Asymmetrical attention to gambling-related stimuli and pupillary dilation in response to wins and losses in problem gamblers

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Abstract

Gambling disorder and problem gambling are characterized by persistent and repetitive problematic gambling behavior. Attentional bias toward gambling-related stimuli such as casino chips, dice, roulette, etc. have been observed in problem gamblers, but it remains unclear whether stimuli in gambling tasks elicit greater attention and pupillary responses in problem gamblers. To address this issue, we administrated problem and non-problem gamblers a gambling task accompanied by eye-tracking measurements, in which the participants were required to choose one of the paired pictures to receive monetary rewards and avoid punishments. Concerning attentional allocation, problem gamblers showed a greater attentional preference for the right-hand pictures in the decision and feedback phases, and compared to non-problem gamblers, problem gamblers’ attention was particularly high around the center. Concerning pupillary dynamics, pupillary dilation in response to rewards and punishments was observed only in problem gamblers. Accordingly, asymmetrical allocation of attention by problem gamblers may reflect greater concentration on the gambling task, and pupillary dynamics in problem gamblers may reflect hypersensitivity to wins and losses.

Introduction

Gambling disorder, previously known as pathological gambling, is defined as persistent and recurrent problematic gambling behavior leading to clinically significant impairment or distress. [1] Problem gambling can lead to financial and social difficulties, psychiatric comorbidities, poor physical health, suicide, and criminal behavior. [2–4] A recent public health review suggested that the increasing availability of, and participation in, online gambling has increased the prevalence of gambling disorder and contributed to higher rates of associated morbidities and other gambling-related problems. [5] To address these problems, there is a need to elucidate the pathology of gambling disorder and problem gambling. A systematic review determined that problem gamblers (PGs) and pathological gamblers exhibited attentional bias toward gambling-related stimuli, such as the words “casino”, “poker,” and “jackpot”, as well as toward pictures of poker chips, roulette, and dice, compared to neutral stimuli. [6] Brevers et al. reported that PGs detected changes in gambling-related stimuli more rapidly, and that the stimuli were more likely to elicit the first saccade and a longer fixation. However, attentional biases in PGs during gambling tasks have not been examined. In this study, we used an eye tracker to investigate differences in attentional allocation between PGs and non-problem gamblers (NPGs) during a gambling task. Previous studies concerning attentional allocation during gambling tasks have indicated that participants gaze at the stimuli they ultimately select before selecting them [7], and that stress and sensory cues denoting a win modulate attentional allocation and promote riskier choices. [8,9] Therefore, we hypothesized that PGs would show greater attention, even to neutral stimuli, in a gambling task compared to NPGs.

Pupillary diameter measurements are used to determine the salience of objects, while gaze allocation assessments enable identification of the spatial location of attention. Thus, simultaneous gaze allocation and pupillary diameter assessments can help elucidate cognitive processing in PGs.
Pupillary diameter is modulated by the noradrenergic locus coeruleus and reflects various cognitive processes and emotions, such as attraction, mental effort, surprise, attention, and exploration. Previous studies using non-gambling tasks demonstrated that greater pupillary dilation occurs during anticipation of a reward, and that excessive pupillary diameter in response to reward predicts failure in a stopwatch task. Pupillary diameter has been presumed to be modulated by uncertainty and violations of expectations during gambling. However, pupillary dynamics in PGs during gambling tasks have not been examined. Therefore, in this study, pupillary dynamics during a gambling task were investigated in PGs and NPGs. Previous studies indicated that physiological indices other than the pupillary diameter (e.g., heart rate and skin conductance) predict performance on gambling tasks, and that PGs show greater responses to the outcomes of gambling tasks. Thus, we hypothesized that greater differences in pupillary dynamics would be observed in PGs than in NPGs in response to reward and punishment feedback during gambling tasks.

In this study, PGs and NPGs were chosen from among 100 gamblers on the basis of their South Oaks Gambling Screen (SOGS) scores. The eye-tracking gambling task was composed of decision, feedback, and fixation phases (Fig 1). In the decision phase, pairs of pictures were presented on the left- and right-hand sides of the screen; PGs and NPGs were required to choose one of the two pictures. In the feedback phase, the PGs and NPGs received a monetary reward or a punishment if the selected picture was framed by a red (reward condition) or blue line (punishment condition). If the chosen picture was framed by a gray line (control condition) or the unchosen picture was framed by red, blue, or gray lines, there was no reward or punishment. Half of the chosen pictures were framed (congruent condition) while the other half were not (incongruent condition), in each of the reward, punishment, and control conditions. This enabled comparison between PGs and NPGs in terms of attentional allocation to stimuli in a gambling task and the modulation of pupillary dynamics by wins and losses.

