

Winning and Losing: Sleep and Circadian Rhythm Effects on Risky Decisions in a Gain-Loss
Framing Paradigm

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Abstract

Research and anecdotal evidence indicate that lack of sleep and circadian factors impact how one makes decisions involving monetary risk. And, because risky choices have been shown to differ over gains versus losses, whether a risky choice is framed against a loss or gain sure alternative may play an important role in understanding these sleep effects. In this three-week within-subjects randomized crossover design, n=149 participants were exogenously assigned to one-week of sleep-restriction (SR) and one-week of well-rested (WR) sleep levels in their naturalistic at-home environment--sleep treatment order was randomly assigned, and a wash-out week of ad lib sleep levels occurred between treatment weeks. After each treatment week, participants were administered an incentivized, framed monetary risk choice task at a time-of-day that was aligned or misaligned with a validated measure of their diurnal preference. The findings showed that SR and suboptimal circadian timing (i.e., circadian mismatch) are both associated with increased risk-taking behavior, while being both sleep-restricted *and* circadian mismatched mutes some of the individual effects. Furthermore, the study revealed that sleep and circadian mismatch both interact with characteristics of the risky choice task in ways that underscore the complex interplay between sleep, circadian rhythms, and other task attributes in risky decision-making.

Winning and Losing: How Sleep and Circadian Rhythm Effects Risky Decisions in a Gain-Loss Framing Paradigm

Prospect theory, the foremost theory of risk in decision-making, highlights the importance of framing risky choice environments as involving gains or losses (Kahneman & Tversky, 1979). A key finding is that people tend to be risk averse for gains but risk seeking for losses, which is theoretically consistent with having nonlinear probability weighting and a separate risk-averse (i.e., concave) value function for gains that contrasts with a risk-loving (convex) value function for losses. Dual-process models of choice suggest that human decision-making relies on two cognitive systems: the rapid, automatic, intuitive System 1 and the analytical, deliberative System 2 (Stanovich and West, 2000; McElroy and Seta, 2003; Camerer et al., 2005, Kahneman, 2011). In the context of gain/loss framing, the emotional reactions triggered by prospective gains and losses tend to activate the bias-prone System 1. However, if decision-makers are sufficiently motivated and not cognitively taxed, they can engage the rational System 2 processes to overcome these framing effects.¹

Sleep loss can be thought of as a cognitive “tax” that disproportionately impacts activation in prefrontal brain regions, which had led researchers to hypothesize that sleepy decision-makers use relatively more automatic system 1 processes. Ample evidence indicates that sleep loss affects choices that rely on deliberative system 2 decision processes (Harrison and Horne, 2000; Dickinson, 2021), such as risky monetary choices. While many studies have reported increased risk taking under sleep restriction (SR) (Womack et al., 2013), the effects of sleep loss on risky choices may depend on numerous factors, which includes whether the risky

¹ Proposed neurobiological mechanisms for how sleep loss affects risky choice include altered functioning of the ventromedial prefrontal cortex (VMPFC) (Killgore et al., 2006; Maric et al., 2017) and heightened nucleus accumbens activity during risky choice (Venkatraman et al., 2011).

choice is framed as a gain or loss (McKenna et al., 2007). Also, there has been less research examining the influence of circadian timing on risky choices, and some have suggested the need for additional research examining how circadian misalignment affects risky choices (Hisler et al., 2023). While sleep deprivation has been shown to dampen the one's tendency to avoid risk in the gains domain but seek risk in the losses domain (McKenna et al., 2007), risk-taking tendencies using the same risky choice paradigm were amplified during circadian misalignment of the decision maker (Hisler et al., 2023). Such results suggest complex relationships between sleep and risk-taking behaviors (Wei et al., 2025).

While research on sleep and risky choice often involves highly controlled and restrictive laboratory conditions, studies that use more ecologically valid protocols that more closely align with the type of insufficient sleep (e.g.,) common in the real world is are needed (Wei et al., 2025)—the key public health concern in many countries is chronic levels of insufficient sleep closer to 6 hours per night compared to recommended 7-8 hours per night levels (e.g., see Hafner et al., 2017). Examples of more real-world parallel sleep protocols include Maric et al. (2017), who reported partial sleep restriction to 5 hours per night of sleep opportunity for 7 nights under supervised lab conditions led to increased risk taking. Most like the present paper is Sundelin et al. (2019), which used an established risky choice framing paradigm without feedback (De Martino et al., 2006) to specifically examine the impact of two nights of SR (4h time in bed) on the framing effect and probability distortion. It is noteworthy that their participants experienced SR in their ecologically valid at-home environment, as we do in the present paper. Sundelin et al. (2019) reported no significant effects of this SR on overall risky choices rates, the framing effect, or probability distortion, compared to two nights of habitual sleep. These results

contradict some prior total sleep deprivation findings and suggest the framing effect may be resistant to modest real-world sleep loss.

In the real world, decision making can also be challenged at suboptimal times of the day (i.e., circadian misalignment). Suboptimal circadian times of day/night, relative to one's diurnal preference, has been shown to negatively impact theory-of-mind decision making (Dickinson & McElroy, 2010; 2012) complex decision-making performance (McElroy & Dickinson, 2019), and riskiness of trading strategies in an asset market environment (Dickinson et al., 2020). Regarding individual risky choice task environments, circadian mismatch has been shown to increase one's preference for monetary risk (McElroy & Dickinson, 2010; Castillo et al., 2017). Only one study, of which we are aware, examined circadian influences and risky choice framing effects, with results indicating circadian timing matters (Hisler et al., 2023). However, circadian timing was not experimentally (i.e., exogenously) manipulated in this previous study, and so even the observational effects they report may be due to other unobservable factors.

The present study contributes to the literature by examining experimentally assigned SR and circadian misalignment, or mismatch (MM), on risky choices in a validated task that includes both positively and negatively framed risky choices. As noted in our Methods, the design has high ecological validity in that SR versus well-rested (WR) nightly sleep levels are assigned as a within-subjects manipulation for a full week each at levels approximating commonly experienced insufficient sleep (i.e., 5-6 hours/night) and recommended nightly sleep (i.e., 8-9 hours/night), respectively. Additionally, participants slept in their at-home environment with no restrictions placed on compensatory behaviors during SR (other than sleeping!). And finally, in our mixed design, a novel contribution is that we employ a random between-subjects assignment to either a circadian matched or mismatched condition, which varies the time of the

laboratory decision session (7:30am versus 10:00pm) in consideration of each participant's validated diurnal preference (see Figure 1 for the 3-week protocol timeline).

