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DOI:
10.1093/sleep/zsac120

SLEEP, 2022, 1–11

https://doi.org/10.1093/sleep/zsac120
Advance Access Publication Date: 6 June 2022
Original Article

ORIGINAL ARTICLE

Sex moderates the effects of total sleep deprivation and sleep restriction on risk preference

Jeryl Y. L. Lim[1,], Johanna Boardman[1], Jeff Dyche[2], Clare Anderson[1,], David L. Dickinson[3,4,5,] and Sean P. A. Drummond[1,*,]

[1]Turner Institute for Brain and Mental Health and School of Psychological Sciences, Monash University, Melbourne, VIC, Australia, [2]Department of Psychology, James Madison University, Harrisonburg, VA, USA, [3]Department of Economics and CERPA, Appalachian State University, Boone, NC, USA, [4]Economics Science Institute, Chapman University, Orange, CA, USA and [5]Institute of Labor Economics, Bonn, Germany

*Corresponding author. Sean P. A. Drummond, Turner Institute for Brain and Mental Health and School of Psychological Sciences, Monash University, 18 Innovation Walk, Room 542, Clayton, VIC 3800, Australia. E-mail: sean.drummond@monash.edu.

Abstract

Sleep loss has been shown to alter risk preference during decision-making. However, research in this area has largely focussed on the effects of total sleep deprivation (TSD), while evidence on the effects of sleep restriction (SR) or the potentially moderating role of sex on risk preference remains scarce and unclear. The present study investigated risky decision-making in 47 healthy young adults who were assigned to either of two counterbalanced protocols: well-rested (WR) and TSD, or WR and SR. Participants were assessed on the Lottery Choice Task (LCT), which requires a series of choices between two risky gambles with varying risk levels. Analyses on the pooled dataset indicated across all sleep conditions, participants were generally more risk-seeking when trying to minimise financial loss (LOSSES) than while trying to maximise financial gain (GAINS). On GAINS trials, female participants were more risk-averse during TSD and SR, whereas male participants remained unchanged. On LOSSES trials, female participants remained unchanged during TSD and SR, whereas male participants became more risk-seeking during TSD. Our findings suggest the relationship between sleep loss and risk preference is moderated by sex, whereby changes in risk preference after TSD or SR differ in men and women depending on whether the decision is framed in terms of gains or losses.

Statement of Significance

While sleep loss has been shown to impact risk preference, few studies have investigated how sex moderates this relationship. Most studies also utilise total sleep deprivation (TSD) protocols, while the effects of sleep restriction (SR) remain under-researched. We found males and females responded differently to sleep loss. While females became more risk-averse during TSD and SR when maximising gains, males became more risk-seeking during TSD when minimising losses. This has operational relevance for professions where risky decision-making is an intrinsic aspect of the job. Efforts by organisations to reduce detrimental risky decisions made by employees should take into consideration the employees' sex, the type of sleep loss experienced, and the way decisions are framed.

Key words: risk preference; decision-making; sleep; insufficient sleep; sex

Submitted: 14 January, 2022; **Revised:** 16 May, 2022

Introduction

Insufficient sleep is an increasingly common phenomenon among Western populations. The proportion of people who report less than 7 h of sleep per day range from 35.2% in the United States [1] to 47% in the United Kingdom [2] and 67.8% in the Netherlands [3]. Additionally, 12% of Australian adults report less than 5.5 h of sleep per day [4]. This represents a significant public health and safety concern as sleep deprivation can result in erratic on-the-job decisions in several professions including pilots [5], physicians [6], emergency and military personnel [7–9]. Notably, decisions made in these lines of work may come with significant consequences. As such, it is important to investigate how sleep deprivation may affect risk preference in the process of decision-making.

Early efforts to investigate how experimentally induced sleep loss affects risky decision-making commonly employed the Iowa Gambling Task (IGT) to measure risk attitudes. The IGT requires individuals to maximise monetary reward by selecting card draws between a low-risk deck (i.e., small gains and small losses, and ultimately advantageous) or a high-risk deck (i.e., large gains/losses and ultimately disadvantageous) over several trials. Across these studies, sleep-deprived participants consistently showed higher frequencies of high-risk choices compared to well-rested participants [8, 10, 11]. Additionally, sleep-deprived participants in these studies tended to persevere with disadvantageous card draws over consecutive trials, whereas well-rested participants gradually learned to avoid riskier choices in favour of the more advantageous option. This finding has been replicated in later studies using a variety of other risky choice tasks [11, 12], indicating sleep loss generally drives individuals toward more risk-seeking behaviour. However, it is important to note not all studies have replicated this general effect [13–16], and several factors can influence the effects of sleep loss of risky decision-making.

One such factor is whether a risky choice is framed as an attempt to maximise gains or an attempt to minimise losses. Specifically, individuals tend to be more risk-averse when the consequences are framed in terms of gains, and more risk-seeking when consequences involve losses [17, 18]. Despite this observation, several studies examining sleep and risk preference have used a variety of risky choice tasks that either assess decisions only in the gains domain [12, 13, 19] or do not distinguish between both domains at all [10, 15, 20], confounding decisions made under different contexts. So far, the few studies taking the framing effect into account when investigating how sleep loss affects risky decision-making report conflicting findings. In a within-subjects design, McKenna et al. [21]. reported participants showed the expected pattern of being risk-averse when making decisions in the gains domain and risk-seeking in the losses domain. After one-night total sleep deprivation (TSD), they became less risk-averse on gains and less risk-seeking on losses, suggesting sleep loss results in more risk-neutral attitudes by attenuating risk sensitivity. A separate study by Venkatraman et al. [16]. showed participants increasingly preferred maximising the magnitude of gains over minimising the magnitude of losses after one night of TSD, indicating a general shift toward risk-seeking as a result of sleep loss. Others have failed to replicate either of these findings. While Sundelin et al. [14]. found no significant difference in participants' risk preference on either gains or loss framing trials before and after 2 nights of sleep restriction (SR) to 4 h in bed, Dickinson et al. [22]. similarly found no effect of self-selected shorter sleep duration on risky choices framed either as gains or losses. In addition to the variety in risky choice tasks employed, these conflicting findings even among the studies accounting for the framing effect further contribute to inconsistency in the evidence base. Thus, it remains unclear the extent to which the classic framing effect moderates the influence of sleep loss on risky decisions.

