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Circadian photoreception influences loss aversion

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Gambling behaviour is a persistent and growing societal problem. An unexplored factor that may encourage gambling behaviour is the impact of circadian photoreception on cognitive processes underlying the behaviour. We investigated the influence of circadian photoreception on loss aversion in gambling by altering the blue content of light while maintaining the same visual brightness. Fifteen participants (age 18–27 years, *M* = 20.40, *SD* = 2.03) completed an economic decision-making task under blue-enriched and blue-depleted light, of equivalent visual brightness, on separate occasions in a randomised order. The task required participants to choose between taking a risky gamble of a positive and negative outcome, or a less risky guaranteed outcome. Hierarchical Bayesian Modelling was conducted to derive individual parameter estimates for loss aversion, and trial-by-trial performance was analysed using linear mixed models. The findings demonstrated that individuals were significantly less loss averse under blue-enriched light compared to blue-depleted light (β = − .43, 95% *CI* [− .82, − .04], *p* = .03). This study shows that exposure to light that preferentially targets circadian photoreception reduces loss aversion, which may encourage gambling behaviour.

Keywords Circadian rhythms, Loss aversion, Blue light, Inhibition, ipRGCs, Cognition

Approximately 1.6 billion people worldwide engage in gambling activities[1]. The widespread availability of smartphones and computers has led to a surge in online gambling (e.g., sports betting), with the online gambling market projected to reach over US$136 billion by 2029[2]. The manipulation of gambling product designs can significantly influence gambling behaviour. For example, sound effects commonly associated with gambling, like the ringing bell on a slot machine following a win, have been shown to reinforce gambling behaviour[3]. Additionally, the use of light and colour may further exacerbate gambling behaviour[4,5].

Light has profound effects on cognition, enhancing alertness and attention through direct and indirect input to multiple brain regions[6,7]. Intrinsically photosensitive retinal ganglion cells (ipRGCs), a group of specialised retinal ganglion cells, contain the photopigment melanopsin and respond preferentially to short wavelength 'blue' light (~ 480 nm)[8]. Blue-enriched light typically exhibits the most considerable non-visual effects and is most effective for improving alertness, attention[9,10] and subjective wellbeing[6]. ipRGCs convey non-visual, largely non-conscious effects of light, projecting to brain regions involved in inhibitory control, risky decision-making, and emotion-regulation, including the inferior frontal gyrus,dorsal prefrontal cortex[11], and amygdala[12]. Light exposure can lead to suppression of activity in the amygdala[12], which plays an important role in motivation and sensitivity to reward. The ability of light to suppress amygdala activity may reduce fear-related effects commonly associated with gambling. Furthermore, decreased activity of the habenula, a brain region involved in reward regulation[13,14], is associated with increased expectation of reward[13], and has been shown to be impacted by light exposure in humans[15]. The ability of ipRGCs to suppress brain regions involved in decision-making and reward may enhance the encoding of rewarding stimuli while diminishing responses to loss. Consequently, light that preferentially activates ipRGCs could alter how likely someone is to engage in risky decision-making.

When individuals need to make a decision that involves risk and uncertainty (as per "Prospect Theory"), they are likely to value losses and gains disproportionately[16,17]. Prospect Theory suggests that we evaluate outcomes based on their relative utility, rather than absolute utility[16,17]. Therefore, individuals are more likely to feel worse about losing $100 than feel good about gaining $100. Loss aversion, a key component of Prospect Theory, refers to the preference for certainty over uncertainty[16,17], whereby the psychological pain of losing is stronger than the pleasure of gaining[16,17]. Loss aversion is modelled by a value function with an asymmetric 'S' curve[16]. In this model, gains and losses are defined relative to a reference point, often called the *status quo*, and the slope of the value function for losses is steeper than that for gains[17]. In gambling, reduced loss aversion is often associated with riskier gambling patterns[18,19].

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Using computational modelling, choice data in gambling tasks can be explained in terms of underlying parameters[20]. The loss aversion coefficient, lambda (λ), represents the weighting of the psychological value of losses compared to gains[16,21]. When λ is less than 1, gains are considered more valuable than losses, indicating a propensity for seeking gains[22]. Conversely, when λ exceeds 1, losses are perceived as more significant than gains, indicating heightened loss aversion[22]. By utilising such computational modelling techniques, we can evaluate an individual's responsiveness to loss and gain insights into how light exposure influences loss aversion.