**Materials And Methods**

**Participants**

One hundred individuals (mean ± SD age: 39.2 ± 11.2 years; 49 men and 51 women) who had previously engaged in gambling were assessed using the SOGS and Massachusetts Gambling Screen. SOGS scores of ≥ 5 and 3–4 indicated probable and possible pathological gambling, respectively. There were 21 probable gamblers and 1 possible gambler among the PGs (mean ± SD age: 38.5 ± 11.2 years; 15 men and 7 women). After matching for age, years of education, and sex, 22 participants with SOGS scores of 0–1 were included in the NPG group (mean ± SD age: 38.7 ± 10.4 years; 13 men and 9 women) (Table 1). The optimal sample size was calculated using G*Power for a power of 0.95, medium effect size (F) of 0.25 and α level of 0.05, for analysis of variance (ANOVA). The SOGS and Massachusetts Gambling Screen scores showed significant differences between the PGs and NPGs [t(22.6) = 16.88, p < 0.001, r = 0.96; t(21.3) = 7.17, p < 0.001, r = 0.84, respectively]. The study protocol was approved by the Ethics Committee of Chuo University. All participants provided written informed consent in accordance with the Declaration of Helsinki.
Table 1. Demographic data.

<table>
<thead>
<tr>
<th>Problem gamblers (PGs)</th>
<th>Non-problem gamblers (NPGs)</th>
<th>t/χ²</th>
<th>p</th>
<th>r/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years (mean ± SD)</td>
<td>38.5 ± 11.2</td>
<td>38.7 ± 10.4</td>
<td>-0.04</td>
<td>0.97</td>
</tr>
<tr>
<td>Age range, years</td>
<td>22–57</td>
<td>22–57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex (male: female)</td>
<td>15:07</td>
<td>13:09</td>
<td>0.39</td>
<td>0.53</td>
</tr>
<tr>
<td>Years of education (mean ± SD)</td>
<td>15.2 ± 1.6</td>
<td>15.5 ± 1.1</td>
<td>-0.86</td>
<td>0.40**</td>
</tr>
<tr>
<td>South Oaks Gambling Screen score (mean ± SD)</td>
<td>8.2 ± 2.2</td>
<td>0.2 ± 0.4</td>
<td>16.88</td>
<td>0.00**</td>
</tr>
<tr>
<td>Massachusetts Gambling Screen score (mean ± SD)</td>
<td>4.0 ± 2.6</td>
<td>0.0 ± 0.2</td>
<td>7.17</td>
<td>0.00**</td>
</tr>
</tbody>
</table>

SD = standard deviation  
** = p < 0.01, * = p < 0.05, + = p < 0.1

Stimuli

In total, 120 pairs of pictures of non-living objects (e.g., daily goods, furniture, vehicles, and clothes) were chosen from a dataset used in previous studies.[24] During the experimental task, pictures were presented on either side of the computer screen (Fig. 1). The pairs of pictures were divided into six homogeneous sets, with similar levels of complexity, familiarity, arousal, and valence between the left and right sides (p ≥ 0.1 in all comparisons). Furthermore, the level of similarity between pairs of pictures did not differ among the sets (p ≥ 0.1). The combinations of stimulus sets and experimental conditions were counterbalanced to prevent differences in behavioral data, gaze, and pupil diameter due to the physical characteristics of the stimulus set.

Experimental task

Gaze positions and pupillary diameters were obtained from both eyes using a Tobii Pro Nano eye tracker and Tobii Pro Lab Presenter version 1.152 (Tobii Technology, Stockholm, Sweden). The sampling rate was set at 60 Hz, and the screen resolution was set to 1,024 × 768 pixels. To calibrate the eye gaze position on the screen, a standard nine-point calibration procedure was conducted before the experimental task. The experimental task consisted of two 60-trial sessions and was conducted using MATLAB R2010b (MathWorks, Natick, MA, USA) and Cogent 2000 version 1.33 (www.vislab.ucl.ac.uk/cogent.php). Each trial was composed of a 3 s decision phase, 1.5 s feedback phase, and 1 s fixation phase. In the decision phase, the pairs of pictures and a fixation cross were presented, and participants were required to choose one of the pictures by pressing keys with their index
and ring fingers. A yellow inverted triangle was presented above the chosen picture after it had been selected. In the feedback phase, one of the pictures was framed with a red (reward condition), blue (punishment condition), or gray (control condition) line. If the chosen picture was framed by a red line, the participant won 100 yen (equivalent to approximately 1 US dollar). If the chosen picture was framed by a blue line, the participant lost 100 yen. If the chosen picture was framed by a gray line, or if the unchosen picture was framed by a red, blue, or gray line, the participant would neither win nor lose any money. In the fixation phase, only the fixation cross was shown on the screen. Participants were instructed to maximize gain and minimize loss. In each of the reward, punishment, and control conditions, half of the chosen pictures were framed (congruent condition) and the remaining half were not framed (incongruent condition).