A second factor shown to influence risk preference is sex, where, typically, women are more risk-averse than men when making risky decisions [23], and this observation appears consistent regardless of how decisions are framed [24]. Potential explanations for this sex effect include women having higher risk sensitivity [25, 26] and/or a tendency to underestimate potential upside gains carried by decision outcomes [27]. Relatively few studies have examined whether sex influences the changes in risk preference during sleep loss. One study showed women became more risk-averse while men became more risk-seeking when making risky decisions related to financial gains after one night of TSD [19], indicating a potential amplifying effect of sleep loss on the inherent risk biases of women and men. However, while findings from Acheson et al. [28]. replicate women becoming more risk-averse after TSD, men were unaffected in that study. Given the scarcity of research in this area and the mixed results yielded, more evidence is needed to better understand how sex moderates the relationship between sleep loss and risky decision-making.

Lastly, virtually all the previously cited studies investigating sleep loss and risk preference utilised TSD protocols. Their findings are limited in ecological validity as most of the general population experiences sleep loss in the form of partial sleep deprivation, or SR, rather than a total absence of nightly sleep. The few studies investigating the effects of SR on risky decision-making have yielded conflicting findings. While Maric et al. [12]. found 7 nights of SR resulted in increased risk-seeking, Sundelin et al. [14]. failed to replicate this relationship in their sample. Additionally, recent findings from Dickinson et al. [22]. indicate shorter actigraphically-derived nightly sleep times over a week did not significantly predict changes in risk preference. Hence, while the majority of TSD studies report an influence of sleep loss on risk preference, the effects of SR on risk preference remains unclear.

Here, we aimed to address each of these potential moderators of the impact of sleep loss on risk preference. Specifically, we investigated whether framing, sex, and the type of sleep loss (TSD vs SR) affect risky decision-making. In a within-subjects design, male, and female participants completed a risky choice task based on that presented in McKenna et al. [21]. and recently reported in Dickinson et al [22]. during both a well-rested condition and after either 24-h TSD or four nights of SR. We hypothesised sex would have a moderating effect on the relationship between sleep loss and risky decision-making, and this effect would be the same regardless of how the risk was framed. Specifically, across both gain and loss frames, female participants would become more risk-averse after TSD and SR, whereas male participants would become more risk-seeking.

Methods

Participants

We collected data from 47 healthy adults (M_{age} = 24.57, SD_{age} = 5.26; 24 females, 23 males). Eligibility criteria were: between 18 and

39 years old, no current, and/or unmanaged medical or psychiatric diagnoses, and no personal history of Axis I disorders or family history of mood or psychotic disorders, and regular consumption of ≤ 300 mg caffeine/day. Additionally, participants were required to have habitual sleep-wake schedules of 7–9 h of time-in-bed (TIB) with bedtimes of 2200–0000 h, and wake times of 0600–0800 h. Prior to participation, all participants were screened for medical disorders via a physical examination by a physician. Drug use was assessed through laboratory tests, and psychiatric (Axis I) disorders were screened using the Structured Clinical Interview for DSM-IV (SCID-IV), administered by a trained researcher. During the first night in-lab, participants were screened for sleep disorders via polysomnography.

Design and Procedure

Ethical approval was obtained from the ethics committees of the University of California, San Diego, and the VA San Diego Healthcare System prior to commencement. All participants provided written informed consent.

The present study employed a 2 × 2 mixed within- and between-subjects, repeated-measures design. Participants were required to complete a Well-Rested (WR) condition consisting of 9 h TIB for 6 nights (four at-home and two in-lab), and one of two randomly assigned experimental conditions: SR, consisting of 4 h TIB for 4 nights in-lab, or TSD, involving a 24 h sleep deprivation period. Condition order was counterbalanced. For WR, if the participant's habitual sleep schedule did not involve 9 h TIB, we extended their sleep period equally in the evening and morning to achieve 9 h. For SR, we used the midpoint of their habitual sleep period as an anchor to reduce sleep time equally in the evening and morning. Test times were scheduled according to each participant's habitual wake time rather than a set clock time to ensure each participant was tested at the same time since habitual wake. Before undergoing each condition, participants were required to maintain their habitual sleep schedules for one week. Adherence to at-home sleep schedules was ensured via sleep actigraphy, sleep diaries, and voicemail call-ins. Actigraphy data from at-home weeks indicated participants were generally compliant with their sleep-wake schedules at home. Across participants, mean bedtimes, and waketimes were 2332 h (min = 1059 h, max = 0011 h) and 0804h (min = 0727 h, max = 0845 h) respectively for the pre-WR week, and 2320 h (min = 2255 h, max = 2352 h) and 0757 h (min = 0725 h, max = 0846 h) for the week prior to their assigned TSD/SR conditions. Participants clocked an average time-in-bed (TIB) of 8.47 h (SD = 0.66) time-in-bed (TIB) for their at-home week prior to WR, and 8.58 h (SD = 0.60) for the week prior to their assigned sleep conditions. In the lab, actigraphy data indicated an average 9.12 h (SD = 0.23) TIB during WR, and 4.03 h (SD = 0.06) TIB during SR.

