all statistical tests, Greenhouse-Geisser epsilon correction was applied for nonsphericity when appropriate (Jennings & Wood, 1976). The partial eta-squared ($\eta^2_p$) is reported as a measure of effect size. A post hoc pairwise analysis was performed using the Bonferroni procedure.

Results

Behavioral Data

Table 1 shows the number of trials encountered by the participants for each of the four possible outcomes in each context. The total points earned by the participants were 613.1 ± 612.8 for the gain context and 2600.9 ± 287.0 for the loss context. The average decision-making time was 893 ± 258 ms, which was similar between the low-risk and high-risk choices and between the gain and loss contexts ($p > .1$).

The average probability of making risky decisions, which was computed as the number of times that participants selected the high-risk options divided by the total number of choices, was 0.39 ± 0.17 for the gain context and 0.53 ± 0.20 for the loss context. Participants were more unwilling to make risky decisions in the gain context compared to the loss context, $t(15) = 2.35, p < .05$. Specifically, they were risk averse in the gain context, making significantly fewer risky decisions compared to chance, $t(15) = -2.68, p < .05$, but their decisions were risk neutral in the loss context, making risky choices no more than chance, $t(15) = 0.51, p > .1$.

A further analysis was performed to examine how risk preference was influenced by the outcome of the previous trial (Figure 2). The participants tended to make more risky decisions when the previous outcome was a loss than when it was a gain, $F(1,15) = 10.66, p < .01, \eta^2_p = .42$. The participants were also more risk seeking when the previous value was large compared to when it was small, $F(1,15) = 14.45, p < .005, \eta^2_p = .49$. Their behavioral patterns were similar across the two contexts, as indicated by the absence of significant interactions involving context ($p > .1$).

Electrophysiological Data

Anticipation stage: The SPN. As shown in Figure 3, the SPN develops gradually as a relative negativity after the choice and

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Table 1. Number of Trials Encountered by Participants for Each of the Four Possible Outcomes in Each Context (M ± SD)

<table>
<thead>
<tr>
<th></th>
<th>High risk</th>
<th></th>
<th>Low risk</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gain</td>
<td>Loss</td>
<td>Gain</td>
<td>Loss</td>
</tr>
<tr>
<td>Gain context</td>
<td>46 ± 19</td>
<td>47 ± 21</td>
<td>75 ± 19</td>
<td>71 ± 21</td>
</tr>
<tr>
<td>Loss context</td>
<td>63 ± 25</td>
<td>63 ± 23</td>
<td>57 ± 20</td>
<td>57 ± 28</td>
</tr>
</tbody>
</table>

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Figure 2. The effect of the preceding outcome on the riskiness of behavior in the gain and the loss contexts. Standard errors are also shown.
reaches its maximum immediately prior to the feedback onset. The
topography of the SPN tends to be larger over the right hemisphere
compared to the left hemisphere, especially in the frontal areas.
These patterns are consistent with the SPN characteristics: it
appears as a plateau-shaped, right hemisphere-lateralized distribution
in the frontal areas and a symmetrical distribution in the parietal
areas (Brunia et al., 2011). ANOVA of the SPN data revealed
that the SPN amplitude was larger over the right compared to the
left hemisphere, as reflected in a significant main effect of hemi-
sphere, $F(1,15) = 5.96, p < .05, \eta^2 = .28$. Although the main
effect of context was marginally significant, $F(1,15) = 3.92, p =
.066, \eta^2 = .21$, the interaction between context and risk was sig-
nificant, $F(1,15) = 10.55, p < .01, \eta^2 = .41$. The post hoc analysis
indicated that the SPN amplitude was greater following high-risk
choices compared to following low-risk choices in the gain context
($-4.52 \mu V$ vs. $-2.47 \mu V, p < .01$), but this risk effect disappeared
in the loss context ($-1.68 \mu V$ vs. $-2.32 \mu V, p > .1$). In addition,
the SPN amplitude following high-risk choices was greater in the
gain context compared to the loss context ($p < .01$), but there was
no significant difference in the SPN amplitude following the low-
risk options between the two contexts ($p > .1$). Moreover, there
was a significant interaction among context, risk, and site, $F(1,15) =
3.89, p < .05, \eta^2 = .21$. The post hoc analysis suggested that the
interaction between context and risk was presented at FC3/4, C3/4,
and T3/T4 ($p < .05$), but not at FT7/8 ($p > .1$). No other sig-
ificant effects were found (Table 2).