Given that decision-making is influenced by underlying cognitive processes that are directly impacted by circadian photoreception, we anticipated that activation of circadian photoreceptors would alter an individual's sensitivity to loss. In this study, we tested the hypothesis that when exposed to blue-enriched light, individuals would exhibit lower levels of loss aversion, as indicated by higher λ values, compared to when exposed to blue-depleted light of the same visual brightness.

Method

Participants

A total of 15 young, healthy adults (five men) aged 18–27 years ($M = 20.40$, $SD = 2.03$) provided informed consent and completed this within-subjects study. All participants completed both light conditions, with the order of blue enriched/depleted light randomly assigned. Participants were free from major medical conditions, were not taking regular prescription medications, and had no personal history of psychiatric conditions. Participants were largely classed as intermediate types on the Morningness-Eveningness Questionnaire[23] (60% intermediate, $M = 44.13$, $SD = 7.57$). Mean self-reported bedtime and waketime were 24.76 and 8.50 in decimal clock time (SD = 1.62 and 1.38, respectively). The Monash University Human Research Ethics Committee (MUHREC) approved the study (Project #32054), and the study was conducted in accordance with the relevant guidelines and regulations.

Materials

Melagen lighting device

Light exposure was controlled using Melagen lighting (Versalux Lighting, Mitcham, VIC, Australia). The device is an LED light source (CR189), where participants are exposed to one of two lighting conditions: blue-depleted (peak wavelength of ~630 nm and colour temperature of ~2700 K) and blue-enriched (peak wavelength of ~485 nm and colour temperature of ~6500 K). The two lighting conditions were delivered at different melanopic equivalent daylight illuminance (~191.23 lx for the blue-enriched condition and ~77.57 lx for the blue-depleted condition), but the same photopic illuminance (visual brightness) of ~200 lx. The photopic illuminance of 200 lx for both conditions was chosen as it aligns with typical office settings[24], and as melatonin suppression is an indicator of melanopsin activation, photopic illuminance of 200 lx indicates that ipRGCs (which contain melanopsin) are activated. See Fig. 1 for a visual representation of the two lighting conditions' spectral qualities and visual differences.

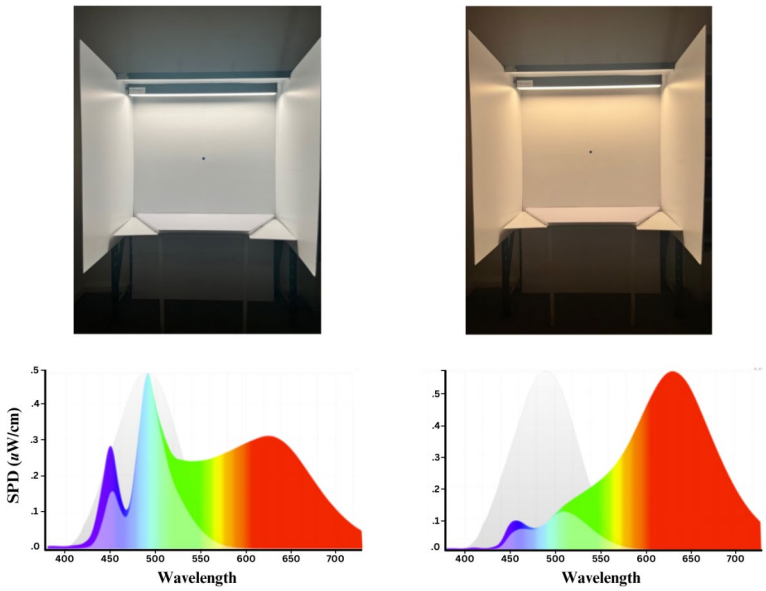

Fig. 1. The visual appearances and spectral distributions of the blue-enriched light condition (left) and blue-depleted light condition (right). Spectral power distributions (SPDs) were generated by the software f.luxometer LLC (Los Angeles, California, USA) and show the light's spectrum (coloured area), the melanopic action spectrum (grey curve with peak at ~480 nm), and the relative melanopic activation due to the light source (lightened area under coloured spectrum).