In the lab, participants were monitored using actigraphy during sleep and wake periods, and with polysomnography during sleep periods. Participants stayed in a windowless sleep lab, and in-lab lighting was kept constant at 100 lux throughout waking hours and 0 lux during sleep. Consumption of stimulants or alcohol was prohibited from 48 h before and during lab stays. Wakefulness was ensured continually via staff interaction, especially during the subjective night where participants were particularly vulnerable to sleepiness. While not undergoing testing, participants were allowed access to books, television, and the internet. In WR, the risky choice task was administered 1.5–2.5 h post-habitual wake. For TSD and SR, task administration occurred between 0.5 h before and 0.5 h post-habitual wake time in order to match the 23 h TSD protocol in our prior published paper using the same task [21]. Illustrations of each experimental protocol and the sleep-wake schedule during testing week for each condition are included in Figure 1,A and B respectively.

Materials

Karolinska Sleepiness Scale (KSS)

The KSS [29] was used post-test to capture subjective ratings of sleepiness in each sleep condition. The KSS consists of a 9-point scale on which participants indicated current levels of sleepiness, where "1" indicates "Extremely Alert", and "9" indicates "Extremely Sleepy". Scores on the KSS correlate highly with behavioural and electroencephalographic (EEG) measures of sleepiness [30].

Lottery Choice Task (LCT)

The LCT was used to assess risk preference, as previously described in Dickinson et al. [22]. and McKenna et al. [21].. Two different versions of the LCT were used, each with 40 trials. On one version of the task (Figure 2A), participants sought to maximise monetary gain (GAINS), and on the other (Figure 2B), they sought to minimise monetary losses (LOSSES). Within each risky choice trial, participants were given a choice between two sets of gambles (A or B). Risk levels associated with each choice varied across trials, and none of the trials were risk-free. As is standard, risk was defined as the variance in win/loss possibilities for that choice, with greater risk being associated with greater variance. The low-risk option of every choice was constant, and only the high-risk choice varied. Decisions made by the participants were associated with real monetary gains and losses. One trial from each version of the LCT was randomly selected following the completion of all trials to determine the payout. That is, the computer would randomly select a red, blue, or yellow chip from the participant's chosen gamble on the selected trial, and the individual would then win or lose the amount of money associated with that colour chip in the gamble they chose.

For each trial, decisions were classified as "risk-averse" if participants chose the less risky gamble (i.e. the one with smaller payoff variance), and "risk-seeking" if they chose the more risky gamble (i.e., the one with the higher variance). Decisions on all trials were used in the analyses. Stimulus materials for the LCT can be found in the supplemental materials section of our previous paper using the same task [22].

Data Analyses

Data analyses were performed using the *lme4* and *lmerTest* packages in *RStudio* and residual diagnostics were conducted with the *DHARMa* package [31]. Significance levels were set at $\alpha = 0.05$. The prior published paper using this same basic task with TSD showed robust effects [21]. Within that study, the effect size of the condition (TSD vs Normal sleep) by framing (gains vs