Based on the dual-systems framework and the extant literature, we hypothesize:

H1: SR and circadian MM will increase risk-taking

H2: Framing effects on risky choice will be accentuated during SR and MM

H3: Combined SR and MM will lead to differential effects on risk-taking

Our research design enables a robust test of sleep and circadian influences on risky choice, building upon recent work by Sundelin et al. (2019) and addressing weaknesses in the existing literature noted in Wei et al. (2025). Examining sleep, circadian effects, and gain-loss framing in the same study provides novel insights, and the use of an ecologically valid extended SR paradigm helps address another limitations of many prior studies. In their systematic review, Wei et al. (2025) highlighted that the mechanisms underlying sleep loss effects on risky choice remain underexplored. The current study aims to clarify a key, but under-studied, interaction between framing effects and circadian timing of decisions to elucidate the cognitive pathways linking sleep restriction, circadian timing, and risk preferences.

With insufficient sleep becoming increasingly pervasive in modern society, this line of research has important real-world implications. Understanding precisely how different facets of sleep and circadian preferences shape specific components of risk-taking behaviors can inform interventions and policies to facilitate adaptive decision-making. By employing a mechanistically-informative, ecologically-relevant design, the present study seeks to meaningfully advance this timely research agenda.

Results

Protocol Validity

We first document the validity of the mixed design to generate significant within-subject differences in objectively measured SR versus WR nightly sleep, and in generating differences in subjective sleepiness in the between-subjects comparison of circadian matched versus mismatched participants. A total of $n=149$ participants completed the within-subject sleep manipulation protocol, while a smaller sample of $n=30$ control condition participants were assigned two weeks of WR sleep levels to further substantiate the validity of restricting sleep via the treatment condition SR assignment and to examine repeat administration effects. These control participants also had validated diurnal preferences in the intermediate range (neither morning-type nor evening-type tendencies), and they completed the risky choice task at a non-extreme time-of-day.

Average actigraphy-measured nightly sleep was 336.14 minutes per night ($SD = 38.26$ min) during SR compared to 429.942 min per night ($SD = 32.29$) during WR for the treatment participants. For control participants, average nightly sleep was 436.54 min ($SD = 28.60$) during Week 1 compared to 436.60 ($SD = 32.42$ min) during Week 3 of the protocol. The within-subject difference comparing SR to WR in treatment participants is statistically different using a non-parametric signed-rank test ($z = 10.417, p < .01$), while the within-subject difference for control participants across treatment weeks is not significant ($z = -0.093, p > .10$), as expected. Self-reported sleepiness is also greater during SR compared to WR ($z = 3.468, p < .01$), but the difference in subjective sleepiness is only marginally significant in the between-subject comparison of mismatched (MM) versus circadian matched (CM) participants, using average sleepiness ratings across both treatment weeks ($z = -1.750, p = .08$: Mann-Whitney test of medians). It was noted previously from this protocol that the SR manipulation had a more

significant and sizable impact on subjective sleepiness as compared to the MM (Dickinson et al., 2017: they also noted the SR manipulation had a significant impact on self-reported emotion states, while the effect of MM on self-reported emotions was not statistically significant.

Preliminary Analysis

Before exploring the influence of SR and MM on framing effects, we first assessed the traditional gain/loss framing effect on risk from the 32 trials of gain and 32 trials of loss frame choices. Participants were first given a starting amount of money, and then they had to choose between a safe (certain) monetary amount they could keep (or amount lost in loss trials) out of the starting amount and a risky outcome with the same expected value as the safe option—the risk of the uncertain outcome, visually depicted as a pie-chart *Win %* (i.e., probability one keeps the entire monetary pie at stake in that trial) was varied across trials (see Figure 2 for an example of a gains and losses trial stimulus), as was the *Starting Cash*. A separate set of 32 “catch trials” that presented extreme differences in expected values between the safe versus risky options, to assess whether participants would typically favor a clearly higher expected value outcome among choice options (see De Martino et al., 2006). Risk choice was coded as risky choice = 1 and risk-free = 0. Collapsing across the different probabilities and starting amounts of the experimental framing conditions, after catch trials are removed, we found that the framing effect was robust $F(1,15563) = 284.73, p < .001, \eta^2 = .018$, with participants exhibiting a lesser preference for the risky choice in the gain presentation ($M=.38, SD=.49$) compared to the losses condition ($M=.52, SD=.5$). Analysis of catch trials demonstrated high participant attentiveness throughout the study, with participants selecting the option with higher expected value in over

95% of trials across all experimental conditions (gains/losses, circadian match/mismatch, and sleep restriction/well-rested).

Exposure Effects on Risk-Taking

To determine whether repeated task exposure or time-between task administration affected risk-taking, independent of SR and MM, we analyzed data from our control participants ($n=30$), who maintained consistent WR sleep levels across both experimental weeks. Control participants showed significantly decreased risk-taking from Week 1 ($M=5.15$, $SD=4$) to Week 3 ($M=4.69$, $SD=3.99$), $t(2479) < .001$. This indicates reduced risk-taking upon repeat administration of the task, independent of sleep condition. This exposure effect underscores the importance of our counterbalanced design for treatment participants, where approximately half were assigned a SR-WR treatment order (with a washout week of ad lib sleep levels in between), and the other half experienced a WR-SR treatment order (with a washout week in between). This counterbalancing ensures that the overall effects of SR reported in our main analyses are not confounded by this repeat-administration or time-related exposure decrease in risk-taking. Our multi-variate regression models further control for session effects, allowing us to isolate the impact of our key manipulations while accounting for the general tendency toward decreased risk-taking upon repeat administration of the task.

Sleep, Circadian rhythm and Risky-choice

We next conducted an analysis to investigate whether risky decision-making differed during SR compared to WR conditions. The results showed a significant difference between the sleep conditions, $F(1, 7727) = 9.25$, $p < .002$, $\eta^2 = .001$, with participants exhibiting higher levels of risk-taking during SR ($M = 4.69$) compared to WR ($M = 4.5$). Furthermore, there was no significant *Frame* $\times$ *Sleep Condition* interaction, $F(1, 7726) = .032$, $p = .86$, $\eta^2 = .0$,

indicating that the observed difference in risk-taking was a general trend occurring across both the gain and loss conditions.