Economic decision-making task

Participants completed the Economic Decision-Making task to assess loss aversion, an adaptation of the Loss Aversion Task[22]. Participants were asked to take a risky gamble between a positive and a negative outcome or take a less risky guaranteed outcome (see Fig. 2 for a task schematic). After each decision was made, participants were informed of their result (e.g., "you won $10", "you lost $2.50", or "trial missed" if they failed to respond within 2 s of the signal). Participants were given a practice block of 7 trials, and once they confirmed their understanding of the task, they were presented with a further 140 trials. One hundred and twenty trials contained a mixture of positive and negative outcomes (e.g., win or lose), and 20 trials were positive gain-only gambles. Before completing the task, participants were informed of a $20 bonus, which was contingent upon their performance.

Procedure

Before attending the laboratory session, consented participants were asked to obtain a normal night's sleep and abstain from alcohol and caffeine for 24 h before each visit. Laboratory visits took place between four and seven hours after the participants' usual waketime, to avoid confounding by potential time of day or sleep inertia effects. The two sessions were completed at least two weeks apart (on average 14.5 days after the participant's first visit).

Upon arrival, participants were seated under the light device, with distance and height standardised by eye-level of 123 cm from the floor and 63.3 cm from a fixation point. Participants completed an initial 'dark' period (< 3 lx) for five minutes, and then completed the rest of the session under either the blue-enriched or blue-depleted light condition. Lighting condition order was randomised for the two sessions (blue-enriched-blue-depleted = 9 and blue-depleted-blue-enriched = 6). After ~ 34 min of light exposure, participants were asked to complete the economic decision-making task as quickly and accurately as possible (~ 10 min in duration). Participants were reimbursed up to $100 for their participation ($50 for study completion and an additional $50 dependent on task performance). Participants were required to reach a certain threshold to receive the additional compensation. The threshold was designed to enhance participation motivation; however, it was set at a level whereby all participants received the full payment.

Behavioural analysis and results

All statistical analyses were performed using R Statistical Software (v4.3.1)[25]. Hierarchical Bayesian Modelling was used to investigate differences between lambda (λ; loss aversion parameter) and the light conditions. Hierarchical Bayesian Modelling is based on the Prospect Theory framework, whereby loss aversion is formalised in accordance with the general formula[16]:

$$u\left(x^{+}\right) = x^{\rho}$$

$$u\left(x\right) = -\lambda \times \left(-x\right)^{\rho}$$

In this formula, u is the logit sensitivity, x is the outcome, λ represents the loss aversion coefficient and ρ is the curvature of the utility function.

Hierarchical Bayesian Modelling estimates the lambda parameter for individuals and pools information across individuals for group-level (condition) data. This results in "shrinkage" effects, where individual estimates inform the group estimates and sequentially inform the estimates of individual parameters[21].