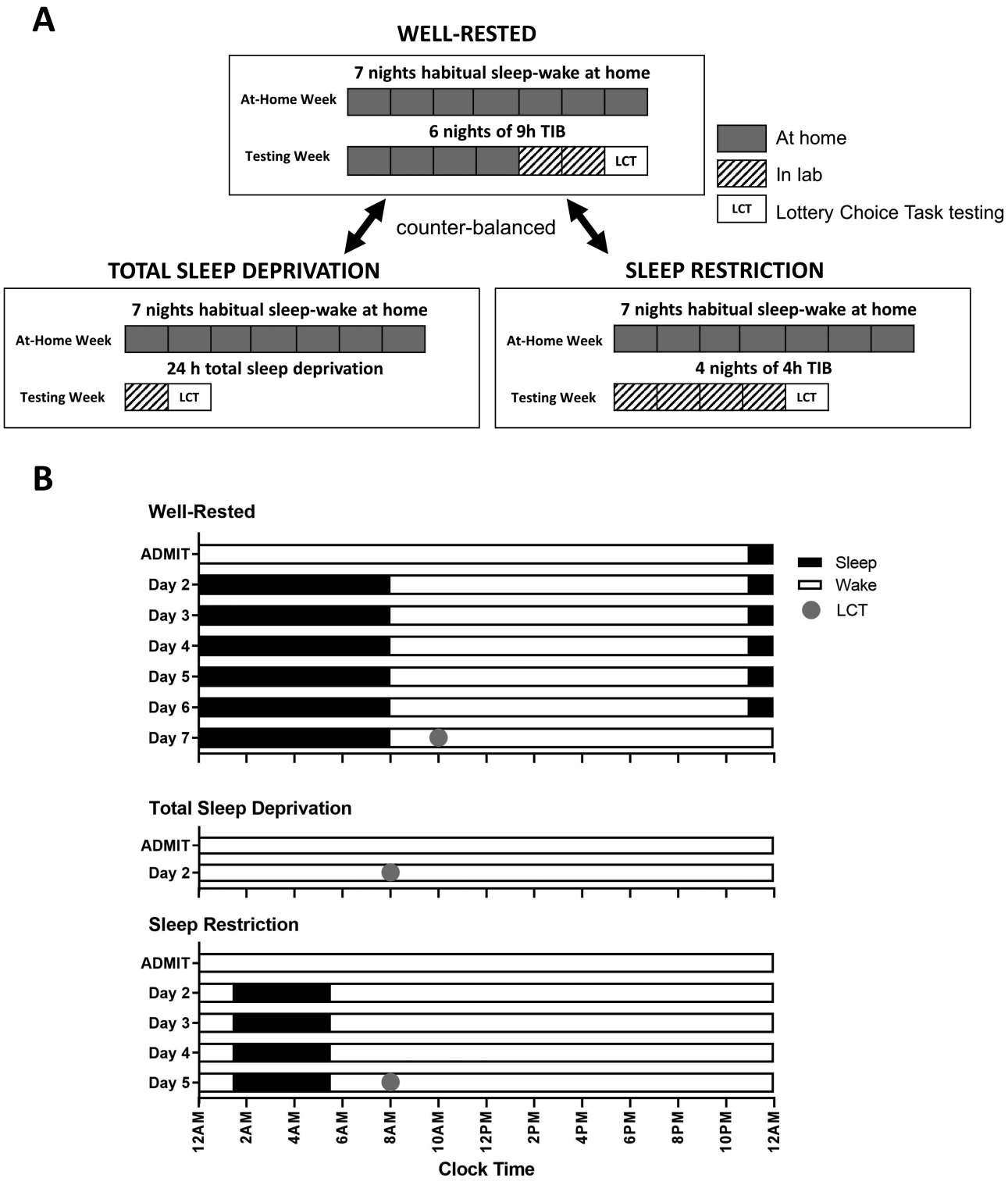

Figure 1. Study timeline of each condition. (**A**) Shows the timeline of the study protocol. LCT = Lottery Choice Task. All participants underwent a Well-Rested (WR) condition and were randomly assigned to either the Total Sleep Deprivation (TSD) or Sleep Restriction (SR) condition. The order in which participants completed their assigned sleep conditions was counterbalanced. Participants adhered to their habitual sleep-wake times during the at-home week. (**B**) Presents the sleep-wake schedules during testing week for each condition (nominal 8 am habitual wake time).

losses) interaction was $f = .65$. Based on that, for this study, we estimated power = .975, with $n = 20$/group (i.e., TSD vs PSD). The two studies cited above examining sex*sleep loss reported effect sizes of $f = .5$ and f = .45 [19, 28]. Using the smaller of the two, $n = 22$/group provides power = .953. We exceed those sample size estimates, here.

Of the 47 participants, three failed to complete their respective sleep loss conditions, but were able to complete their

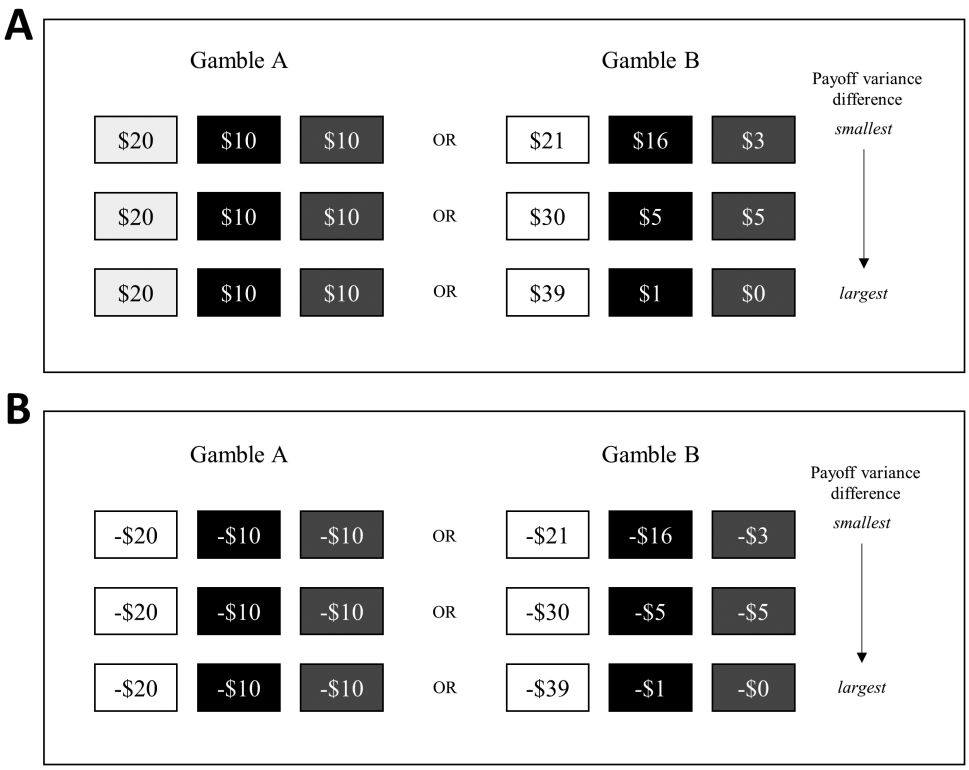

Figure 2. Lottery choice task paradigm examples. Examples of trials on the GAINS (**A**) and LOSSES (**B**) versions of the Lottery Choice Task, ordered by increasing difference in payoff variance between gambles (top to bottom). Participants were told there was an equal chance of drawing a red, blue, or yellow chip on each chosen gamble, and payoff values depended on the colour of the chip chosen. In each example depicted here, Gamble A is the safer choice due to a smaller variance across payoff values compared to Gamble B.

WR stays. KSS data were missing in 8 instances across 6 participants. We chose to include data from these participants in the final analyses due to the tolerance of mixed effects modelling for missing data. Table 1 presents the breakdown of participant characteristics by sleep condition.

Subjective Sleepiness

To examine if our TSD and SR manipulations influenced participants' subjective sleepiness, we fitted a random intercept linear mixed model where KSS score was regressed on a factor variable *Condition* that coded for each of the three sleep conditions. Our assumption checks revealed a positive skew in the distribution of KSS scores and heterogeneity of residual variance, but attempted data transformations did not alleviate these issues. In the interest of maintaining interpretability of KSS scores, we decided to proceed with the untransformed data. Furthermore, prior research has demonstrated linear mixed model estimates to be generally robust toward violations of distributional assumptions [32].

Risky Decision-Making

To evaluate participant responses on the LCT, we coded responses on each trial as "0" if they selected the riskier gamble and "1" if they picked the safer gamble. This created a dichotomous *Risk Choice* dependent variable. Next, we clarified if participant responses on the LCT exhibited the basic gain versus loss framing effects. To achieve this, we subset the data by *Condition* (WR, TSD, and SR) and on each subset, we ran a random intercept logistic mixed model where *Risk Choice* was regressed on a dichotomous variable *Frame* that denoted if the response was on a GAINS (0) or LOSSES (1) trial.

