Thinking About Complex Decisions: How Sleep And Time-Of-Day Influence Complex Choices

By: Todd McElroy and **David L. Dickinson**

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Thinking about complex decisions: How sleep and time-of-day influence complex choices

Todd McElroy[a,*], David L. Dickinson[b,c,d]

[a] Florida Gulf Coast University, United States
[b] Economics Department, CERPA (Center for Economic Research and Policy Analysis), Appalachian State University, United States
[c] IZA (Institute for the Study of Labor), Bonn, Germany
[d] ESI (Economic Science Institute), Chapman University, United States

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ABSTRACT

In this study, we systematically manipulate a person's state of sleep; Sleep-deprived and Well-rested along with Matching or Mismatching the decision time-of-day to their circadian preferred time-of-day. We assessed how these conditions influenced performance on an incentivized complex decision task. In the overall analysis of these variables no differences emerged. However, a comparison of the more cognitively depleting Sleep-deprivation/Circadian-mismatch condition to the cognitively enhancing Well-rested/Circadian-match condition showed improved performance in the Well-rested/Circadian matched group for one complex decision task but not for the other. These findings build upon the existing literature on sleep and circadian rhythm effects while uniquely observing the combined effects of these variables on complex decision making.

1. Introduction

How well we think about complex decisions is an important topic, especially given the serious nature of so many complex decisions. Yet, it is unclear when and under what conditions we can optimize our abilities to make better complex decisions. In this article we examine how two factors common to everyone, sleep and circadian timing, impact a person's decision-making performance.

1.1. Sleep effects on decision making

Sleep loss is a common human experience and its detrimental effects are evident even with basic psychomotor skills (e.g., Dinges et al., 1997). However, the effects are not limited to basic skills. In fact, a meta-analysis by Pilcher and Huffcutt (1996) highlights how sleep deprivation affects cognitive tasks more than basic motor skill tasks and how it especially affects mood. The cognitive effects are further complicated by brain scans and behavioral data that show how sleep deprivation may impair some cognitive functions but not others (e.g., Drummond et al., 1999, 2000; Harrison & Horne, 2000). Because not all cognitive functions may be impaired by sleep deprivation, it is important that research address the question of sleep deprivation within specific areas of human behavior.

While the cognitive impairment resulting from sleep deprivation likely has rippling effects on human behavior, one important

* Corresponding author at: Department of Psychology, Florida Gulf Coast University, United States.
E-mail address: tmcelroy@fgcu.edu (T. McElroy).

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area that research shows can be affected is decision making. For example, sleep deprived participants alter their decisions by simply preferring more risk (e.g., Killgore, Balkin, & Wesensten, 2006) or, more generally, by becoming desensitized to monetary risk (McKenna, Dickinson, Orff, & Drummond, 2007). There is also evidence that sleep restriction can reduce prosocial behaviors and lead to less beneficial decision choices in a short-term social interaction (Dickinson & McElroy, 2017; Holbein, Schafer, & Dickinson, 2019), as well as increase reliance on a simple reinforcement-heuristic in a Bayesian decision environment (Dickinson & McElroy, 2019).

In a direct test of whether decision making was affected by sleep deprivation, Harrison and Home (1999) implemented a critical reasoning task to determine whether sleep deprivation effects were due to faulty decision making or errors in information acquisition. Their results showed that decision making deficits were not due to a participant's ability to assimilate the decision information, rather, it appeared that faulty processes such as increased perseveration on errors and lack of updating were to blame. In related research Bruck and Pisali (1999) found that sleep inertia, or the cognitive impairment just after awakening, had detrimental effects on decision making for at least 30 min after awakening.