To explore the role of sleep and circadian timing in risk-taking, we conducted a *Sleep Condition* $\times$ *Circadian Condition* mixed ANOVA. The results revealed a significant main effect of sleep condition, $F(1, 7726) = 10.4$, $p < .001$, $\eta^2 = .001$, but no significant main effect of circadian condition, $F(1, 7726) = .095$, $p = .76$, $\eta^2 = .00$. However, there was a significant interaction between sleep condition and circadian timing, $F(1, 7726) = 17.08$, $p < .001$, $\eta^2 = .002$. Specifically, participants exhibited higher levels of risk-taking when they experienced only one adverse sleep state (either SR or MM) as opposed to having both or neither (see Table 1 for summary outcomes in details).

Sleep, Circadian rhythm and Decision Parameters in Risky-choice

To test the effects of sleep and circadian match across the different decision parameters, we first performed a 2 *Sleep Condition* (WR, SR) $\times$ 2 *Circadian Condition* (CM, MM) $\times$ 2 *Frame* (Gain, Loss) $\times$ 4 *Win %* (20,40,60,80) mixed repeated-measures ANOVA. The entire ANOVA reporting can be found in Appendix A and the descriptive data are reported in Table 3. The results of this analysis revealed that there was a significant main effect of sleep condition on risky-choice $F(1, 7712) = 10.438$, $p = .001$, $\eta^2 = .001$, indicating again that SR significantly increased preference for risk. There was also a significant main effect of frame on risk $F(1, 7712) = 218.365$, $p = .001$, $\eta^2 = .028$, supporting the framing effect whereby individual make riskier choices in the loss frame. Additionally, there was a significant main effect of *Win %* on risk $F(1, 7712) = 70.026$, $p = .001$, $\eta^2 = .027$, indicating a significant increase in the risky choice for higher *Win %* (even though the expected value still matched that of the safe option). Further, there were significant interaction effects: *Sleep Condition* $\times$ *Win %*, $F(1, 7712) = 4.221$,

$p = .005$, $\eta^2 = .002$; *Circadian Condition* x *Win %* $F(1, 7712) = 10.524$, $p = .001$, $\eta^2 = .004$; and *Frame* x *Win %* $F(1, 7712) = 7.562$, $p = .001$, $\eta^2 = .003$. These findings suggest that SR, the loss frame, and higher *Win %* all increased one's willingness to take risk, and some of these effects interacted with each other or were moderated by other variables such as circadian match.

A separate 2 *Sleep Condition* (WR, SR) x 2 *Circadian Condition* (CM, MM) x 2 *Frame* (Gain, Loss) x 4 *Starting Cash* (\$2.5, \$5, \$7.5, \$10) repeated-measures ANOVA was conducted to examine the effects of each of these variables on risky decision-making. All ANOVA results are reported in Appendix A and the descriptive data are reported in Table 4. The results showed a significant main effect of *Starting Cash*, $F(3, 7712) = 18.029$, $p < .001$, $\eta^2 = .007$, on risky decision-making. Additionally, there was a significant *Frame* x *Start Cash* interaction, $F(3, 7712) = 4.753$, $p < .003$, $\eta^2 = .002$.

Additional sensitivity analysis was performed using multivariate regression analysis. Here, the data were structured as a panel set of 96 observations per participant, and *Risk Choice* was a binary dependent variable (*Risk Choice* = 1 if the risky choice was selected in that trial; otherwise *Risk Choice* = 0) in a series of linear probability models.² Table 5 shows results for models with and without a full set of two-way interactions terms between design factors (columns (1) and (2)). Additional, for sensitivity analysis we also estimated similar models in columns (3) and (4) of Table 5 for the subset of $n=119$ participants who had complete actigraphy data records and had at least a 60 minutes lesser amount of nightly sleep during the SR compared to WR treatment week, which we arbitrarily deemed more “compliant” with the conditions of the sleep protocol—the full sample of $n=149$ treatment participants would be considered the “intent-to-treat” sample. Importantly, given the panel nature of our data, we estimated random effects

² Similar results are found when using nonlinear Probit estimations, and these results are relegated to the Appendix given the ease of interpretation of the linear probability model coefficient estimates (see Table A4).

models that account for the error correlation structure across trials for a given participant. All models included demographic controls for *Age*, *Female*, *Minority*, and *NonStudent*, which were always statistically insignificant ($p > .10$) and therefore suppressed from the Table for space considerations.

Results here support the ANOVA findings regarding risky choice specific factors, such as *Start Cash*, *Win %* and *Loss* frame. Specifically, we estimate a significant increase the likelihood of choosing the riskier option for *Loss* frame trials, lower *Start Cash* levels, and a higher *Win %* for the risky choice.³ Regarding the impact of sleep state (*SR* and *Circadian Mismatch*), the results also support the ANOVA findings earlier in that *SR* and *Circadian Mismatch* both have a main effect of increasing the likelihood of choosing the riskier option. Being both *SR* and *Circadian Mismatched*, however, removes this increased tendency to make the riskier choice. Results in Table 5 also show that *Circadian Mismatch* reduces some of the *Loss* frame main effect of additional risk taking, and both *SR* and *Circadian Mismatch* increase the probability distortion effect (i.e., increased importance of the risky choice's *Win%*, even though the risky choice always has the same expected value as the safe option).

Additional finding from Table 5 highlight that the repeated administration of the task is associated with a lesser likelihood of choosing risky choice option—this is true both within a session, as documented by the significant negative coefficient effect on *Trial*, as across sessions, as documented by the negative coefficient on *Session3*.⁴ This pattern was also observed in our

³ We estimated the same model on the control participant data ($n=4,301$ trial-level observations) and similarly find and increase in the likelihood of choosing the risky outcome in the *Loss* frame ($p < .05$), for lower *Start Cash* amounts ($p < .001$), and for higher *Win %* for the risky choice ($p < .001$).