Test battery

After finishing the experimental task, the participants completed a test battery that included the forward and backward digit span tasks [25], Rey-Osterrieth Complex Figure test [26,27], BIS/BAS scale [28], Sensitivity to Punishment and Sensitivity to Reward Questionnaire (SPSRQ) [29] and Sensation Seeking Scale-Abstract Expression (SSS-AE) [30,31], to confirm group differences in attention, visuospatial cognition, episodic memory, and personality traits.

Data analysis of behavioral data

The left/right index was defined as [(right decisions − total decisions/2)/(total decisions/2)] × 100. A left/right index of −100 indicated that the participant always chose left, and a left/right index of 100 indicated that the participant always chose right. To determine whether responses differed between PGs and NPGs, the left/right indices were analyzed by two-sample t-tests. The response times were also analyzed by two-way ANOVA, with side (left and right) and group (PGs and NPGs) as the independent variables. Two-sample t-tests between PGs and NPGs were performed for each component of the test battery. IBM SPSS Statistics was used for statistical analyses (version 26.0; IBM Corp., Armonk, NY, USA).

Analysis and descriptive statistics of the eye-tracking data

Data concerning gaze position and pupillary diameter were processed, analyzed, and graphed using custom scripts in MATLAB 2017b (MathWorks). For the X and Y coordinates of gaze position and
to determine temporal changes in pupillary diameter under each experimental condition, three-step data processing was performed. [14,15] First, invalid samples (e.g., those with blinks) and the three samples before and after the invalid samples were removed to eliminate outliers. After the data were extracted, the proportions of samples averaged 83.5 (SD: 11.4) for PGs and 84.0 (SD: 10.6) for NPGs. Blanks were interpolated using the piecewise cubic Hermite interpolating polynomial method. [32] Second, the interpolated data were smoothed using a Savitzky–Golay filter with ± 200-ms width to reduce sampling noise. [33] Third, the smoothed data were z-normalized within each individual, and the mean of the time points within each trial was calculated under six conditions generated by combining the factors of motivation (reward, punishment, and control) and result (congruent and incongruent). The resulting data were analyzed to compare the influence of reward and punishment between the PGs and NPGs. The differences between the congruent and incongruent conditions in each sample were calculated under the reward, punishment, and control conditions, and data for each sample were averaged every second from 0 to 5 s and for the last 500 ms. Each time point for the reward and punishment conditions was compared with the time points obtained under the control condition using one-tailed paired t-tests for PGs and NPGs, because our hypothesis regarding pupil dilation was unidirectional (i.e., greater pupil dilations
for reward and punishment). P-values were corrected using the Bonferroni procedure for multiple comparisons. This analysis made no a priori assumptions regarding the shape of the pupillary response waveform.[15]

**Results**

**Experimental gambling task**

The results of the gambling task were analyzed to confirm response bias to the left- or right-hand pictures (Table 2). Two-sample t-tests showed no statistically significant differences in the left/right response indices between the PGs and NPGs \(t(42) = 0.81, p = 0.42, r = 0.12\). Two-way ANOVA of the response times, with side and group as the independent variables, revealed no statistically significant main or interaction effects [main effect of side: \(F(1,42) = 1.14, p = 0.29, \eta^2 = 0.03\); main effect of group: \(F(1,42) = 2.31, p = 0.14, \eta^2 = 0.05\); interaction between side and group: \(F(1,42) = 0.01, p = 0.90, \eta^2 = 0.00\)]. Thus, no response biases were identified during the task.
Table 2. Results of the experimental task and test battery (mean ± SD).