### Outcome-appraisal stage: The FRN and P300

As shown in Figure 4, the FRN exhibits a negative deflection over the frontocen-
tral regions after the feedback onset in the difference waveform,
as calculated by subtracting the gain trial activity from the loss trial
activity. Interestingly, whereas the FRN was greater following high-
risk choices compared to following low-risk choices for the gain
context ($-4.36 \mu V$ vs. $-2.09 \mu V, p < .01$), there was no difference
of risk for the loss context ($-2.03 \mu V$ vs. $-2.05 \mu V, p > .1$), as
revealed by a significant interaction between context and risk,
$F(1,15) = 5.85, p < .05, \eta^2 = .28$. No other significant effects
were found (Table 2).

ANOVA of the P300 amplitude revealed a significant main
effect of risk, $F(1,15) = 18.32, p < .001, \eta^2 = .55$, indicating that

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**Table 2. Summary of the Analysis of Variance Performed on SPN, FRN, and P300 Amplitudes**

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>$F$</th>
<th>$p$</th>
<th>$\eta^2$</th>
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<td><strong>SPN</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Context (C)</td>
<td>(1,15)</td>
<td>3.92</td>
<td>.066</td>
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<tr>
<td>Risk (R)</td>
<td>(1,15)</td>
<td>2.23</td>
<td>.156</td>
<td>.13</td>
</tr>
<tr>
<td>Hemisphere (H)</td>
<td>(1,15)</td>
<td>5.96</td>
<td>.028</td>
<td>.28</td>
</tr>
<tr>
<td>Site (S)</td>
<td>(3,45)</td>
<td>.98</td>
<td>.383</td>
<td>.06</td>
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<tr>
<td>C × R</td>
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<td>.005</td>
<td>.41</td>
</tr>
<tr>
<td>C × H</td>
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<td>0.38</td>
<td>.546</td>
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<tr>
<td>R × H</td>
<td>(1,15)</td>
<td>0.76</td>
<td>.398</td>
<td>.05</td>
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<tr>
<td>C × R × H</td>
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<td>1.45</td>
<td>.240</td>
<td>.09</td>
</tr>
<tr>
<td>C × S</td>
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<td>.106</td>
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<tr>
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<td>C × R × H × S</td>
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<td><strong>FRN</strong></td>
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<td>Risk (R)</td>
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<td>2.71</td>
<td>.121</td>
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<td>Site (S)</td>
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<td>0.42</td>
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<tr>
<td>C × R</td>
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<td>.029</td>
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<td><strong>P300</strong></td>
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</tbody>
</table>
the P300 was greater for high-risk compared to low-risk outcomes. The P300 was also greater for gain compared to loss outcomes, $F(1,15) = 8.38$, $p < .05$, $\eta^2_p = .30$. The valence effect was significant after high-risk options ($p < .005$), but not after low-risk options ($p > .1$), leading to a significant interaction of risk and valence, $F(1,15) = 12.11$, $p < .005$, $\eta^2_p = .45$. As shown in Figure 5, this interaction was modulated by context, $F(1,15) = 5.94$, $p < .05$, $\eta^2_p = .28$. In the gain context, the valence effect was

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**Figure 4.** ERPs for low-risk (LR) gains, LR losses, high-risk (HR) gains, and HR losses at FCz. FRN (calculated as the difference between loss and gain waveforms) for LR and HR outcomes is shown, where shaded areas depict the FRN time window. Scalp maps (290–350 ms) show the topography for the FRN for risk and context, where red triangles indicate the electrodes selected for analysis.