⁴ We also explored the possibility of sample selection given that not all who enrolled in the study initially actually completed the study and appear in our final data set. Here, we estimated a selection equation to predict whether observable characteristics of the participant predict the likelihood of completing the study. These results, shown in Appendix Table A5, found that none of the observable characteristics we had on participants predicted their completing the study. In this case, selection bias of this sort is therefore not a significant concern in our data.

control group, which showed decreased risk-taking from Week 1 to Week 3 despite control participants being WR in both instances. This demonstrates the value of our counterbalanced design and statistical approach, which appropriately controls for time and repetition effects while isolating the impact of our sleep and circadian manipulations.

Discussion

This study investigated the impact of ecologically valid sleep restriction and circadian timing on risky decision-making using an incentivized gain-loss framing paradigm. Our results revealed several key findings: First, one week of SR led to significantly increased risk-taking compared to a week of WR sleep levels. Second, circadian misalignment interacted with sleep in complex ways to influence risky choice. Individuals exhibited the highest levels of risk-taking when sleep restricted but at a more preferred time-of-day, with slightly attenuated but still elevated risk-taking when both SR and circadian mismatched, regardless of sleep condition. Well-rested participants at their circadian peak showed the lowest risk-taking propensity, suggesting that optimal sleep and circadian alignment supports enhanced cognitive control over risk-taking impulses.

Furthermore, task factors like the stakes of the choice and the probability of a favorable outcome modulated the impact of sleep and circadian states on risk preferences, highlighting the interplay between these state and task variables in shaping choice. Collectively, these findings underscore the critical roles of sufficient sleep and circadian synchrony in promoting adaptive decision-making, particularly in the face of risk. The complex interactions uncovered here also emphasize the need for more granular, ecologically valid investigations into how distinct components of sleep and circadian rhythms impact specific facets of decision-making. These

results have implications for individuals making high-stakes decisions, as well as for organizations and policymakers seeking to understand decision-making processes.

Our control group findings revealed an important exposure effect, with participants becoming less risk-taking from Week 1 to Week 3 even under consistent well-rested sleep conditions. This observation highlights the methodological strength of our counterbalanced design, which ensures that time-related changes in risk preference do not systematically bias our estimates of sleep and circadian effects. The decrease in risk-taking over time may reflect increasing familiarity with the task structure, strategic adaptation, or a general shift toward more risk-averse decision-making with repeated exposure. Future research might further investigate the mechanisms underlying this temporal-exposure pattern and its interaction with sleep states.

Despite the valuable insights that our study provides, there are limitations that need to be acknowledged. One limitation is that our sample consisted of young adults without major risk of depressive or anxiety disorder, and with no diagnosed or suspected sleep disorder (as self-reported), which limits the generalizability of our findings to other populations. Future research should include a more diverse sample, such as older adults or a clinical population, to help determine whether our results hold across different age groups and health conditions.

Furthermore, our study focused on the effects of sleep and circadian rhythms on risky decision-making, but did not consider other factors that could influence decision-making, such as personality traits or stress levels. Future studies could examine the interplay between these factors and sleep/circadian rhythms to better understand how they collectively impact decision-making. It is also important to note that our study only assessed decision-making behavior in one specific type of (visual) risky choice paradigm, which limits the generalizability of our findings involving risky choice given the large variety of risky choice paradigms in the literature.

Another important area for future research is to examine how individual differences in sleep and circadian rhythms influence decisions in other choice domains, such as moral or social decision-making. Moreover, future studies could investigate how sleep and circadian rhythms may interact with different types of decision-making frames, such as attribute framing, or temporal framing. Future studies could explore how sleep and circadian rhythms affect behavior across a broader range of choice domains.

Finally, it would be interesting to investigate the neural mechanisms underlying the observed effects of sleep and circadian rhythms on decision-making, using techniques such as functional magnetic resonance imaging (fMRI) or electroencephalography (EEG). Despite these limitations, our study provides valuable insights into the relationship between sleep, circadian rhythms, and risky decision-making.

Methods

We conducted an *a priori* power analysis before the initial investigation using GPower version 3.1.9.4. Using an unconditional matched pairs test (d effect size = 0.35) or a conditional regression analysis (f^2 effect size = 0.10), we determined that a sample size of $n=140$ would have 0.95 power to detect a medium-to-small effect size of SR on a single outcome measure. The final sample was comprised of 149 treatment condition participants ($n=92$ female; $n=9$ minority) who followed the research protocol and possessed retrievable actigraphy data. A smaller set of control condition participants was used to validate the effects of the sleep manipulation in the treatment conditions and assess repeat task administration effects. These control participants were intermediate or “indeterminant” chronotypes (as assessed by the validated morningness-eveningness scale in Adan and Almirall, 1991) who completed sessions at non-extreme times of

day and were assigned two weeks of WR sleep levels for weeks one and three of the protocol (N=30). All participants were adults between the ages of 18 and 39 (mean age: 21.29) who were not at risk for major depressive disorder (Kroenke et al., 2003), anxiety disorder (Spitzer et al., 2006), or self-reported sleep disturbance. The design plans, rational for hypotheses and planned analyses for this study were presented to the funding agency prior to the study being conducted (National Science Foundation Grant number: BCS-1229067). The Institutional Review Board at Appalachian State University authorized the protocol for this study (IRB 12-0079).

Protocol

An online survey was widely distributed in a regional university and its moderate-sized community using free and paid ad postings to establish a large and diverse participant pool. The study promoted a gift card drawing for survey participants. The initial survey drew thousands of college students across several academic semesters. The online survey included demographic questions, a self-report question about any diagnosed or suspected sleep condition, validated reduced-form screeners for major depressive illness and anxiety disorder (assessed with validated instruments in Kroenke et al., 2003, and Spitzer et al., 2006 respectively), and a validated rMEQ to assess circadian preference (Adan, & Almirall, 1991). The screener survey also administered the Epworth daytime sleepiness scale (Johns, 1991) and elicited self-reported habitual sleep behaviors. The exclusion criteria for the treatment condition were: age outside of 18–39 years old; self-reported sleep disorder (or suspected disorder); significant risk of major depressive or generalized anxiety disorder, and diurnal preferences in the most central "indeterminate" range of morningness-evenness questionnaire values (Adan, & Almirall, 1991). Control participants, however, were only recruited from the indeterminate range of diurnal

preferences, which intended to remove any confounding circadian influences from the control participant data.