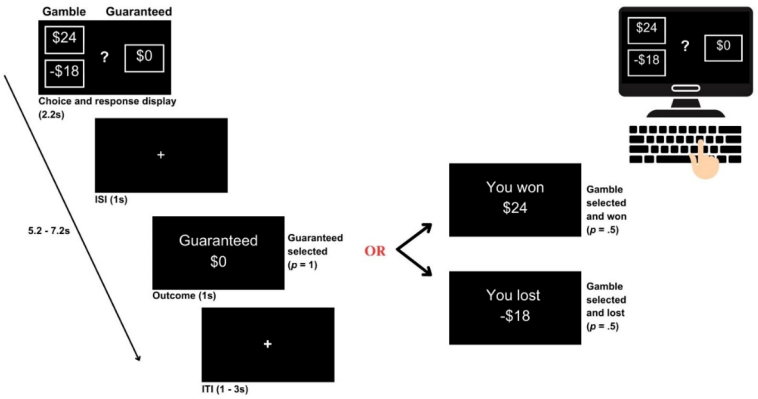

Fig. 2. A schematic of the Economic Decision-Making Task. Participants were asked to make monetary choices between gambles (winning and losing with equal probability = .5) and a guaranteed alternative (probability = 1), with the outcome following each choice. Participants were presented with the gamble and guaranteed amount and were required to accept the gamble or reject it for the guaranteed alternative (2.2 s). After an interstimulus interval (ISI) of 1 s, the outcome screen was presented consisting of a win or lose screen with equal probability if the gamble had been accepted, otherwise the guaranteed alternative if the gamble had been rejected (1 s). An intertrial interval (ITI) of 1–3 s separated each trial from the next. The schematic was generated by Canva.com.

	BE	BD	*t*	*p*	Cohen's *d*
RT_{gamble} (ms)	1.14 (.28)	1.12 (.29)	(11) .36	.72	.10
$RT_{guaranteed}$ (ms)	1.11 (.25)	1.09 (.26)	(11) .33	.75	.09
Risky propensity (Males)	60.27 (14.97)	55.13 (8.35)	(6.27) – .67	.53	.42
Risky propensity (Females)	39.7 (18.09)	36.05 (20.78)	(11.78) – .36	.73	.19

Table 1. Summary of economic decision-making task variables. BE, Blue-enriched light; BD, blue-depleted light; RT, response time.

Model ranking	Model equation	K	LL	AICc	delta AICc	AICc weight
1	Loss aversion (λ) ~ (1|participantID) + condition + sex	5	– 31.26	75.02	.00	.61
2	Loss aversion (λ) ~ (1|participantID) + condition + sex + condition*sex	6	– 30.11	75.88	.86	.39

Table 2. AICc-based comparison and marginal log-likelihood (LL) of linear mixed-effects for predicting loss aversion parameters, influenced by light condition and sex. K is the number of fitted parameters and AICc weight represents the likelihood of each model being the best description of the dataset. . condition = blue-enriched or blue-depleted light condition; delta AICc = difference in AIC score between the best model and respective model; AICc weight = proportion of the overall predictive power contributed to by the respective model compared to the set of models; (1|participant) = random intercept for each participant.

The hBayesDM package in R was used to estimate lambda coefficients (λ), the loss aversion parameter. Parameter estimates were obtained using a hierarchical Bayesian method that uses Markov-chain Monte Carlo (MCMC) sampling to generate full posterior distributions of model parameters. Models separated by sex were fit, and individual parameter values (λ) were computed using the ra_noRA function. The ra_noRA function used 10,000 iterations to produce λ values for individuals in light conditions (blue-enriched and blue-depleted). Convergence of the Markov chains was determined by visual inspection of the chains for all parameters. Convergence was also quantitatively diagnosed to ensure that samples were adequately mixed and converged, indicated by trace plots and Rhat values < 1.1.

Summary behavioural data

Under blue-enriched light, males exhibited an average propensity to choose the gamble option in 60.27% of trials, compared to 39.76% for females. Under blue-depleted light, males demonstrated a slightly lower propensity (55.15%), as did females (36.05%). Therefore, males were more likely to choose the riskier option across both light conditions, but the differences between conditions were not statistically significant ($p > .05$; see Table 1). In addition, response times for guaranteed and gamble options did not significantly differ between blue-enriched and blue-depleted light (see Table 1 for a summary).

Loss aversion (λ) parameter estimation

Under blue-enriched light, the computed mean (with 95% HDI) for men was λ = .79, [.56, 1.06]. As λ < 1, under blue-enriched light, men tended to be more gain-seeking than loss averse. In comparison, the computed mean (with 95% HDI) for women was λ = 1.39, [1.08, 1.77]. As λ > 1, women under blue-enriched light were more loss averse than gain-seeking.

Under blue-depleted light, the computed mean (with 95% HDI) for men was λ = .82, [.63, 1.05], indicating that men were gain-seeking under blue-depleted light (λ < 1). In comparison, the computed mean (with 95% HDI) for women was λ = 2.01 (1.45, 2.66), indicating that women were highly loss aversive under blue-depleted light ($\lambda \gg 1$). There was no meaningful difference between the groups.