More to the topic at hand, there is evidence that decisions in complex tasks are the most sensitive to the need for sleep (Dickinson & McElroy, 2019; Hood & Bruck, 1997) which may account for deficits in areas crucial to complex decision making such as attentional processes (e.g., Wimmer, Hoffman, Bonato, & Moffitt, 1992) and updating (e.g., Harrison & Home, 1999). In one study Wickens, Hutchins, Laux, and Sebok (2015) focused on the role of sleep and circadian effects on complex tasks, though they did not focus their analysis on decision tasks. They found that performance on complex cognitive tasks declined with increasing levels of sleep deprivation and was greatest during circadian off-peak hours. Dickinson and McElroy (2019) found that Bayesian choice accuracy was negatively impacted only on complex versions of the task that could not otherwise be successfully handled with a simple decision heuristic. Relatedly, early research using a distinct Bayesian task reported that sleep deprived individuals placed less decision weight on new evidence relative to existing information (Dickinson & Drummond, 2008; Dickinson, Drummond, & Dyche, 2016). Finally, research involving iterative reasoning where anticipating others' choices was important has also reported that lower sleep levels were associated with sub-optimal decision choices (Dickinson & McElroy, 2012).

It is also important to examine whether decision making detriments caused by sleep deprivation are fixed or whether this is something that a person can overcome. In their review of the literature, Harrison and Horne (2000) point out that more directed research shows that some elements of decision making remain impaired by sleep-deprivation even when more effort is applied. A study by Horne and Pettitt (1985) looked at this question by testing the influence of monetary incentive on sleep-deprived participants. In their study they included three conditions for sleep-deprived participants; one with no incentive, one with monetary incentive and a control group and they increased incentive with greater sleep deprivation. They found that the monetary incentive appeared to motivate participants and they were able to compensate for sleep deprivation for up to 36 h, but after that the monetary incentive failed to increase performance. Thus, it appears possible to overcome some of the effects of sleep deprivation, at least for limited sleep loss.

1.2. Circadian rhythm effects on decision making

Circadian rhythm refers to diurnal variations in both physiological and behavioral patterns. Circadian rhythms are relatively stable (e.g., Wever, 1992) and function independent of other physiological rhythms such as the sleep–wake cycle (Folkard, Hume, Minors, Waterhouse, & Watson, 1985). Research has shown that cognition or "effortful thinking" also varies, such that people expend more effortful thought during circadian on-times than off-times (e.g., Martin & Marrington, 2005; Monk & Leng, 1986).

In a series of studies that highlight the effects of circadian timing, Bodenhausen (1990) investigated how circadian match/mismatch could influence stereotyping responses. Bodenhausen rationalized that during circadian mismatch individuals should have decreased cognitive resources making them less thoughtful and more reliant on stereotypes and heuristics. Across two studies, Bodenhausen (1990) demonstrated that during circadian "off-times", participants were more likely to rely on stereotypes when making judgments relative to circadian "on-times". Using a similar protocol to manipulate circadian match versus mismatch, Kruglanski and Pierro (2008) reported increased incidence of the transference effect among circadian mismatched participants, which they attributed to misapplication of an available schema when at circadian off-peak times-of-day. In another study manipulating circadian timing, McElroy and Dickinson (2010) investigated how circadian time-of-day across the full 24-hr cycle would influence risky-choice decisions in a framing paradigm. They reasoned that participants should approach the decision task with more cognitive effort during circadian matched times and less effort during circadian mismatched times; as prior research has shown more cognitive effort should attenuate framing effects (McElroy & Seta, 2003). Their findings supported this view with framing effects being most prominent during circadian off-times. Finally, two studies by Dickinson and McElroy (2010, 2012) showed that choices in the middle of the night, relative to more circadian optimal times, were consistent with reduced ability to anticipate others' decisions, which is generally considered a component of complex theory-of-mind skills. While none of these findings directly tested complex versus simple decisions, they do show how circadian match can enhance or impede cognition and lead to more or less thoughtful decisions.