<table>
<thead>
<tr>
<th></th>
<th>Problem gamblers (PGs)</th>
<th>Non-problem gamblers (NPGs)</th>
<th>t</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental task</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Left/right index</td>
<td>-1.4 ± 21.2</td>
<td>-6.0 ± 15.7</td>
<td>0.81</td>
<td>0.42</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Digit span</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Forward</td>
<td>8.9 ± 1.8</td>
<td>9.0 ± 1.7</td>
<td>-0.09</td>
<td>0.93</td>
<td>0.01</td>
</tr>
<tr>
<td>Backward</td>
<td>7.3 ± 1.7</td>
<td>7.3 ± 2.4</td>
<td>-0.07</td>
<td>0.94</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Rey-Osterrieth Complex Figure Test</strong></td>
<td></td>
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<tr>
<td>Copy</td>
<td>35.1 ± 1.0</td>
<td>35.4 ± 0.9</td>
<td>-1.25</td>
<td>0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>Retrieval</td>
<td>23.7 ± 6.2</td>
<td>25.5 ± 5.0</td>
<td>-1.03</td>
<td>0.31</td>
<td>0.16</td>
</tr>
<tr>
<td><strong>Behavioral Inhibition System/Behavioral Approach System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behavioral Inhibition</td>
<td>17.8 ± 3.3</td>
<td>18.0 ± 3.4</td>
<td>-0.22</td>
<td>0.82</td>
<td>0.03</td>
</tr>
<tr>
<td>Behavioral Approach</td>
<td>43.9 ± 4.2</td>
<td>37.5 ± 5.3</td>
<td>4.5</td>
<td>0.00**</td>
<td>0.57</td>
</tr>
<tr>
<td><strong>Sensitivity to Punishment and Sensitivity to Reward Questionnaire</strong></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Sensitivity to Punishment</td>
<td>63.5 ± 12.1</td>
<td>61.5 ± 8.8</td>
<td>0.61</td>
<td>0.54</td>
<td>0.1</td>
</tr>
<tr>
<td>Sensitivity to Reward</td>
<td>64.5 ± 7.9</td>
<td>49.8 ± 7.3</td>
<td>6.4</td>
<td>0.00**</td>
<td>0.7</td>
</tr>
<tr>
<td><strong>Sensation Seeking Scale - Abstract Expression</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thrill and Adventure</td>
<td>16.1 ± 4.4</td>
<td>10.2 ± 3.4</td>
<td>5.03</td>
<td>0.00**</td>
<td>0.61</td>
</tr>
<tr>
<td>Disinhibition</td>
<td>16.9 ± 3.9</td>
<td>12.6 ± 3.8</td>
<td>3.73</td>
<td>0.00**</td>
<td>0.5</td>
</tr>
<tr>
<td>Experience Seeking</td>
<td>22.2 ± 3.1</td>
<td>16.8 ± 4.5</td>
<td>4.69</td>
<td>0.00**</td>
<td>0.59</td>
</tr>
<tr>
<td>SD = standard deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Test battery</strong></td>
<td></td>
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</tr>
</tbody>
</table>

Test battery

A test battery including the forward and backward digit span tasks [25], Rey-Osterrieth Complex Figure test [26,27], BIS/BAS scale [28], SPSRQ [29] and SSS-AE [30,31] was administered to test for group differences in attention, visuospatial cognition, episodic memory, and personality traits. Two-sample t-tests revealed significantly higher scores for PGs than NPGs on the BAS $[t(42) = 4.50, p < 0.001, r = 0.57]$, sensitivity to reward $[t(42) = 6.40, p < 0.001, r = 0.70]$, and multiple SSS–AE subscales (thrill and adventure seeking, $t[42] = 5.03, p < 0.001, r = 0.61$; disinhibition, $t[42] = 3.73, p < 0.001, r = 0.50$; and experience seeking, $t[42] = 4.69, p < 0.001, r = 0.59$). There were no group differences in any other scores (Table 2).
Gaze allocation