Effects of light condition and sex on loss aversion parameters

Linear mixed-effects models were fit to investigate the influence of light conditions (blue-enriched and blue-depleted light) on loss aversion (λ) parameters, estimated and analysed on a trial-by-trial basis and within-subjects (estimated using restricted maximum likelihood (REML) and nloptwrap optimizer). Random intercepts for each individual were included to control for individual differences across conditions (*formula: ~ 1|participant)*. We included 'condition' (blue-enriched or blue-depleted light), 'sex' and the interaction between 'condition' and 'sex' (condition*sex) as predictor variables in a possible set of models (see Table 2 for model comparison). The best overall model was assessed using the Akaike Information Criterion corrected for small sample sizes (AICc)[26]. A Wald t-distribution approximation method was used to calculate 95% confidence intervals and p-values. Assumptions of linearity, homoscedasticity and normal distribution of the y-intercept were met. Although the normal distribution of the outcome variable was not met, it did fit the expected distribution of lambda, and thus no transformation was conducted.

The best overall model included the intercept, condition, and sex. The model explained a majority of the variance, as indicated by the conditional R^2 value of .66. The proportion of variance explained by the fixed effects alone was 31%, as indicated by marginal R^2. The ICC indicated that 50% of the total variance in λ (loss aversion) was attributable to between-person differences (τ00 = 0.27). See Table 3 for model parameter estimates.

Fixed effects	β	SE	95% CI [UL, LM]
Intercept	1.94***	.22	[1.48, 2.40]
Condition (blue-enriched)	− .43*	.19	[− .82, − .4]
Sex (male participant)	− .92*	.35	[− 1.64, − .21]

Table 3. Linear mixed effects model coefficient (β) for predicting loss aversion (λ) by light condition (blue-enriched and blue-depleted light) and sex. Presented in order of ranking of Table 2; β = model coefficient; SE = standard estimates; LL = Lower Confidence Interval; UL = Upper Confidence Interval; * = $p \leq .05$; ** = $p \leq .01$; *** = $p \leq .001$.

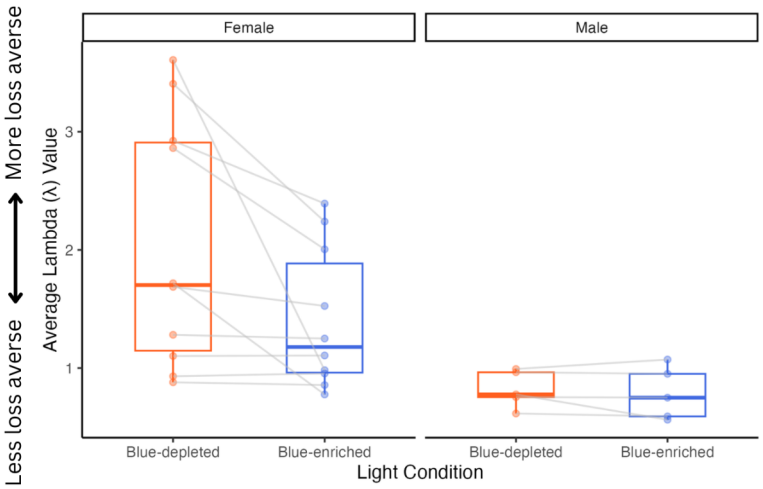

Fig. 3. Distribution of individual loss aversion (λ) parameter values across lighting conditions (blue-enriched and blue-depleted light), separated by sex. See supplementary table 1 and 2 for the individual Lambda parameter (λ) for each participant under the different light conditions.

For the best-fit model, the intercept indicates that women in the blue-depleted condition had an average loss aversion parameter of λ = 1.94. Light condition significantly affected the loss aversion parameter, whereby blue-enriched light condition was associated with a − .43 average decrease in loss aversion (see Fig. 3). Conceptually, the loss aversion parameter can be viewed as an equivalent monetary amount in dollars. Therefore, under blue-depleted light, women participants required a potential win of $204 (λ = 2.04) to risk losing $100. When exposed to blue-enriched light, λ decreased by 0.43 (λ = 1.51). Therefore, women required a lower potential win of $151 to risk losing $100 under these conditions. Additionally, sex significantly affected the loss aversion parameter, with a.92 decrease in the loss aversion parameter (λ = 1.02) in men.