1.3. Summary and predictions

In the current study, we examine how both sleep deprivation and circadian match influence complex decision making. Prior research has suggested that both sleep deprivation and circadian mismatch may have detrimental effects on at least some cognitive variables related to complex decision making. Consequently, we predict that when individuals are well-rested and at their circadian matched time-of-day, their performance on complex decision tasks will be optimized. Conversely, when a person is sleep-deprived and circadian mismatched, this should represent their most depleted cognitive state and as a result, the greatest performance decrements in complex decision making should be observed.

2. Method

2.1. Power considerations

To examine statistical power, we took into consideration key variables: two sleep levels ("sleep-deprived" and "well-rested"); two chronotypes (morning- and evening-type); and two times-of-day (morning and evening). Based upon this we examined power of the between-subjects circadian and time-of-day effects (and their interaction to generate circadian mismatch) and the within-subjects sleep deprivation. The sample size targeted in the design phase of the study was based off conservative power calculations using non-parametric Mann-Whitney tests of medians. Specifically, an *a priori* sensitivity-type power analysis was performed using G*Power, version 3.1.3, with an $\alpha = 0.05$ error probability, a desired power level = 0.80 (recommended by Cohen (1992) for behavioral research), and samples size for separate within-subjects (the sleep restriction factor) and between-subjects (the circadian mismatch factor) tests. (Cohen's d suggestion is that values of 0.2, 0.50, and 0.80 represent small, medium, and large effect sizes for such tests).

Considering the Control subjects (n = 30) as separate, our sample of n = 110 treatment subjects were used to calculate the detectable effect size for a between-subjects (n = 55 in each of the circadian matched and circadian mismatched groups) is an effect size of $d = 0.488$. For the within subjects test of the sleep restriction effect, we used a sample size of n = 110 and considered the difference between responses between the SR and WR condition as the unit of observation on all treatment subjects. Here, we found that we would have sufficient power to detect small sized effects $d = 0.244$.

The actual analysis used deviated from the nonparametric means tests considered ex ante, and so the actual power achieved would therefore differ for the multivariate analysis performed. A re-assessment of the statistical power can be done, post hoc, using a Chi-squared goodness of fit test G*Power. We report χ^2 results below in our Results section. Here, a χ^2 (1, $N = 110$) test for our sample size with $\alpha = 0.05$ error probability is found to achieve the recommended power level = 0.80 to detect a medium effect size of w = 0.27 (the convention is that w = 0.10, 0.30, and 0.50 represent small, medium, and large effect sizes for this test). Alternatively, a power analysis using the ANOVA approach indicates sufficient power to detect medium-large effects of the between-subjects factors and sufficient power to detect medium-small effects of the within-subjects (sleep restriction) effects. Though actual power always depends on the exact analysis approach used, this indicates that our design should have sufficient power to detect approximately medium sized effects, at least for the within-subjects sleep restriction factor.

2.2. Participants

We had ongoing participant recruitment until we achieved our targeted number of 140 participants for a 3-week mixed study design. In total, we attempted to recruit 256 participants from a large database of local respondents to an online survey.[1] From this recruitment attempt, 35 failed to show up for the initial introduction session and 37 of the participants failed to complete the prescribed protocol at some point during the three-week period and were removed from the study. A total of 184 participants took part in the three-week study. Actigraphy devices were used to objectively verify compliance to the sleep manipulation and sleep diaries. During the study, nine of the devices malfunctioned and the participant data associated with these devices was not retrievable so their responses to the decision tasks could not be used. Additionally, 35 participants either did not meet the criteria for being sleep compliant as verified through actigraphy and sleep diaries[2] or failed to complete the decision tasks correctly or completely. Among the 140 participants with complete actigraphy and decision data, 88 of them were female and 52 were male. Participants ranged in age from 18 to 40 (M age = 21.9).