Recruitment continued until 140 treatment condition subjects, and 30 control condition subjects, met protocol standards and had retrievable actigraphy data. As these investigations were conducted in cohort groups, the total number of participants for analysis exceeded 140. The study initially enrolled 256 participants, however, 35 failed to attend the introductory session and 37 dropped out over the course of the study. Thus, 30 control participants and 154 treatment participants completed the study. Of those $n=154$ treatment participants who completed the protocol, 5 did not complete the risky choice task, such that the final sample was $n=149$ treatment participants (and $n=30$ control participants remained).⁵ If we use an arbitrary compliance standard requiring at least a one-hour within subject additional amount of nightly sleep during WR compared to SR, sleep compliance was 82% among the treatment participants.

The study lasted for three weeks (Fig. 1 displays the timeline of the study). Prescreening metrics allowed the researchers to balance each group with approximately equal percentages of morning- and evening-type diurnal preferences. Throughout the course of the three weeks, members of the research team checked-in with participants via phone every two to three days to remind them of their individual sleep prescription for the current week (either SR, WR, or ad lib sleep) and during the SR part of the study, the researchers warned the participants about the negative impacts of sleepiness to help manage any personal risk associated with the study.

Sleep measurement

⁵ In some instances, a participant would arrive late to one of the decision sessions and, rather than withdraw the participant we chose to have the participant complete at least a subset of the decision tasks run during the session. That is, losing one participant worth of data for one decision task from a set of several tasks run during the session was considered preferable to dropping the participant entirely because of the large fixed costs we incurred with each participant enrolled.

Actigraphy devices (Actiwatch Spectrum Plus devices; Philips Respironics) were used to continuously measure participants adherence to the sleep protocol throughout the study (See Dickinson et al., 2017 for procedural details). During the three-week trial, the actigraphs were programmed to sample activity at 30-second intervals. The actigraph captures data at 32 Hz using a Microelectromechanical Systems (MEMS) accelerometer. The same process was used for both experimental treatment weeks (Weeks 1 and 3) and continued to record during the wash-out week, though those data were not utilized for this study. Daily voice messages and sleep diary entries were used as a supplementary resource for sleep assessment, which is a valid approach to use in scoring actigraphy data for sleep (Goldman et al., 2007 provide additional information on the scoring method we employed).

Sleep Weeks

This study measured sleep objectively in the participants' at-home environment during two treatment weeks (and a washout week in between, which we do not analyze) using wrist-worn actigraphy: the sleep-restricted (SR) treatment week prescribed participants to 5-6 hours per night of attempted sleep, whereas the well-rested (WR) treatment week prescribed 8-9 hours per night of attempted sleep. The order of the treatment weeks SR-WR or WR-SR, was randomly assigned to each individual experimental group by session.

During Session 1 at the beginning of Week 1, participants were provided informed consent, protocol requirements were relayed and actigraphy devices were assigned. Participants were also instructed on the importance of reporting in with morning and evening phone-ins and maintaining their daily sleep journal. Participants were advised that the actigraphy device had to be worn at all times; exceptions were allowed (e.g., playing contact sports) for short periods of time that would be reported in the sleep diary. During this first session, participants were told of

the monetary compensation for study participation, which included a fixed payout of \$80 for sleep compliance and the opportunity to earn additional funds through tasks that would be provided in following sessions. Importantly, participants were reminded that they were to abide by the assigned nightly sleep levels during the first week of the study (Week 1) as they were informed in the study invitation (either SR or WR). The order of the sleep conditions for each group was randomly assigned before participant recruitment, and this information was included in the initial study invitation email sent out to all participants as well as reiterated to them with a reminder card they could take with them once the Session 1 lab visit concluded. Upon leaving the lab at the end of Session 1, they did not return to the lab until the following week, and so participants went about their normal daily activities and experienced their assigned sleep levels in their at-home environment. At the end of Week 1, participants returned to the lab room for the first decision task session: Session 2. Participants were provided with the risky framing task and other unrelated choice tasks, and variable cash payoffs based on decisions made in these tasks were given at the end of Session 2. After completion of all tasks, participants were instructed about the week that would follow (Week 2).

In Week 2 of the study (“ad lib sleep” week), participants were instructed that they could sleep as many hours as they liked. Participants were instructed to continue wearing the actigraphy device for consistency between experimental weeks. The goal of this week was to include a “washout” phase so that any effects of the previous treatment week could be removed, and the participant should return to their regular sleep baseline prior to initiating the next treatment week. Experimenters communicated with participants via email reminders at the end of Week 2 in order to remind them that there would be no laboratory visit at the end of Week 2, but

the participants were to sleep the assigned amount of nightly sleep during Week 3 according to their treatment assignment.

In the final Week 3, treatment participants were assigned the alternative sleep condition (SR or WR: balanced with Week 1), while control participants were again assigned to WR nightly sleep levels. Email instructions were sent out and the researchers contacted participants to remind them to maintain the prescribed sleep times throughout the entire week. At the conclusion of Week 3, participants returned to the same lab room as before for the final Session 3, at which time they performed the risky framing task and several unrelated tasks and their participation in the study concluded. At the end of Session 3, participants returned the actigraph, received their Session 3 decision payments, were debriefed and thanked for their participation. Participants were also reminded that fixed compensation for study participation, which was separate from variable payments for choices in the decision tasks, would be received by check after the researchers downloaded the actigraphy data to verify they wore the devices as at least attempted to adhere to the assigned sleep levels they agreed to—what we deemed “compliant” for purposes of payment. Participants for study participation was a rather loose standard intended to validate what looked like a good faith effort to comply with the study sleep conditions, which was entirely independent of what we coded as “compliant” for the sensitivity analysis we conducted. After completion of the Week 3 session, participants' Actiwatch data were downloaded to Philips' Actiware (manufacturer) software and scored using procedures described above.