To investigate how sex moderates the effect of sleep loss on *Risk Choice*, we ran two separate random intercept logistic mixed models, one using only data from GAINS trials and the other with data from LOSSES trials. We ran separate GAINS and LOSSES models, rather than combining both task versions into one analysis, given: a) the well replicated finding of framing effects on risk preference; b) the differential effects on GAINS vs LOSSES seen in prior sleep loss studies; and c) the fact each version was administered as a separate task within the study. In each model, we regressed *Risk Choice* on *Sex* (male = 1), *Condition* and the *Condition***Sex* two-way interaction term. Finally, significant *Condition**Sex interactions were followed up by examining the simple main effect of *Condition* within each sex.

Table 1. Characteristics of participants pooled across sleep conditions and by assigned sleep conditions

	Age		Sex	
	M	SD	Male	Female
Total sample (n = 47)	24.57	5.26	24	23
TSD (n = 23)	25.22	5.13	10	13
SR (n = 21)	24.48	5.57	10	11

M, mean; *SD*, standard deviation; *SR*, sleep restriction; *TSD*, total sleep deprivation.

We further entered three covariates into the logistic mixed models. The first covariate was subjective sleepiness, as assessed by KSS scores. While increased subjective sleepiness may be a by-product of sleep deprivation, it may not track sleep loss in a linear or dose-response fashion, especially during sleep restriction [33]. In addition, past studies have shown subjective sleepiness itself alters risk preference and performance across different decision-making tasks [34–36]. The aim of the present study was to examine the impacts of TSD and SR, independent of any effects of sleepiness. Thus, controlling for KSS scores in our models provides a clearer estimate of the predictive relationship between TSD/SR and performance on the LCT.

Secondly, we included as a covariate the difference in variance between gamble payoffs on each trial, calculated by taking the absolute value after subtracting the variance on Gamble 1 from Gamble 2. This allowed us to control for any potential dose-response effects of variance differences on participants' choice within each trial. The original range of values of this last measure was too wide and resulted in eigen value errors during analyses, so we applied a logarithmic transformation to create a *logVarDiff* variable.

Lastly, to control for possible sequence effects on task performance, we created an *Order* variable representing whether trials belonged to the first or second assessment undertaken by participants. Across each of the models predicting *Risk Choice*, assumption checks indicated normality and homogeneity of variance of the scaled residuals.

Results

Subjective Sleepiness

Results from the manipulation check showed both TSD and SR were significantly associated with increased sleepiness, indicating our sleep manipulations increased participants' subjective sleepiness (Figure 3).

Lottery Choice Task

The models predicting *Risk Choice* with *Frame* alone indicated, for all three sleep conditions, participants were more risk-seeking for LOSSES than for GAINS. Main effects of these analyses are presented in Table 2.

GAINS

The GAINS-only model revealed participants were significantly more likely to pick the safer gamble as the difference in variance between gamble payoffs increased. *Order* was non-significant, indicating an absence of sequence effects on GAINS trials. Controlling for *logVarDiff,* subjective sleepiness, and *Order,* both TSD, and SR showed significant interactions with *Sex* (Table 3A). Follow-up analyses showed females became significantly more risk-averse during both TSD and SR, relative to the WR condition. Males, on the other hand, did not change risk preference during either TSD or SR, relative to WR. Table 4A and Figure 4 present results of the follow-up analyses.

LOSSES

Results from the LOSSES-only model indicated participants were significantly more likely to pick riskier gambles as the difference in variance between gamble payoffs increased. *Order* was non-significant, indicating an absence of sequence effects on LOSSES trials. Controlling for *logVarDiff*, subjective sleepiness, and *Order*, there was not a significant *SR*Sex* interaction, but there was a significant *TSD*Sex* interaction (Table 3B). Follow-up analyses showed female participants did not change risk preference after TSD, while male participants became significantly more risk-seeking after TSD (Table 4B and Figure 5).

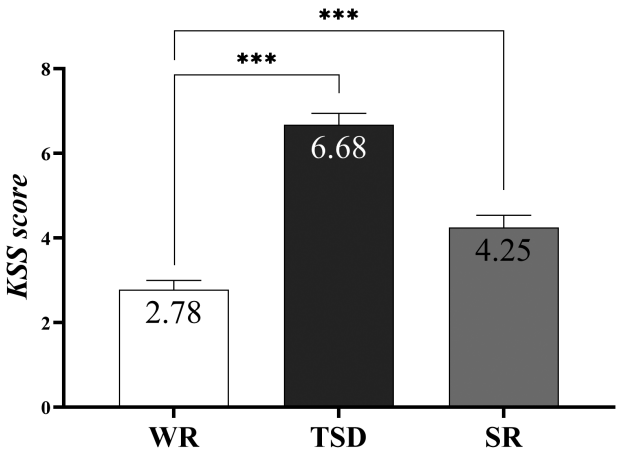

Figure 3. Least-square estimates of KSS scores (with SEM) of subjective sleepiness levels of participants in each sleep condition. Overall model $R^2 = .74$. Error bars denote SEM. WR, well-rested; TSD, total sleep deprivation; SR, sleep restriction. TSD and SR results in significantly higher KSS scores, indicating subjects feel sleepier after sleep loss. $^*p < .05$. $^{**}p < .01$. $^{***}p < .001$. Probability estimates obtained using Satterthwaite approximation for degrees of freedom (see Luke [60]).