2.3. Apparatus and materials

To measure participant's sleep/wake times across the three-week period of our study we used an Actigraphy Acquisition Device (Actiwatch Spectrum Plus devices; Philips Respironics). The actigraph uses an MEMS type accelerometer and samples data at 32 Hz. For our experiments, we set devices to sample activity at 30-second epochs. The actigraph is waterproof and participants were instructed to wear them at all times during the course of the three-week study unless they were engaging in activity that might harm the device. The actigraphy device records wrist movement as a proxy for gross motor movements and is well-validated in use with non-sleep disordered subjects (see Sadeh, 2011, for a discussion of actigraphy validity and limitations). Device software automatically scores each epoch as "sleep" or "wake", but scoring the beginning/end points of a subject's attempted rest period is done manually in conjunction with sleep diaries kept by subjects.[3] All manual scoring was done using a common sleep research actigraphy scoring

[1] For a more extensive review and validation of the protocol used in this study see Dickinson and Drummond (2017).

[2] In order to be sleep compliant a subject must have at least 60 min or more of nightly sleep during the well-rested week than the sleep-restricted week.

[3] For example, manual scoring also allows the researcher to dictate that specific time period with little or no activity is counted as "wake" by the software. Such would be the case if the subject indicates that he/she removed the watch to play contact sports for a couple of hours, for example.

protocol (Goldman et al., 2007) in conjunction with participant's sleep diaries which acted as a type of secondary source to verify compliance, anomalies or any uncertain data points.

The complex decision tasks used in this study were structurally the same and both were taken from prior research measuring complex decisions (Dijksterhuis, Bos, Nordgren, & van Baaren, 2006). In the first decision round (Week 1) The decision task involved choosing among four computers, each computer contained 12 attributes. All of the attributes were balanced for valence which was validated by Dijksterhuis et al. (2006). Among the computers, one was designated as "correct", it contained 75% positive attributes, two had 50% positive attributes and one computer had 25% positive attributes. Similar to the computer task presented in round 1, the second decision task we used in round 2 (Week 3) involved a decision among four cars, each of which contained 12 attributes with one car possessing 75% positive attributes (correct response), two with 50% positive attributes and one with 25% positive attributes. The complex car task used in Week 3 is presented in Appendix A. In terms of complexity, these decision tasks first require an evaluation of the 12 attributes. Subsequently, a comparison among alternatives must take place while consistently maintaining the value of alternatives and updating relative standing among the four alternatives. Thus, both attentional processes and updating are necessary.

2.4. Procedure

An online survey was widely circulated around a campus community to create a sizeable pool of participants for possible recruitment in our study. Participants who completed the survey were entered into a drawing for a gift card as well as being made eligible for compensated research studies involving sleep and decision making. Over the course of multiple academic semesters several thousand people responded to the survey. Respondents were mostly university students. The survey asked basic demographic information as well as validated screener questions for anxiety and depression.

Central to our survey was a validated measure of circadian preference, the short form of the morningness-eveningness questionnaire (rMEQ) (Adan & Admiral, 1991). The rMEQ is a shortened version of the Horne and Östberg (1976) scale. The rMEQ is designed to rank individuals on a range from 4 to 25, with morning-types scoring from 18 to 25, evening-types scoring from 4 to 11, and middle types 12to 14. This circadian preference measure has been well validated (Adan & Admiral, 1991; Horne & Östberg, 1976) and is standard in circadian research.

After a sizable database was established, we began recruiting morning-type[4], middle circadian types and evening-type subjects. Because of the association between anxiety, depression and sleep disturbance, individuals scoring at risk for either major anxiety or depressive disorder were omitted as possible participants in the study, as were those who reported a diagnosed sleep disorder. Finally, we focused on young adults between 18 and 39 years of age and so being outside this age range was also an exclusion criterion. Both morning-type and evening-type participants were randomly assigned to either the early morning (7:30–9:00 am) or late evening (10:00–11:30 pm) session time. Approximately half the sample was circadian matched, and half mismatched and, importantly, these random session time assignments were done prior to recruitment to the main 3-week study. Subjects were only offered to participate in a session time to which they were randomly assigned, which helps avoid subject self-selection into preferred session times. A smaller number of middle (Intermediate or Indeterminate) circadian types were all assigned mid-day time slots and used as control subjects who did not complete a sleep restriction week ($n = 30$).