**Figure 5.** ERPs for low-risk (LR) gains, LR losses, high-risk (HR) gains, and HR losses at Pz in gain and loss contexts, where shaded areas depict the P300 time window. Scalp maps (350–450 ms) show the topography for the P300 for context, risk, and valence, where blue triangles indicate the electrodes selected for analysis.
significant following high-risk decisions ($p < .001$) but not following low-risk decisions ($p > .1$). In the loss context, however, no valence effect was obtained regardless of risk ($ps > .1$). There was a significant interaction of risk and site, $F(1,15) = 5.45$, $p < .05$, $\eta_p^2 = .27$, indicating that the P300 was larger at Pz than at CPz, which was significant after high-risk options ($p < .05$) but not after low-risk options ($p > .1$). Similarly, the P300 was larger at Pz compared to CPz, which was significant after losses ($p < .05$) but not gains ($p > .1$), as reflected by a significant interaction of valence and site, $F(1,15) = 11.68$, $p < .005$, $\eta_p^2 = .44$. Finally, the interaction among context, valence, and site was also significant, $F(1,15) = 5.31$, $p < .05$, $\eta_p^2 = .26$. The post hoc comparison revealed that the valence effect was significant at CPz and Pz for the gain context ($ps < .05$), but approached significance at CPz ($p = .09$), and was not significant at Pz ($p > .1$) for the loss context. No other significant effects were obtained (Table 2).

**Discussion**

Reward processing can be parsed at least into the anticipation and outcome-appraisal stages (Berridge & Robinson, 1998, 2003). One previous study demonstrated that both the reward anticipation and outcome-appraisal stages are influenced by motivational salience in a neutral context (Masaki et al., 2006). Adopting a similar gambling task, we extended this work to include a gain and a loss context. We found that participants were generally risk averse during the gain context. However, this risk-avoidance tendency disappeared during the loss context. Although it may be de-motivating to lose money steadily during the loss context, the participants did not differ in their overall task engagement in the two contexts, which was supported by the following observations. First, the decision-making times were similar between the gain and the loss context. Second, the sequential analysis revealed that the risk preference was influenced by the outcome of the previous trial to the same extent for each context. More importantly, this study provides corroboratory evidence, for the first time, that risk processing is modulated by the contextual valence, which is consistently mirrored by the electrophysiological signals from the anticipation stage (the SPN) to the early (the FRN) and late (the P300) outcome-appraisal stages.

One critical approach to unveiling the characteristics of risk taking during reward decision making is to assess the influences of experimental parameters (valence, magnitude, and probability) independently. However, in most previous ERP studies, the magnitude and probability have not been properly manipulated. For instance, the probability is often unknown in advance in a learning task (Cohen et al., 2007) or even in a gambling task (Polezzi, Sartori, Rumia, Vidotto, & Daum, 2010), forcing participants to make decisions under ambiguous conditions rather than risk conditions (Knight, 1921; Pushkarskaya, Liu, Smithson, & Joseph, 2010). Similarly, participants are sometimes not informed of the possible outcome magnitude until feedback is received (Yeung & Sanfey, 2004), and thus cannot make informed decisions. In the present experiment, the magnitude and probability of each option were explicitly specified on each trial, and the expected value and expected risk of each option were orthogonally controlled across the gain and loss contexts, which allowed us to circumvent the above issues.