Discussion

The present study aimed to investigate how sex moderates the effects of two kinds of sleep loss on risky decision-making, and if those effects differ depending on how a risky choice is framed. Prior evidence from Ferrara et al. [19]. suggests TSD has a potentially amplifying effect on sex-specific risk biases in the gains domain. Our findings expand on this by demonstrating sex-specific changes in risk preference during both TSD and SR, and related to both gains and losses domain risky decisions. Specifically, when outcomes of decisions were framed in terms of gains, our female participants exhibited increased risk aversion under the effects of both TSD and SR. When consequences were framed as losses, male participants became more risk-seeking after only TSD. So, in general, we replicated Ferrara et al.'s [19] findings, but our findings provide additional specificity that: 1) while women were impacted by both kinds of sleep loss, men were only impacted by TSD; and 2) women were more impacted on decisions seeking to maximise gains, while men were more impacted on decisions seeking to minimise losses. Surprisingly, we did not find an independent effect of *Sex* during WR. Given the differences in sample sizes and contrasting findings between the two prior studies to directly examine sex differences in risky choice (Powell and Ansic [24] ($n = 126$) found significant sex differences, and Acheson et al. [28] ($n = 20$) did not), this may be attributable to insufficient statistical power in our current study ($n = 47$) to detect such an effect. Nonetheless, our findings suggest sex differences in risk preference are potentially amplified by sleep loss. This has implications for occupations where risk-taking is an intrinsic aspect of the job, especially those with excessive or

Table 2. Main effects of the random intercepts logistic mixed models predicting risk choice within each sleep condition

	β (SE)	95% CI	Odds (95% CI)
WR-only			
Intercept	.84 (.14)***	.56, 1.12	
Frame (LOSSES = 1)	-.57 (.07)***	-.71, -.43	.56 (.49, .65)
Overall R^2	.22		
No. of observations	3760		
TSD-only			
Intercept	1.45 (.25)***	.97, 1.93	
Frame (LOSSES = 1)	-.97 (.11)***	-1.19, -.75	.38 (.30, .47)
Overall R^2	.30		
No. of observations	1760		
SR-only			
Intercept	.67 (.20)***	.28, 1.06	
Frame (LOSSES = 1)	-.58 (.11)***	-.78, -.37	.56 (.46, .69)
Overall R^2	.19		
No. of observations	1680		

CI, confidence intervals; *SE* = standard error of β; *WR*, well-rested; *TSD*, total sleep deprivation; *SR*, sleep restriction
Odds values obtained by transforming β from log odds to the odds scale.
*$p < .05$, **$p < .01$, ***$p < .001$. Probability estimates obtained using Satterthwaite approximation for degrees of freedom.

Table 3. Main effects of the random intercepts logistic mixed models predicting risk choice within each frame on the LCT

	A. GAINS-only			B. LOSSES-only		
	β (SE)	95% CI	Odds (95% CI)	β (SE)	95% CI	Odds (95% CI)
Intercept	-6.74 (.41)***	-7.55, -5.93		6.38 (.46)***	5.48, 7.29	
logVarDiff	3.61 (.16)***	3.30, 3.92	36.88 (26.99, 50.40)	-2.94 (.14)***	-3.22, -2.65	.05 (.04, .07)
KSS	.04 (.05)	-.05, .14	1.04 (.95, 1.15)	.11 (.05)	.02, .20	1.11 (1.01, 1.22)
Order	.10 (.09)	-.09, .28	1.10 (.92, 1.32)	-.06 (.09)	-.24, .11	.94 (.78, 1.12)
Sex (male = 1)	-.17 (.32)	-.80, .46	.84 (.45, 1.58)	-.33 (.47)	-1.25, .58	.72 (.29, 1.79)
TSD	.48 (.22)*	.04, .92	1.62 (1.05, 2.51)	-.22 (.22)	-.66, .21	.80 (.52, 1.23)
SR	.44 (.22)*	.003, .87	1.55 (1.00, 2.39)	-.40 (.21)	-.82, .006	.68 (.44, 1.01)
TSD*Sex	-.52 (.25)*	-1.01, -.02	.60 (.36, .98)	-.58 (.24)*	-1.06, -.10	.56 (.35, .90)
SR*Sex	-.62 (.28)*	-1.17, -.07	.54 (.31, .93)	.33 (.29)	-.23, .89	1.34 (.79, 2.43)
Overall R^2	.42			.48		
No. of observations	3360			3240		

CI, confidence intervals; *SE*, standard error of β; *WR*, well-rested; *TSD*, total sleep deprivation; *SR*, sleep restriction.
Odds values obtained by transforming β from log odds to the odds scale.
*$p < .05$. **$p < .01$. ***$p < .001$. Probability estimates obtained using Satterthwaite approximation for degrees of freedom.

irregular working hours that may restrict sleep schedules of personnel (e.g., healthcare, military, emergency personnel, business executive, etc.). Given several studies investigating occupational performance have shown sleep loss results in increased risk-seeking behaviour [6, 9, 37], it may be beneficial for organisations to account for sex differences in efforts to minimise detrimental risky decisions on the job.

Neuroimaging evidence may offer a perspective to understanding the mechanisms by which sex moderates the impacts of sleep loss on risk preference. Studies have shown risky decision-making engages several prefrontal brain regions, including the orbitofrontal cortex (OFC), involved in weighing the consequences of one decision against another [38–42], and the dorsolateral prefrontal cortex (DLPFC), which plays a role in suppressing risk-seeking behaviour [43, 44]. Additionally, other regions such as the ventromedial prefrontal cortex (VMPFC), ventral striatum, and insular cortex contribute to reward valuation and risk assessment [15, 45, 46]. While these specific observations are independent of sex, there is evidence of sex differences in neural activity when performing risky choice tasks. One study reported task-related activation in men was lateralised to the right OFC and DLPFC, while left DLPFC activation was greater in women [39]. Additionally, Cazzell et al. [47]. found men exhibited weaker DLPFC activation than women in response to losses realised from risky decisions. This latter result is especially consistent with our data showing greater risk-seeking during loss-related decisions in men after TSD.