The main protocol in this study was three weeks long, and included three in-lab meetings, all taking place at the same session time. For example, one cohort (group) would be an evening session group, with all sessions being in the evening, although the cohort would be comprised of a mix of morning-types and evening-type subjects. All participants first met in the laboratory to be introduced to the experiment. During this session they were assigned random subject numbers and actrigraphy devices, instructed on how to do morning and evening call-ins (another way we helped ensure accurate bed/wake times for scoring), sleep diary recording, and were informed more specifically about monetary compensation for participation in the study.[5] The specifics on the timeline of the protocol are shown in Fig. 1.

During week 1 participants in the circadian match/mismatch conditions were prescribed either one week of Sleep-Restriction (SR: 5–6 h/night attempted sleep) or one week of Well-Rested sleep (WR: 8–9 h/night attempted sleep), with order counterbalanced across groups. Participants in the middle circadian groups were prescribed WR weeks in both experimental weeks. At the end of week 1 all participants returned to the lab for the first experimental session, which was scheduled at the same time-of-day.[6] During Session 1 participants were presented via computer a complex decision task adopted from Dijksterhuis et al. (2006).

Week 2 of the 3-week protocol was an ad lib sleep week, and subjects did not return to the lab after week 2. This week was included to wash out the effects of the week 1 treatment (either SR or WR) prior to administration of the opposite sleep condition (WR or SR, respectively) in week 3. At the end of week 3 participants returned to the lab and were administered the second complex decision task which involved choosing among four cars which possessed 12 attributes for comparison and were balanced for valence.

[4] Because legitimate morning-types are infrequent in subject populations, usually less than 10%, we included rMEQ scores as low as 17 as morning types (i.e., Intermediate-types that are close to being categorized as morning-types). Evening-type rMEQ scores recruited ranged from 4 to 9.

[5] The basics of the experiment protocol, including compensation, was also discussed and summarized for subjects in the recruitment email they initially received. Subjects received a fixed $80 payment for compliance with the parameters of the 3-week protocol and provision of the actigraphy and diary data. Additional compensation was earned during Sessions 2 and 3 for participant's decision-making performance.

[6] Control subject sessions took place between 10 am and 3 pm, as the intention was to remove the circadian and sleep-restriction elements from the design for the small set of Control subjects.