In the present study, the SPN was enhanced over the right hemisphere relative to the left hemisphere. The right-hemisphere predominance is a fairly robust effect in the SPN literature, possibly reflecting contributions from the ventral attention system (for a recent review, see Brunia et al., 2011). This system mainly includes the inferior frontal cortex and the temporoparietal cortex and is largely lateralized to the right hemisphere (Corbetta & Shulman, 2002). A main finding of the present study was that the SPN was greater after high- compared to low-risk decisions, which only appeared during the gain context but not during the loss context. The SPN is highly sensitive to the anticipation of a forthcoming motivational stimulus (Foti & Hajcak, 2012; Fuentemilla et al., 2013; Ohgami et al., 2006), presumably reflecting the involvement of the approach and withdraw motivational systems (Brunia et al., 2011). Our SPN findings suggest that the motivational salience of an anticipated outcome can be modulated by the context of valence. In the present experiment, the expected value was positive in the gain context, but negative in the loss context. Therefore, the gain relative to the loss may be implicitly more emphasized during the gain context because participants increasingly win money (at an average rate of 2.5 points per trial). In contrast, a loss may be implicitly more salient than a gain during the loss context because participants lose money gradually as the gambling continues (at an average rate of −2.5 points per trial). Correspondingly, the approach-motivational significance seems to be enhanced following high- compared to low-risk options during the gain context, which may be downgraded in the loss context. Therefore, different types of motivational salience may induce different risk effects on the SPN across the two contexts.

Similarly, we observed a significant interaction between context and risk for the FRN amplitude (calculated as the difference between the loss and gain outcomes). In the gain context, the FRN was larger following high-risk choices compared to low-risk choices, an effect that disappeared in the loss context. Recent studies, using the same difference measure of the FRN that isolates valence-related activity, have demonstrated that the variation in the FRN is mainly driven by reward-related brain activity (Carlson et al., 2011; Foti et al., 2011; Holroyd, Pakzad-Vaezi, & Krigolson, 2008; Proudfit, 2014). Moreover, previous studies have proposed that the FRN component indexes a flexible evaluative system that encodes whichever information is contextually more salient in the environment (Gu et al., 2011; Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen, 2004). For example, when feedback stimuli conveyed both performance and utilitarian information, the FRN was sensitive to both aspects of the feedback, depending on which aspect was more salient (Nieuwenhuis et al., 2004). Whereas salient information was highlighted via perceptual manipulation in previous research, the present study manipulated the salience motivationally: gain was more highlighted in the gain context, whereas loss was more highlighted in the loss context. Taken together, the FRN finding is in accord with the emerging view that variations of the FRN are more associated with gain-related, rather than loss-related, brain activity, such that the risk effect emerged during the gain context but not during the loss context.

In contrast to the FRN, which represents a fast evaluation of a feedback, the P300 is thought to reflect the allocation of attentional resources based on the motivational significance of a stimulus or process (Nieuwenhuis et al., 2005), such as task relevance and memory updating (Donchin & Coles, 1988; Duncan-Johnson & Donchin, 1977). For the gain context, the P300 was enhanced in response to gains versus losses, indicating that gains relative to losses were more target related (Ferdinand, Mecklinger, Kray, & Gehring, 2012); that is, gains signaled the participants’ intended goal because of the approach-motivational salience imposed by the gain context. Moreover, the effect of outcome valence was presented after high-risk choices, but disappeared after low-risk
choices, which may suggest that the motivational significance was enhanced by risk-taking behavior (Nieuwenhuis et al., 2005). Consistent with this interpretation, previous studies have found that the P300 target effect is markedly enhanced for highly arousing affective stimuli compared to neutral stimuli (Ferrari, Codispoti, Cardinale, & Bradley, 2008; Schupp et al., 2007). Surprisingly, when shifted into the loss context, the interaction between outcome valence and risk disappeared, indicating that gains were no longer implicitly represented as a target. Consequently, the participants might direct similar attentional resources to different outcomes regardless of risk.