Incidentally, brain regions associated with risky decision-making are particularly susceptible to the effects of sleep loss. Neuroimaging studies have shown sleep loss negatively impacts prefrontal cortex activation [48–51], with one suggesting women may be more susceptible to its impact on the frontal lobes [52]. Furthermore, Venkatraman et al. [15]. reported participants who had undergone 24 h of TSD showed greater activation in the VMPFC and ventral striatum when decisions on a risky choice task resulted in gains, and diminished activation in the insular cortex when decisions resulted in losses. Given the neurophysiological differences in men and women when making risky decisions, sex-specific changes in risk preference after sleep loss in the present study may therefore be a result

Table 4. Main effects of sex-specific post-hoc analyses on significant condition*sex interactions within each frame on the LCT

	A. GAINS-only			B. LOSSES-only		
	β (SE)	95% CI	Odds (95% CI)	β (SE)	95% CI	Odds (95% CI)
Female-only						
Intercept	-6.48 (.52)***	-7.49, -5.47		5.62 (.47)***	4.69, 6.55	
logVarDiff	3.54 (.22)***	3.11, 3.97	34.41 (22.34, 53.01)	-2.61 (.18)***	-2.96, -2.25	.07 (.05, .11)
KSS	.01 (.07)	-.12,.15	1.01 (.88, 1.16)	.11 (.06)	-.004, .23	1.11 (1.00, 1.26)
TSD	.58 (.27)*	-.05, 1.12	1.79 (1.05, 3.06	-.26 (.25)	-.74, .22	.77 (.48, 1.25)
SR	.53 (.26)*	.013, 1.04	1.69 (1.01, 2.83)	-.43 (.22)	-.87, .01	.65 (.42, 1.01)
Overall R^2	.39			.35		
No. of observations	1840			1800		
Male-only						
Intercept	-7.03 (.57)***	-8.15, -5.92		7.06 (.71)***	5.68, 8.44	
logVarDiff	3.68 (.23)***	3.23, 4.14	39.81 (25.33, 62.57)	-3.45 (.24)***	-3.92, -2.98	.03 (.02,.05)
KSS	.05 (.06)	-.07, .17	1.05 (.93, 1.19)	.13 (.07)	-.006, .27	1.14 (.99, 1.31)
TSD	-.10 (.33)	.75, .55	.91 (.47, 1.73)	-.93 (.38)*	-1.67, -.19	.39 (.19,.83)
SR	-.18 (.18)	-.52, .17	.84 (.59, 1.18)	-.05 (.20)	-.45, .35	.95 (.64, 1.42)
Overall R^2	.44			.61		
No. of observations	1520			1440		

CI, confidence intervals; *SE*, standard error of β; *WR*, well-rested; *TSD*, total sleep deprivation; *SR*, sleep restriction.
Odds values obtained by transforming β from log odds to the odds scale.
*$p < .05$. **$p < .01$. ***$p < .001$. Probability estimates obtained using Satterthwaite approximation for degrees of freedom.

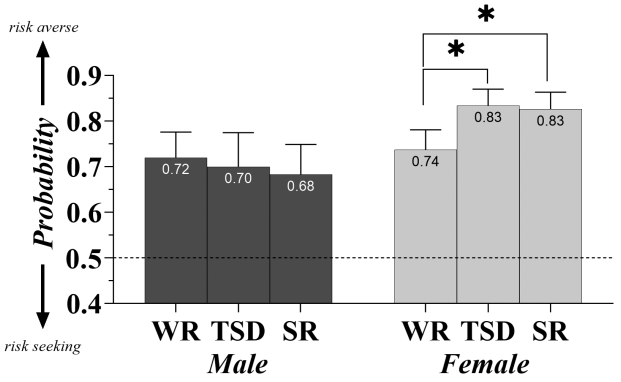

Figure 4. Least-square estimates (with SEM, converted to probabilities) of participants' likelihood to pick the safer gamble for GAINS trials on the Lottery Choice Task within each Condition, separated by Sex. Error bars denote SEM. *WR*, well-rested; *TSD*, total sleep deprivation; *SR*, sleep restriction. For female participants, both TSD and SR resulted in higher probabilities of picking the risk choice during GAINS trials on the Lottery Choice Task. *$p < .05$. **$p < .01$. ***$p < .001$.

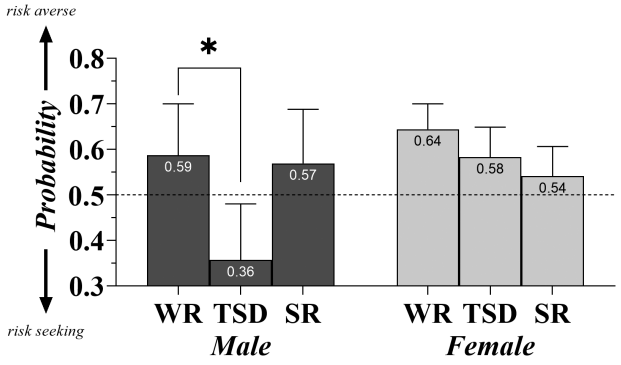

Figure 5. Least-square estimates (with SEM, converted to probabilities) of participants' likelihood to pick the safer gamble for LOSSES trials on the Lottery Choice Task within each Condition, separated by Sex. Error bars denote SEM. WR = Well-rested. TSD, total sleep deprivation; SR, sleep restriction. For male participants, TSD resulted in a significantly lower probability of picking the Risk Choice during LOSSES trials on the Lottery Choice Task. *$p < .05$. **$p < .01$. ***$p < .001$.

of how sleep loss further alters activation of key neural structures. In this regard, future research may attempt to collect task-concurrent neuroimaging evidence to shed light on the neural mechanisms that underlie the sex differences in risk preference before and after sleep loss.