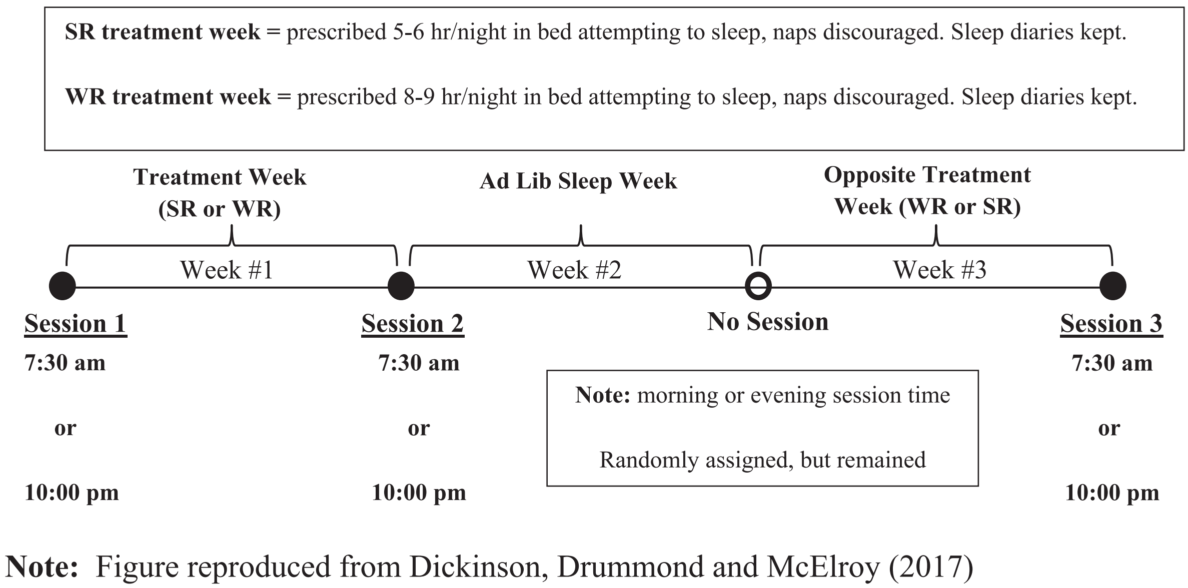

Fig. 1. Protocol details and timeline. *Note:* Figure reproduced from Dickinson, Drummond, and McElroy (2017).

In this way, each participant in the circadian matched/mismatched groups was prescribed one WR and one SR week, such that these participants received both sleep levels but only one condition of circadian match or mismatch. Control participants who were neither evening- nor morning-types all had mid-day times and were prescribed to sleep the 8–9 h in both weeks 1 and 3. We communicated with subjects every 2–3 days of the 3-week protocol to remind them of the current sleep prescription (which included a cautionary message in the SR week concerning the risk of drowsiness) and reminders of when the upcoming in-lab sessions would take place.

3. Results

The purpose of our investigation was to examine how sleep and circadian match would influence performance in complex decision tasks. To test our hypothesis, we performed a series of analyses with Sleep Level and Circadian Match as our independent variables. Participant's performance on the complex decision task acted as our dependent variable.

Because we used different complex decision tasks in the two experimental sessions, we first wanted to test whether the two different decision tasks yielded consistent findings across the two experimental sessions. To make this comparison, we utilized our baseline control group (Middle-circadian Well-rested) and compared their scores on the first decision task to those on the second decision task. The chi-square comparison of this group revealed that the tasks did differ significantly χ^2 (1, N = 30) = 4.45, p = .04. Therefore, because the two tasks appear to differ, we analyzed each experimental session independently.

We first performed a nominal logistic regression analysis using the experimental circadian conditions (matched or mismatched) and sleep (sleep-restricted or well-rested) as our independent variables and complex decision scores in the first session as our dependent variable. This analysis yielded a nonsignificant main effect for Circadian Match χ^2 (1, N = 110) = 1.59, p = .21, a significant main effect for Sleep χ^2 (1, N = 110) = 3.94, p = .05 and a nonsignificant Circadian Match × Sleep interaction χ^2 (1, N = 110) = 0.07, p = .8 (See Table 1). We performed the same nominal logistic regression analysis for Session 2 which yielded a nonsignificant effect for Circadian Match χ^2 (1, N = 110) = 0.02, p = .9 and Sleep χ^2 (1, N = 110) = 0.1, p = .75 as well as a nonsignificant Circadian Match × Sleep interaction χ^2 (1, N = 110) = 0.77, p = .38 (See Table 2). Given our earlier discussion of

Table 1
Means and SDs of participant responses to Task 1—administered in the 1st Decision Session.

	M	N	SD
Sleep-deprived			
Match	0.74	27	0.45
Mismatch	0.64	25	0.49
Well-rested			
Match	0.89	28	0.32
Mismatch	0.80	30	0.41
Control	0.8	30	0.41

Note. Correct responses were coded as "1" all incorrect responses were coded as "0".

Table 2
Means and SDs of participant responses to Task 2—administered in the 2nd Decision Session.

Sleep Condition			
Circadian	M	N	SD
Sleep-deprived			
Match	0.78	28	0.42
Mismatch	0.70	30	0.47
Well-rested			
Match	0.74	27	0.45
Mismatch	0.80	25	0.41
Control	0.7	30	0.47

Note. Correct responses were coded as "1" all incorrect responses were coded as "0".

statistical power achieved by our design, we feel our null findings are not an artefact of an underpowered design but represent no impact of our manipulation on outcomes in the second complex task.