Risky Framing Task

The risky decision task we utilized consisted of 96 trials (32 Loss frames, 32 Gain frames, and 32 catch trials)⁶. Where applicable to our design, we followed procedures and analyses from prior research to maintain consistency with existing literature (e.g., De Martino et al., 2006; Sundelin et al., 2019). The sets of alternatives always contained two choices, one that was certain and the other risky (see Figure 2). In the experimental conditions, the expected monetary outcome of the safe option versus risky choice was held constant across all experimental trials. However, the catch trials were purposely unbalanced in expected values comparison of safe versus risky option to assess a type of task comprehension, as described later. At the start of each experimental session, participants were shown a message that informed them of the amount of money they would receive (e.g., "You receive \$5"). One of four different starting sums, or *Start Cash*, was used: (\$2.5, \$5, \$7.5, \$10). The participants were informed that they would not be able to keep the sum, but a random decision trial would be drawn, and they would be awarded the payoff determined by the randomly chosen trial. During Gain frame trials, participants were presented with a certain option that displayed an amount of money kept from the starting amount (e.g., "keep \$3 of a total of \$10"). Conversely, each gamble had a Loss frame trial that replicated the risky choice of one of the Gain frame trials, but where the trial stimulus displayed the certain option as the amount of money *lost* from the starting amount (e.g., 'lose \$7 of a total of \$10'). The risky option was the same in both frames and was displayed visually in the form of a pie chart illustrating the likelihood of winning or losing (See Figure 2). The study employed four distinct probabilities, or *Win %* value, such that the probability of winning (or

⁶ In Groups 1-6 a software glitch did not allocate the catch trials correctly. Because of this, participants in the first 6 cohorts (n=58, 15 of which were control group participants) were administered an equal number of catch versus non-catch trials: 48 catch and 48 non-catch trials equally split across gains and loss frames. In the remaining cohorts 7-17 (n=121, 15 of which were control group participants), 32 catch trials and 64 non-catch trials were administered, equally divided between gains and losses frames.

losing) in each particular trial was either 20%, 40%, 60%, or 80%. The study was designed so that all the conditions (starting amount, risk percentages) were equally distributed across the gain/loss frames.

We included "catch" trials (32 trials per session) to ensure that participants remained fully engaged throughout the experiment. The catch trials were designed with clearly imbalanced expected values for both the certain and risky options in each frame. Specifically, in half of the trials, the risky option was highly favorable (e.g., 95% probability of winning by choosing the risky option, whereas the certain option only contained 50% of the initial amount). In the other half of the catch trials, the certain option was more desirable (e.g., only a 5% probability of winning by choosing the risky option compared to a sure choice). These catch trials were identical to the experimental trials in all other aspects. The entire task was presented and recorded using E-prime software.

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Tables

Table 1

Risky choice as a function of *Sleep Condition, Circadian Condition*

	<u>Well-rested</u>		<u>Sleep-restricted</u>	
	Mean (SR)	N responses	Mean (SR)	N responses
<u>Circadian</u>				
Match	4.42 (3.96)	3693	4.81 (4.0)	3693
Mismatch	4.61 (3.98)	4035	4.57 (3.98)	4035

Table 2

Risky choice as a function of *Sleep Condition, Circadian Condition, Frame*

	<u>Well-rested</u>		<u>Sleep-restricted</u>	
	M (SR)	N responses	M (SR)	N responses
<u>Circadian</u>				
<u>Match</u>				
Gain	3.8485 (3.83)	1862	4.2 (3.9)	1864
Loss	4.9935(4.0)	1853	5.4 (4.0)	1854
<u>Mismatch</u>				
Gain	4.1269 (3.9)	2057	4.1 (3.9)	2055
Loss	5.1013 (4.0)	2013	5.1 (4.0)	2007

Table 3

Risky choice as a function of *Sleep Condition*, *Circadian Condition*, *Frame* and *Win %*.

		<u>Well-rested</u>		<u>Sleep-restricted</u>	
		M (SR)	N responses	M (SR)	N responses
<u>Circadian</u>					
<u>Match</u>					
<u>Gain</u>					
20%		4.91 (4.00)	457	5.22 (4.00)	457
40%		3.32 (3.64)	462	3.34 (3.64)	462
60%		3.81 (3.83)	459	4.35 (3.95)	459
80%		3.35 (3.65)	473	3.88 (3.84)	473
<u>Loss</u>					
20%		5.53 (3.97)	464	5.99 (3.88)	467
40%		4.48 (3.97)	455	4.71 (3.99)	462
60%		4.81 (4.00)	458	5.34 (3.99)	459
<u>Mismatch</u>					
<u>Gain</u>					
20%		4.74 (3.99)	511	4.41 (3.96)	511
40%		3.32 (3.63)	507	3.07 (3.51)	507
60%		4.20 (3.92)	510	4.50 (3.97)	510
80%		4.28 (3.94)	513	4.46 (3.97)	513
<u>Loss</u>					
20%		5.59 (3.96)	502	5.21 (4.00)	502
40%		4.00 (3.88)	491	3.98 (3.87)	491
60%		4.85 (4.00)	491	5.24 (4.00)	491
80%		5.94 (3.89)	510	5.68 (3.95)	510

Table 4

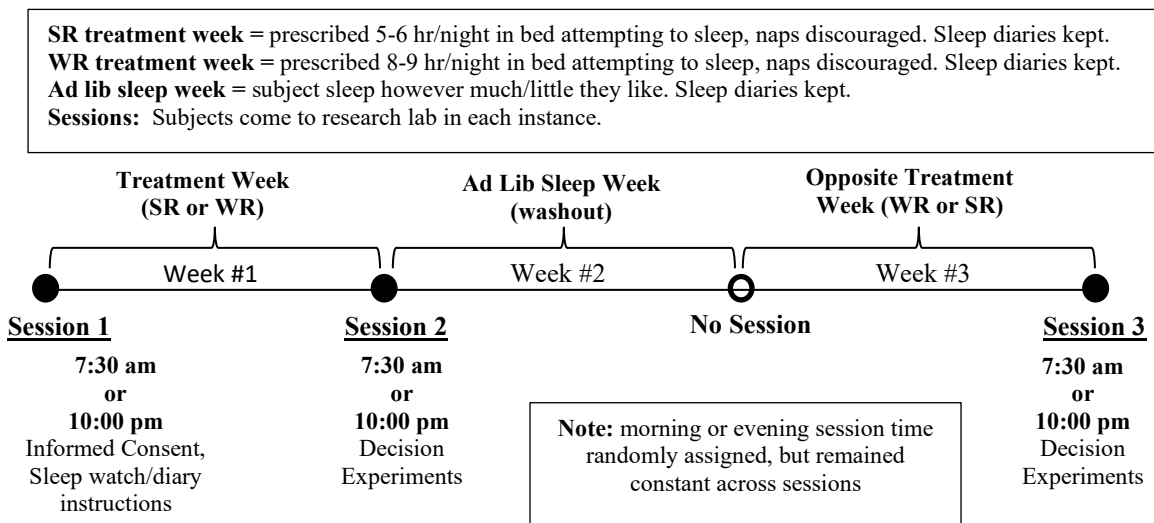
Risky choice as a function of *Sleep Condition*, *Circadian Condition*, *Frame* and *Start Cash*.