The proportions of validated measurements were sufficiently high and did not differ between the PGs (mean: 91.6, standard deviation [SD]: 7.4) and NPGs (mean: 92.1, SD: 6.3; \( t[42] = -0.24, p = 0.81, r = 0.04 \)). For each pixel, the ratios of gaze-allocation times in the decision, feedback, and fixation phases were calculated for both PGs and NPGs (Fig 2a). Their gaze was concentrated on the pictures in the decision and feedback phases, and on the fixation cross in the fixation phase, in both the PGs and NPGs. The ratios of gaze-allocation times at intervals of 25 pixels from each peak were compared between PGs and NPGs using the two-sample \( t \)-test with false discovery rate (FDR) corrections (Fig 2b). On the right side during the decision phase, the ratios of gaze-allocation times of PGs were significantly higher than those of NPGs only around the peaks (\( t[42] = 2.87, p = 0.03, r = 0.40 \)). Furthermore, the same pattern of differences was observed as a trend near the peaks on the right side during the feedback phase (\( t[42] = 2.34, p = 0.10, r = 0.34 \)). On the left side in the feedback phase, the reverse pattern (higher NPG ratios than PGs) was observed in the peripheral area. Higher PG ratios were not observed around the peaks on the left side (\( t[42] = -2.96, p = 0.02, r = 0.42 \)). No other significant differences were observed (\( p > 0.1 \) for all comparisons). Thus, two-way ANOVAs were performed on the sum of the gaze allocation times for the pixels corresponding to the left and right pictures. These analyses showed a significant interaction between side (left and right) and group (PGs and NPGs) in the decision and feedback phases [decision phase: \( F(1,42) = 6.46, p = 0.01, \eta^2_p = 0.13 \); feedback phase: \( F(1,42) = 6.06, p = 0.02, \eta^2_p = 0.13 \)] (Fig 3). Post hoc analyses revealed that the ratio of gaze allocation times was greater on the right side than on the left side in PGs (decision phase: \( p = 0.05 \); feedback phase: \( p = 0.02 \)), and that the ratio of gaze allocation on the right side was greater in PGs than NPGs (decision phase: \( p = 0.03 \); feedback phase: \( p = 0.00 \)). The main effect of side was statistically significant (right > left) in the feedback phase [\( F(1,42) = 4.34, p = 0.04, \eta^2_p = 0.09 \)]. No other main or interaction effects were statistically significant in the decision, feedback, or fixation phases (\( p > 0.1 \) for all comparisons).

Pupillary dynamics

The temporal dynamics of pupillary diameter were analyzed in each experimental condition based on the factors of motivation (reward, punishment, and control) and result (congruent and incongruent). To identify changes in pupillary diameter related to receiving rewards and punishments, differences in z-values between congruent and incongruent conditions were calculated (Fig 4a) and paired \( t \)-tests with FDR corrections were used to compare the averages of every 1 s and the last 500 ms (Fig 4b) between the reward and control conditions, and between the punishment and control conditions. In the PGs, punishment-related significant differences were observed during the time points over the feedback and fixation phases (\( t[21] = -3.02, p = 0.02, r = 0.55 \)), while significant reward-related difference was observed at the fixation phase time point (\( t[21] = 2.86, p = 0.02, r = 0.53 \)). These differences were not observed at other time points of the PGs and NPGs (\( p > 0.1 \) for all comparisons).
Discussion

In this study, eye-tracking measurements were made during a gambling task to compare gaze allocation and pupillary dynamics between PGs and NPGs. In the decision and feedback phases, gaze allocation was more concentrated around the peaks in PGs than in NPGs on the right side, and gaze was allocated more to the right picture than to the left picture in PGs, but not in NPGs. In addition, higher peripheral attention was observed for the left-hand pictures in the feedback phase in NPGs than in PGs. Furthermore, PGs showed a significantly greater pupil diameter in the reward and punishment conditions than the control condition. To our knowledge, this study is the first to demonstrate distinctive gaze allocation and pupillary dynamics characteristics in PGs while engaged in gambling.