To further explore our hypothesis, we wanted to compare the two conditions that should reflect the greatest differences in thinking enhancement and degradation. To test this, we performed a nominal logistic regression analysis comparing the SR/Circadian- mismatched condition to the WR/Circadian-matched condition for each of the two experimental sessions. This comparison yielded a significant difference for the Session 1 decision task: χ^2 (1, N = 53) = 4.96, p = .03. As can be seen in Table 1, participants in the Well-Rested Circadian-matched condition scored significantly higher than participants in the Sleep-Restricted Circadian-mismatched condition. When we performed the same comparison for Session 2, the results yielded a nonsignificant difference: χ^2 (1, N = 57) = 0.12, $p \leq .74$ between these conditions.

4. Discussion

The current study investigated how enhanced and attenuated thinking influences complex decision making. In line with prior research (e.g., Dickinson & McElroy, 2012, 2019; Harrison & Home, 1999; Hood & Bruck, 1997; McElroy & Dickinson, 2010; Wimmer et al., 1992) we predicted that when a participant was well-rested and circadian matched this would lead to maximum enhancement of cognitive abilities and optimization of complex decision performance. Conversely, we predicted that sleep-deprivation and circadian mismatch would lead to the greatest degradation of cognitive abilities and the lowest complex decision performance.

The results from our study shed light on how this combination of sleep and timing of circadian rhythm cycle influences complex decisions. Prior research (e.g., Hood & Bruck, 1997; Dickinson & McElroy, 2019) has shown that sleep restriction degrades performance on complex decision tasks and circadian research has shown similar effects of less thoughtful decision making during circadian off-times (e.g., Dickinson & McElroy, 2010; McElroy & Dickinson, 2010). Pitting these variables together did not reveal an overall interaction, suggesting that one may not intensify or degrade the other equally. However, our design makes a novel contribution to understanding complex decision making by allowing us to compare the pooled condition of WR/Circadian-matched to the SR/Circadian-mismatch condition. When we did so, performance was significantly better for the WR/Circadian matched condition in Session 1 but the groups did not differ significantly in the Session 2 complex decision task.

It is unclear why we observed our predicted differences in Session 1 but not in Session 2. Because there was monetary incentive for performance, it is possible that participants in the sleep-restricted circadian mismatched condition may have prepared themselves better for this type of task in the second decision round. Simply put, they knew what to expect the second time around and were determined to perform better. It is also possible that a type of test-retest effect occurred, and they simply performed better the second time. In other words, the beneficial effect of enhanced thinking ability for complex decision making may be more prominent with novel tasks as opposed to familiar tasks (such as would be the case during the second administration of the task in Session 2). Another possibility is that the target of the decision task may have influenced participant's decisions in the second decision round. Some evidence for this can be found in a large meta-analysis by Lim and Dinges (2010) which found that sleep-deprivation effects varied across different cognitive domains, suggesting that sleep-deprivation may impact some types of decision tasks more than others. Another interesting finding in Study 2 was the observation that in the Well-rested condition Circadian Mismatched participants appeared to perform descriptively better than the Matched participants. While only speculative, we believe that this observation may attest to a more robust effect from sleep deprivation compared to circadian match. In other words, if one is well-rested, they may be able to compensate for circadian mismatch and improve their performance.

Our analysis was limited by the type of decision tasks we used. Because research has shown that sleep deprivation can have varied effects on different cognitive processes, future research should consider using complex decision tasks containing different components that are sensitive to the respective types of cognitive processes. For example, developing some tasks which focus on updating elements and others that focus on attentional processes would allow researchers to discern which aspects of complex decision making are affected by cognitive constraints such as those imposed by sleep deprivation and circadian mismatch.