Additionally, though we employed a risky choice task similar to that in McKenna et al. [21], the TSD findings between the two studies are inconsistent. Participants in McKenna et al. [21] who underwent 23 h TSD were less risk-averse on GAINS and less risk-seeking on LOSSES, suggesting an attenuating effect of TSD on risk sensitivity. Main effects from our analyses on pooled sex data instead indicate 24 hours TSD amplified risk sensitivity by increasing participants' risk aversion on GAINS and risk-seeking on LOSSES, though the effect of TSD was non-significant for the latter. Several differences between our studies may have resulted in these discrepancies. Firstly, we chose to control for differences in payoff variance between gambles on each trial because variance alters risk perception, whereby the likelihood of choosing the safer option changes as the spread of possible payoffs on the riskier choice increases [53]. Indeed, *logVarDiff* significantly predicted *Risk Choice* across all our analyses where it was a covariate, confirming there is strength in controlling for the extent to which risk preference was driven by the spread of payoff values presented by the riskier choice on each trial. Secondly, comparing the exact stimuli in McKenna et al. [21]. and the current paper shows three relevant differences: 1) the current paper had a much lower risk inherent in the fixed low-risk choice of each trial, relative to McKenna et al. [21]. (variance of payoff 33.3 vs 133.3, respectively); 2) the current paper had a larger range of variance differences between the two choices on a given trial (range = 36–461 vs 64–400, respectively); and c) McKenna et al.'s [21] low-risk choice included the potential to win $0 (payoff options were 20, 20, 0), whereas the current low-risk choice always ensured some win (payoff options were 20,10,10). These factors may have resulted in the low-risk

choice in the current study being more attractive, overall, than the low-risk choice in McKenna et al. [21].

Prior studies examining the impact of SR on risk preference have been mixed. Sundelin et al. [14]. and Dickinson et al. [22]. both report mild SR (2 nights of 4-h in bed and self-selected sleep schedules almost always averaging ≥ 5 h/night, respectively) did not affect risk preference. However, our sex-pooled models indicate a significant effect of SR on GAINS, and a marginally significant effect on LOSSES (p = .053). One reason for this difference may be we imposed a more prolonged period of SR, as well as greater restriction each night. Additionally, while our sex-specific models suggest these effects are driven by females for GAINS (where we saw a significant SR*Sex interaction), we speculate the same is also likely for LOSSES, wherein our female participants trended toward risk-seeking, though this is nonsignificant at the current sample size (p = .06). Thus, it is possible examination of sex differences in those prior studies may have revealed significant effects of SR. Considering the prevalence of SR in the real-world and the large number of professions where SR is an inadvertent consequence of working hours, our findings of SR-related changes in risky choices warrants concern for risky decisions made by personnel under such circumstances.

Despite SR being a more common occurrence in the real-world than TSD, it is important to acknowledge that unlike in-lab settings, individuals in real-life do not necessarily adhere to the same sleep-wake schedule on a day-to-day basis, meaning there is some night-to-night (N2N) variability in naturalistic sleep schedules. In fact, in a sex-balanced sample of American adults, Dillon et al. [54]. reported N2N variability in total sleep time (TST), number of night-time awakenings and sleep onset latency is highest in young adults, like those studied here. Dickinson et al. [22]. also examined N2N variability in their sample and reported higher night-to-night variability in objective sleep efficiency significantly predicted riskier choices when decision outcomes were framed in terms of losses. Future research might incorporate naturalistic sleep schedules and consider the effects of intra-individual variability in sleep when examining how sex influences the relationship between sleep and risk preference.

There are a few further limitations to be noted. First, we utilised a mixed between-within subjects design, whereby participants underwent WR and either TSD or SR conditions. It is possible that having each participant undergo all three sleep conditions would provide more sensitivity to intra-individual changes in risky decision-making after TSD and SR. We decided against this design, though, due to increased burden on participants and, thus, increased risk of dropouts.

Secondly, compared to WR, testing during TSD and SR occurred at an earlier clock time in the interest of matching the TSD protocol used in our prior work [21]. Cognitive performance is known to be impaired when assessed closer to the circadian nadir [55–57]. Prior evidence from Rogers and Dinges [58] indicates 10 nights of sleep restriction, achieved by delaying bedtimes and advancing wake times equally (as we did here), resulted in a significant phase delay for the majority of their participants (mean delay = 1.2 ± 0.9 h). While we would not expect our SR of 4 nights to create the same magnitude of phase delay, it is possible our participants did experience at least some delay. In addition, we administered the task approximately 2 h earlier in SR and TSD, relative to WR. Hence, the differences in LCT task performance we observed between WR and TSD or SR may be partially influenced by circadian effects, rather than only insufficient sleep. Though this is not desirable, administering the LCT at the same clock time in WR as we did in TSD and SR would mean waking our participants early, effectively restricting their sleep, and possibly having participants perform the task under the influence of sleep inertia.

Lastly, we did not schedule data collection according to the menstrual cycle phases of our female participants. Prior evidence suggests within female individuals, the impact of sleep loss on several cognitive domains (e.g., alertness, memory, and attention) may differ according to phases in the menstrual cycle [57, 59]. While there are no studies, to our knowledge, directly investigating how the impact of sleep loss on risk preference changes throughout different menstrual cycle phases, it is plausible the moderating effects of menstrual cycle phases may extend to risk preference and, consequently, may have influenced the data within the current study.

In conclusion, we examined the effects of TSD and SR on risk preference during decision-making. Our findings indicate sex has a moderating influence on this relationship, whereby female participants were more risk-averse on GAINS during TSD and SR, and male participants were more risk-seeking on LOSSES during TSD. As we are aware, the present study is the first to assess how risk preference is moderated by sex separately for risky decisions in gains and losses domains, under the effects of both TSD and SR. Our findings have implications for several professions that involve on-job risky decision-making, including investment fund managers who balance upsides and risks in managing clients' financial assets, and surgeons whose decisions in the operating theatre may have long-lasting consequences for their patients' health. Nonetheless, future studies that employ naturalistic sleep schedules may provide better generalisability of findings to real-world settings.

Financial Disclosure

This study was funded by a National Science Foundation grant to SPAD: award #0729021.

Non-financial Disclosure

All authors report no conflict of interest.

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