Discussion

We investigated the potential influence of circadian photoreception on loss aversion during a gambling task, by manipulating the melanopic brightness of light while controlling for visual brightness. Our results revealed a decrease in loss aversion under blue-enriched light, which has a greater impact on circadian photoreceptors. We also found significant differences in loss aversion between sexes across the two light conditions, with women displaying greater loss aversion compared with men.

Individuals tend to have an unequal balance of evaluations between losses and gains, with losses typically outweighing gains for subsequent behaviour[16]. Under blue-enriched light, our findings reveal that individuals are less loss averse, suggesting that when under such light, individuals are relatively more comfortable with taking risks and demonstrate a reduced sensitivity to losses compared to gains of equal magnitude. In a gambling scenario, individuals under blue-depleted light might perceive the subjective impact of a $100 loss as significantly larger than the potential $100 gain. However, under blue-enriched light, the subjective impact of a $100 loss may not be as large, leading individuals to have less negative reaction to losses. Manipulations that alter this balance are important for subsequent behaviour as this could affect whether someone decides to continue engaging in gambling activities or discontinuing.

Our findings demonstrate that individuals exhibit reduced loss aversion under blue-enriched light, while controlling for visual brightness (~ 200 lx for both conditions). As both the spectral quality and intensity of light can impact cognition and several brain regions[9,10,12,27], by controlling the visual brightness, we were able to isolate the specific influence of blue content on circadian photoreceptors, which are known to affect brain regions associated with decision-making. It is possible that reduced loss aversion under blue-enriched light may be due to the effect of light, via ipRGCs (which preferentially respond to blue light[8]), on specific brain regions. In rodents, ipRGCs have been found to innervate the amygdala[28], a structure that plays a pivotal role in reward

processing[29] and is part of an impulsive system that triggers emotional responses to immediate outcomes[30]. The amygdala is believed to play an important role in evaluating the subjective appeals and disadvantages of potential gains and losses during mixed gambles[31]. Previous work has found an association between reduced amygdala response to loss and emotional regulation strategies, including reappraisal (i.e., reframing how individuals think about outcomes)[22,32], with damage to the amygdala reducing loss aversion[33]. As bright light suppresses amygdala activity[12], exposure to blue-enriched light may reduce negative emotions and the ability to evaluate subjective appeals, resulting in individuals being less averse to potential losses.

In addition to the amygdala, the habenula plays a role in the decision-making process, including reward regulation[13,34]. Animal studies suggest that the habenula deters behaviours associated with negative outcomes (e.g., punishment), while reinforcing those linked to positive outcomes, influencing motivation and decision-making[35]. Specifically, the lateral habenula is implicated in reward prediction. Neurons in the lateral habenula encode negative reward prediction error and are activated by unexpected, non-rewarding and unpleasant events while being suppressed by unexpected rewarding events[14]. Heightened activation of the lateral habenula may inhibit individuals from accepting risky gambles, guiding them towards safer outcomes and potentially increasing their loss aversion. In humans, light has been found to directly impact habenula activation in fMRI studies[15]. Through direct input from retinal ganglion cells and other brain structures involved in non-visual photoreception, the impact of light on habenula activation may lead to an elevated expectation of reward, reducing the psychological "pain" typically associated with losses and making individuals less averse to loss[35]. The brain's reward system likely contributes to the observed reduction in loss averse behaviour under blue-enriched light. Dopamine, a key neurotransmitter involved in daily functioning, plays a central role in the reward system by processing reward information[36,37]. Dopamine neurons exhibit responses relative to reward prediction, with unexpected rewards triggering increased activation and expected rewards leading to maintained or decreased activity[37,38]. Dopamine neurons project to brain regions such as the insula and striatum, where heightened activity in response to gains causes a reduced sensitivity to loss[31]. These regions are implicated in circadian photoreception, with bright light exposure enhancing their activation[7,39,40]. This suggests that light can boost activity in reward-related brain regions, potentially amplifying the influence of the reward system. Consequently, individuals may value potential rewards more and find riskier decisions more appealing under blue-enriched light.