Given that the frequencies differ in the different conditions, it is possible that all of the effects presented here are solely due to the less frequent choices of the high-risk options in the gain context. However, the present findings are better explained by the risk effect, rather than by the choice frequency effect. Overall, the relative frequencies for low- versus high-risk choices were 0.61 versus 0.39 in the gain context and 0.47 versus 0.53 in the loss context, respectively. If the SPN effects were solely due to the choice frequency, then reversed patterns should have been observed when comparing the ERP amplitudes between the two contexts. In actuality, although the SPN following high-risk choices was greater in the gain context compared to the loss context, the SPN following low-risk choices was similar across the two contexts. Regarding the FRN and P300, which are extremely sensitive to stimulus frequency, we compared the effects of outcome valence between different risk levels such that gain and loss outcomes were encountered with approximately equal frequency (Table 1). Indeed, the frequency differences in the active decision-making task employed here cannot be controlled because the frequency depends on the participants’ choice. One way to rule out a possible confounding effect of frequency is to adopt the more passive task, such as the monetary incentive delayed task during which the outcome frequencies are predetermined (Knutson, Westdorp, Kaiser, & Hommer, 2000).

In risky decision-making studies, it is important to match the expected value of the alternatives with different risk levels because the option corresponding to a higher expected value is naturally preferred (Lee, 2005). In the current experiment, we varied the expected risk while holding the expected value constant, as performed in previous studies (Christopoulos, Tobler, Bossaerts, Dolan, & Schultz, 2009; Polezzi et al., 2010). Unfortunately, this might lead to a convolution between risk attitude and loss attitude. That is, the two options on each trial differed not only in the variance but also in the gain-to-loss ratio, which is associated with loss aversion and has a strong effect on choice behavior (Tversky & Kahneman, 1992). Specifically, in the gain context, the low-risk option had a higher gain-to-loss ratio, whereas the high-risk option had a lower gain-to-loss ratio. In contrast, for the loss context, the low-risk ratio possessed a lower gain-to-loss ratio, whereas the high-risk option possessed a higher gain-to-loss ratio. This may explain why we did not observe risk-seeking behavior during the loss context. However, it seems that our ERP findings are better interpreted considering risk attitude. For instance, if our results were attributable to the gain-to-loss ratio, then the SPN would display the largest amplitude for the low-risk choice in the loss context, which had the lowest gain-to-loss ratio (Figure 1). However, this was not the case, as the high-risk choice in the gain context elicited the largest SPN amplitude, whereas the other three choices elicited similar SPN amplitudes. Indeed, our recent study found that the SPN was enhanced following high- compared to low-risk choices, despite the same gain-to-loss ratio between the two choices (Zheng & Liu, 2014), which is in line with the present findings. Future studies on risk processing should take the loss aversion into account.

Traditional theoretical models of risky decision making, such as the expected utility theory (von Neumann & Morgenstern, 1944) and the prospect theory (Kahneman & Tversky, 1979), emphasize the role of cognitive evaluation in risky decision making. In contrast, recent theories, such as the risk-as-feeling hypothesis (Loewenstein, Weber, Hsee, & Welch, 2001) and the somatic marker theory (Damasio, Tranel, & Damasio, 1991), highlight the role of emotion in risky decision making, suggesting that emotion interacts with the cognitive evaluation of alternative choices to guide decisions. In the present study, risk-taking behavior was strongly modulated by the contextual valence, which was consistently mirrored by the electrophysiological signals from the anticipation stage (the SPN) to the early (the FRN) and late (the P300) outcome-appraisal stages. As discussed above, all of the ERP findings can be interpreted according to the motivational significance imposed by the different contexts. In this sense, our results are broadly supportive of recent theories that suggest emotions are implicated in risky decision making (Damasio et al., 1991; Loewenstein et al., 2001).

To summarize, our behavioral results are consistent with the well-known bias in risky economic decision making (Kahneman & Tversky, 1979) that risk aversion is common during the gain context but not during the loss context. Interestingly, the behavioral bias was mirrored by the ERP findings, corresponding to increased anticipation (the SPN) and outcome (the FRN and P300) processing during the gain context but not during the loss context, which may be driven by the motivational salience imposed by the context of valence. An important goal for future research is to address the mechanisms by which factors associated with emotional disorders, such as anhedonia, influence risk processing during the anticipation and outcome-appraisal stages.

References


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