Though speculative, it seems reasonable to extend the scope of our manipulation and address how our findings might relate to Unconscious Thought Theory (UTT) (e.g., Dijksterhuis et al., 2006). UTT posits that consciousness has a limited capacity for processing information, including decision-relevant information. Conversely, the unconscious has a capacity that far exceeds the consciousness. Therefore, when making complex decisions, UTT predicts a person's performance will be maximized when the *unconscious* is utilized. Assuming that being well-rested/circadian matched will likely lead to more "conscious" processing whereas being sleep-deprived/circadian mismatched will lead to more "unconscious" processing, then our findings do not support UTT and the results of the Session 1 task are the opposite of UTT predictions. As we noted this extends the scope of our study but we believe that it is important that this lack of continuity with UTT be highlighted especially given the number of failures to replicate the effect (e.g., Acker, 2008; Ran et al., 2019), as well as theoretical shortcomings and disregard of relevant findings (Gonzalez-Vallejo, Lassiter, Bellezza, & Lindberg, 2008; Newell & Shanks, 2014). The Dijksterhuis et al. findings have also been scrutinized by Francis, Tanzman, and Matthews (2014) wherein the authors use a statistical measure that is designed to estimate the likelihood that a series of experiments will yield as many "success" outcomes as reported in their findings. Francis et al., determined that the Dijksterhuis et al. (2006) article met their criteria for having an "excess success rate" and researchers should be skeptical of their findings.

Overall, our findings advance and uniquely contribute to the existing literature. The design of the study allowed us to observe both the separate and combined effects of sleep-restriction and circadian mismatch on complex decision-making performance. Prior research had not examined how this combination of variables, which each represent an adverse cognitive state, influences complex decision making. The Session 1 finding of stronger performance for well-rested/circadian-matched participants should be especially robust given that we provided monetary incentives, and prior research (Horne & Pettitt, 1985) has shown that monetarily incentivized participants are able to overcome limited sleep loss effects on performance. Especially for complex tasks that are novel (such as ours is in Session 1), our findings yielded a robust effect that attests to the important influence that sleep and circadian state may have on decision making. These results are in line with previous research that suggests enhanced cognitive states are likely to improve decision making on complex tasks.

Acknowledgment

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Appendix A

Example of four car options with 12 alternatives presented to participants

The Hatsdun

The Hatsdun has good mileage
The Hatsdun has good handling
The Hatsdun has a large trunk
The Hatsdun is very new
The Hatsdun is available in many different colors
For the Hatsdun service is excellent
The Hatsdun has poor legroom
With the Hatsdun it is difficult to shift gears
The Hatsdun has cupholders
The Hatsdun has a sunroof
The Hatsdun is relatively good for the environment
The Hatsdun has a poor sound system

The Kaiwa

The Kaiwa has good mileage
The Kaiwa has poor handling
The Kaiwa has a large trunk
The Kaiwa is available in many different colors
For the Kaiwa service is excellent
The Kaiwa has plenty of legroom
With the Kaiwa it is easy to shift gears
The Kaiwa has no cupholders
The Kaiwa has no sunroof
The Kaiwa is not very good for the environment
The Kaiwa has a poor sound system
The Kaiwa is old

The Dasuka

The Dasuka has poor mileage
The Dasuka has good handling

The Dasuka has a small trunk
The Dasuka is available in very few colors
For the Dasuka service is poor
The Dasuka has little legroom
With the Dasuka it is easy to shift gears
The Dasuka has cupholders
The Dasuka has a sunroof
The Dasuka is not very good for the environment
The Dasuka has a good sound system
The Dasuka is new

The Nabusi

The Nabusi has poor mileage
The Nabusi has poor handling
The Nabusi has a small trunk
The Nabusi is available in many different colors
For the Nabusi service is poor
The Nabusi has plenty of legroom
With the Nabusi it is difficult to shift gears
The Nabusi has no cupholders
The Nabusi has a sunroof
The Nabusi is not very good for the environment
The Nabusi has a poor sound system
The Nabusi is old

Appendix B. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2019.102824.

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