		Well-rested		Sleep-restricted	
		M (SR)	N responses	M (SR)	N responses
<u>Circadian</u>					
<u>Match</u>					
<u>Gain</u>					
	\$2.50	4.60 (3.98)	473	4.48 (3.97)	473
	\$5.00	3.80 (3.82)	440	4.11 (3.90)	440
	\$7.50	3.46 (3.70)	458	4.00 (3.88)	458
	\$10.00	3.52 (3.72)	480	4.15 (3.91)	480
<u>Loss</u>					
	\$2.50	5.17 (4.00)	482	5.47 (3.98)	482
	\$5.00	5.01 (4.00)	447	5.49 (3.97)	447
	\$7.50	5.12 (4.00)	451	5.56 (3.97)	451
	\$10.00	4.69 (3.99)	462	5.19 (4.00)	462
<u>Mismatch</u>					
<u>Gain</u>					
	\$2.50	4.89 (4.00)	514	4.77 (4.00)	514
	\$5.00	4.22 (3.93)	505	3.95 (3.86)	505
	\$7.50	3.48 (3.70)	504	3.76 (3.81)	504
	\$10.00	3.95 (3.86)	518	3.97 (3.87)	518
<u>Loss</u>					
	\$2.50	5.48 (3.98)	507	5.56 (3.96)	507
	\$5.00	4.88 (4.00)	485	4.89 (4.00)	485
	\$7.50	5.07 (4.00)	484	4.95 (4.00)	484
	\$10.00	4.99 (4.00)	518	4.72 (3.99)	518

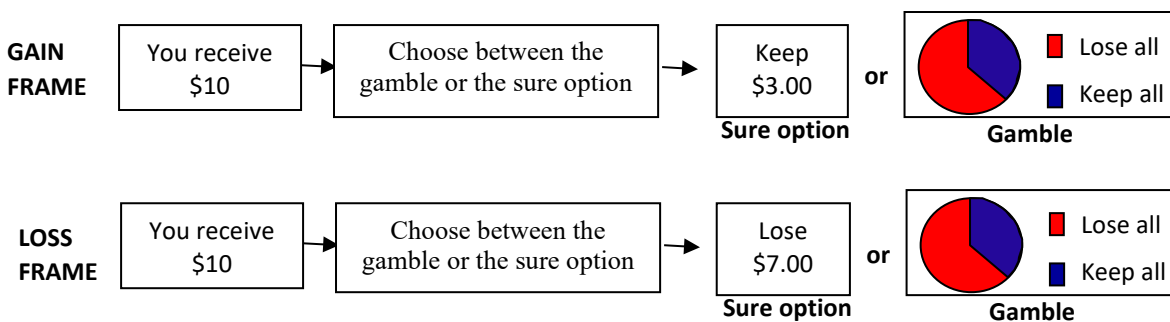
TABLE 5: Determinants of Risky Choice: Multi-variate analysis

VARIABLES	(1) Baseline (n=149 subjects)	(2) Factor Interactions	(3) Compliant Subset (n=119 subjects)	(4) Compliant Subset Factor Interactions
Daytime Sleepiness	-0.006 (0.004)	-0.006 (0.004)	-0.008* (0.004)	-0.008* (0.004)
Trial #	-0.0003*** (0.0001)	-0.0004*** (0.0001)	-0.0003*** (0.0001)	-0.0003*** (0.0001)
Loss Frame (=1)	0.092*** (0.006)	0.095*** (0.016)	0.083*** (0.007)	0.083*** (0.019)
Start Cash	-0.008*** (0.001)	-0.009*** (0.002)	-0.008*** (0.001)	-0.008*** (0.002)
Win %	0.006*** (0.000)	0.006*** (0.000)	0.006*** (0.000)	0.006*** (0.000)
Repeat Admin (=1)	-0.055*** (0.006)	-0.055*** (0.006)	-0.060*** (0.006)	-0.060*** (0.006)
Morning Session (=1)	0.015 (0.028)	0.015 (0.026)	0.016 (0.030)	0.015 (0.029)
Reduced-MEQ score	-0.005* (0.003)	-0.005* (0.003)	-0.003 (0.003)	-0.003 (0.003)
SR (=1)	0.036*** (0.008)	-0.011 (0.018)	0.027*** (0.009)	-0.018 (0.020)
MM (=1)	0.055* (0.028)	0.030 (0.031)	0.072** (0.030)	0.078** (0.034)
SD * MM	-0.041*** (0.011)	-0.041*** (0.011)	-0.031** (0.013)	-0.031** (0.013)
Loss * Start Cash		0.001 (0.002)		0.002 (0.002)
SR * Loss		0.015 (0.011)		0.017 (0.013)
MM * Loss		-0.036*** (0.012)		-0.038*** (0.013)
SR * Win %		0.0004** (0.0002)		0.0004* (0.0002)
MM * Win %		0.001*** (0.0002)		0.001*** (0.0002)
SR * Start Cash		0.003 (0.002)		0.003 (0.002)
MM * Start Cash		-0.001 (0.002)		-0.003 (0.002)
Constant	0.284*** (0.105)	0.325*** (0.099)	0.273** (0.114)	0.297*** (0.109)
Trial Observations	24,348	24,348	19,005	19,005
R-squared	0.167	0.168	0.150	0.150

*** p<0.01, ** p<0.05, * p<0.10. Standard errors in parentheses. Models are random-effects generalized least squares estimates that model the correlation of error terms across trials for a given participant. A Hausman test failed to reject the null hypothesis that the random effects model is the efficient and consistent parameters estimator (compared to a fixed-effects estimator).