Consistent with our hypothesis regarding attentional allocation, higher ratios of gaze allocation time were observed in PGs than in NPGs around the peaks on the right side during the decision and feedback phases. Previous studies have indicated that PGs have attentional bias to gambling-related stimuli compared to neutral stimuli. [6,34,35] Unlike previous studies that used non-gambling tasks (e.g., the Stroop, flicker, and lexical salience tasks) [36–38], in our study the PGs received rewards and avoided punishments based on their choice of neutral stimuli. Therefore, they may have concentrated on the neutral stimuli. While PGs gazed at the right-hand pictures more than the NPGs during the decision and feedback phases, peripheral gaze was greater toward left-hand pictures during the feedback phase for NPGs than PGs. This was presumably because PGs inspected the pictures more carefully to attempt to identify winning strategies that did not actually exist, while the NPGs explored a wider range of pictures. However, this difference in peripheral gaze was not observed for the right-hand pictures, possibly due to a masking effect of the attentional preference for right-hand pictures of PGs. Notably, there is a hemispheric imbalance in spatial attention, unlike visual information processing, in which the left hemisphere reflects the right visual field, and the right hemisphere the left visual field. Left unilateral spatial neglect due to injury in the right hemisphere, including the parietal lobe, has been reported in neuropsychological studies. [39] Heilman et al. proposed a theoretical model of unilateral spatial neglect, in which the left hemisphere directs attention to the right side, and the right hemisphere to both sides. [40] Based on this model, increased activity in the left hemisphere or decreased activity in the right hemisphere may result in an attentional bias to the right side in PGs. Davidson et al. proposed a model of cerebral asymmetry and approach-withdrawal, in which the left hemisphere exhibits greater activation during approach, and the right hemisphere during withdrawal. This model has been supported by numerous studies. [41–43] Other studies have indicated that this hemispheric asymmetry influences the BIS/BAS score [44–46], whereby activation of the left hemisphere is greater in participants with a higher BAS score who also make more disadvantageous choices on the Iowa Gambling Task. [47,48] In the present study, PGs had significantly higher BAS, SR, and SSS-AE thrill and adventure-seeking and experience-seeking subscale scores. In another study, higher novelty-seeking scores were associated with greater rightward attentional bias, and it was suggested that this bias was related to dopamine asymmetry favoring the left hemisphere. [49] Thus, excessive activity in the left hemisphere may lead to an attentional preference to the right side in PGs.
Consistent with our hypothesis regarding pupillary dynamics, the differences in z-values between the congruent and incongruent conditions reflected a significant difference of the punishment and reward conditions with the control condition only in PGs. Because pupillary dilation reflects activity in noradrenergic locus coeruleus neurons [10,11], the sympathetic nervous system of PGs may be excited by rewards and punishments. Previous studies have reported pupillary dilation during reward anticipation and violation of expectations. [12–17] In this study, a significant difference in the response to punishment was observed during the feedback and feedback phases, while a trend toward a difference in the responses to reward was observed during the fixation phase. Therefore, punishments may surprise PGs, and rewards may enhance reward anticipation for the next trial. A previous study showed that the peak pupil diameter response was delayed by 1–2 s from onset. [50] Therefore, it is also possible that pupillary responses reflect cognitive processes at earlier time points. However, there were no discernible differences between the conditions during the decision phase. The differences in response to reward and punishment observed in this study may reflect the feedback phase. Previous studies have reported irrational behavior during gambling (i.e., chasing losses), whereby people make riskier decisions after a loss than a win, and decide to continue gambling despite considerable losses. [51–53] It is possible that these differences may affect the decisions or neural activity of PGs during the next decision phase.

In conclusion, our investigations of attentional allocation and pupillary dynamics during gambling tasks indicate that there are two distinctive cognitive processing pathways in PGs. First, PGs allocate more attention to the right side because of asymmetrical activation favoring the left hemisphere. Second, PGs show pupillary dilation in association with noradrenergic locus coeruleus activity because of punishment-mediated surprise and expectations of future rewards. However, problematic behaviors in PGs could not be identified because the outcomes of gambling were completely controlled. Future studies should examine how these differences in attentional allocation and pupillary dynamics are related to cognitive abnormalities and behaviors in problem gambling and gambling disorder.

Declarations

Acknowledgments

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https://doi.org/10.1038/sj.npp.1300333.


**Figures**

**Figure 1**

**Experimental design.** Participants were required to choose the right- or left-hand picture during the decision phase. An inverted triangle was presented above the chosen picture. In the feedback phase, if the chosen picture was framed by a red line, the participant received a monetary reward. If the chosen picture was framed by a blue line, the participant received a monetary punishment. If the chosen picture was framed by a gray line or was not framed, the participant received no reward or punishment. The pictures
in the figure are not the actual stimuli used in the experiment, as we do not have the rights for their publication herein.

**Figure 2**

Gaze allocation. (a) Ratio of gaze allocation time for each pixel. The bottom indicated by the x- and y-axes represents the screen, and the z-axis represents the ratio. (b) Ratio of gaze allocation time at each distance (increasing in 25-pixel increments) from the peaks of each participant. The red line represents the PG ratios. The blue line represents the NPG ratios. The colored bands along the lines represent the 95% confidence intervals. *p < 0.05, + p < 0.1.

**Figure 3**

Ratio of gaze allocation time for zones corresponding to the left and right pictures. Error bars represent SDs. *p < 0.05.

**Figure 4**

Pupillary dynamics of the differences between the congruent and incongruent conditions in the reward, punishment, and control conditions. Dashed lines represent the onset of the feedback and fixation phases. (a) Pupillary dynamics for each sample. (b) Pupillary dynamics for every second and the last 500 ms. The colored bands along the lines represent the 95% confidence intervals. *p < 0.05, one-tailed.