In addition to the observed effects of light on decision-making processes, we observed substantial interindividual differences in loss aversion. Our findings revealed lower loss aversion among men, consistent with existing literature highlighting sex differences in loss aversion[41–44]. Women often experience more negative emotions (e.g., fear), leading to a lower willingness to undertake financial risk (e.g., invest less money or gamble less)[45,46]. Conversely, men tend to experience more positive emotions associated with gambling (e.g., optimism and confidence), which may predispose them to underestimate negative outcomes[45–47]. Furthermore, neurobiological differences may play a role, as men and women have shown disparities in brain regions associated with decision-making. For example, men often exhibit activation in regions such as the lateral orbitofrontal cortex (OFC) and DLPFC during risky decision-making, whereas women may show activation primarily in a smaller region of the left medial OFC[41,48]. Therefore, the observed sex disparities in loss aversion may arise from a complex interplay between emotions and neurobiological differences in brain activation patterns.

There are substantial interindividual differences in light sensitivity mediated by circadian photoreception. Previous work has found a greater than 50-fold difference in sensitivity to evening light, with some individuals exhibiting > 50% melatonin suppression (a marker of light sensitivity) in response to dim light (~ 10 lx), while less sensitive individuals required ~ 400 lx (equivalent to bright office lights) to achieve the same melatonin suppression[49]. Several factors are associated with individual differences in light sensitivity, with younger individuals exhibiting higher sensitivity to light compared with older populations[50–52]. Additionally, increased sensitivity of the circadian system to light has been found among individuals with bipolar disorder, with increased sensitivity to light suggested to be a trait marker of bipolar disorder[48,49]. Younger adults are more likely to engage in risky gambling behaviour[53–56], and the risk of problem gambling is four times higher in patients with bipolar disorder than the general population[57]. If gambling behaviour and loss aversion are influenced by circadian photoreception, it is likely that individuals with higher light sensitivity would experience less of an impact to loss and therefore gamble more than individuals who are less sensitive to light.

It should be noted that this study had a relatively small sample size for computational modelling[58,59]. However, our model diagnostics indicated that the MCMC samples converged with values less than 1.1, highlighting reliability in the model estimates[19]. Furthermore, the within-subjects design of our study substantially boosted statistical power. However, given the small sample size and sex imbalance, additional studies of light condition and loss aversion are needed as it is possible that this limitation may have masked potential interactions of sex by light condition on loss aversion. Furthermore, with respect to interpretation of the findings, while the visual brightness of both conditions was equivalent, we were unable to exclude the role of differences in visual experience between the light conditions.

The ability to control our light environment is a relatively recent development. In our natural history, light exposure was largely determined by the rise and fall of the sun. Humans now spend ~ 90% indoors under artificial light[60], and with the growing dominance of energy-efficient LED lights, this light tends to be more blue-enriched, leading to increased activation of circadian photoreception. Virtually all machines used for gambling, including slot machines, now employ LED/LCD displays which are known for their high light intensity and blue-enriched light content. Furthermore, with the prevalence of online gambling increasing, individuals are turning to devices that are likely to emit blue-enriched light (e.g., smartphones and tablets). Exposure to blue-enriched displays possibly contributes to increased gambling behaviour, by reducing an individual's loss aversion, thereby making them more likely to select uncertain financial outcomes over guaranteed, safer choices. Targeting the reduction

of "blue" light content in gambling scenarios may be a promising target for reducing gambling behaviour by promoting greater loss sensitivity.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions

This study was designed by Sean W Cain, Alicia C Lander and Malisa T Burge. Data collection was undertaken by Alicia C Lander, Malisa T Burge and Briana G Thomas. Data analysis was conducted by Alicia C Lander, Malisa T Burge and Briana G Thomas. The manuscript was written by Alicia C Lander, with all authors providing critical input on and editing the manuscript prior to submission.

Declarations

Competing interests

SWC and AJKP have received research fundings from Delos and Versalux, and they are co-founders of Circadian Health Innovations Pty Ltd. ACL, MTB, BGT and EMM declare no potential conflict of interest.

Additional information

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