**FIGURE 1:** Protocol Details and Timeline

Note: Figure reproduced from Dickinson, Drummond and McElroy (2017)

**FIGURE 2.** Task stimulus examples (equivalent risky choices in gains versus losses frame).

Appendix

TABLE A1: ANOVA with Sleep, Circadian-match, Frame

Factor	F (1, 7724)	<i>p</i>	η^2
Sleep	10.386	.001	.001
CirMatch	.066	.798	.000
Frame	214.602	.001	.027
Sleep x CirMatch	17.106	.001	.002
CirMatch x Frame	2.881	.090	.000
Sleep x Frame	.036	.849	.000
Sleep x CirMatch x Frame	.428	.513	.000

TABLE A2: ANOVA with Sleep, Circadian-match, Frame, Percentage

Factor	F (1,7712)	<i>p</i>	η^2
Sleep	10.438	.001	.001
CirMatch	.122	.727	.000
Frame	218.365	.001	.028
Percent	70.026	.001	.027
CirMatch x Frame	2.930	.087	.000
CirMatch x Percent	10.524	.001	.004
Frame x Percent	7.562	.001	.003
CirMatch x Frame x Percent	.853	.465	.000
Sleep x CirMatch	16.931	.001	.002
Sleep x Frame	.044	.834	.000
Sleep x Percent	4.221	.005	.002
Sleep x CirMatch x Frame	.404	.525	.000
Sleep x CirMatch x Percent	1.521	.207	.001
Sleep x Frame x Percent	.695	.555	.000
Sleep x CirMatch x Frame x Percent	.389	.761	.000

TABLE A3: ANOVA with Sleep, Circadian-match, Frame, Starting amount

Factor	F (1,7712)	<i>p</i>	η^2
Sleep	10.495	.001	.001
Frame	216.933	.001	.027
CirMatch	.070	.791	.000
StartAmnt	18.029	.001	.007
Sleep x Frame	.042	.838	.000
Sleep x CirMatch	17.098	.001	.002
Sleep x StartAmnt	1.118	.340	.000
Frame x CirMatch	2.946	.086	.000
Frame x StartAmnt	4.753	.003	.002
CirMatch x StartAmnt	1.947	.120	.001
Sleep x Frame x CirMatch	.433	.510	.000
Sleep x Frame x StartAmnt	1.912	.125	.001
Sleep x CirMatch x StartAmnt	1.377	.248	.001
Frame x CirMatch x StartAmnt	.354	.786	.000
Sleep x Frame x CirMatch x StartAmnt	.177	.912	.000

TABLE A4: Determinants of Risky Choice: Probit Estimations

VARIABLES	(1) Baseline (n=149 subjects)	(2) Factor Interactions	(3) Compliant Subset (n=119 subjects)	(4) Compliant Subset Factor Interactions
Daytime Sleepiness	-0.018 (0.012)	-0.019 (0.012)	-0.024* (0.013)	-0.025* (0.013)
Trial #	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)	-0.001*** (0.000)
Loss Frame (=1)	0.301*** (0.018)	0.283*** (0.052)	0.274*** (0.021)	0.253*** (0.058)
Start Cash	-0.025*** (0.003)	-0.030*** (0.006)	-0.024*** (0.004)	-0.028*** (0.007)
Win %	0.019*** (0.000)	0.017*** (0.001)	0.018*** (0.000)	0.017*** (0.001)
Repeat Admin (=1)	-0.180*** (0.018)	-0.180*** (0.018)	-0.193*** (0.020)	-0.193*** (0.020)
Morning Session (=1)	0.043 (0.086)	0.044 (0.086)	0.041 (0.091)	0.040 (0.091)
Reduced-MEQ score	-0.016* (0.008)	-0.015* (0.008)	-0.010 (0.009)	-0.009 (0.009)
SR (=1)	0.117*** (0.026)	-0.044 (0.059)	0.083*** (0.028)	-0.062 (0.066)
MM (=1)	0.172** (0.087)	0.090 (0.102)	0.226** (0.091)	0.262** (0.109)
SD * MM	-0.136*** (0.036)	-0.134*** (0.036)	-0.098** (0.040)	-0.096** (0.040)
Loss * Start Cash		0.008 (0.007)		0.008 (0.007)
SR * Loss		0.041 (0.037)		0.047 (0.041)
MM * Loss		-0.096*** (0.037)		-0.113*** (0.041)
SR * Win %		0.002*** (0.001)		0.001* (0.001)
MM * Win %		0.003*** (0.001)		0.001* (0.001)
SR * Start Cash		0.009 (0.006)		0.009 (0.007)
MM * Start Cash		-0.004 (0.006)		-0.009 (0.007)
Constant	-1.408*** (0.124)	-1.405*** (0.124)	-1.530*** (0.140)	-1.525*** (0.140)
Trial Observations	24,348	24,348	19,005	19,005
Log-Likelihood	-13491.016	-13470.813	-10766.146	-10755.838

*** p<0.01, ** p<0.05, * p<0.10. Standard errors in parentheses. Models are random-effects Probit regressions that model the correlation of error terms across trials for a given participant.

TABLE A5: Determinants of Study Completion (conditional on enrollment)

VARIABLES	(1)	(2)
	Linear Probability	nonlinear Probit estimation
SR week first	-0.08 (0.06)	-0.26 (0.17)
Morning Session	0.07 (0.06)	0.19 (0.18)
rMEQ score	0.01 (0.01)	0.02 (0.02)
Female (=1)	0.02 (0.06)	0.06 (0.18)
Minority (=1)	-0.05 (0.11)	-0.16 (0.32)
Nonstudent (=1)	0.14 (0.13)	0.41 (0.39)
age (in years)	-0.01 (0.01)	-0.03 (0.02)
Optimal Sleep (self-report)	-0.02 (0.03)	-0.08 (0.09)
ANXIETY risk	0.01 (0.01)	0.04 (0.04)
DEPRESSION risk	-0.06 (0.04)	-0.20 (0.11)
Epworth daytime sleepiness score	0.00 (0.01)	0.01 (0.03)
Constant	0.98** (0.31)	1.37 (0.94)
Observations	256	256
R-squared	0.0395	---
Pseudo-R-Squared	---	0.0344

** p<0.01, * p<0.05. Standard errors in parentheses

Notes: The lack of significant predictors implies that observable characteristics do not predict inclusion into the final sample from those initially enrolled into the study.