

Sleep Restriction Reduces Cognitive but Not Physical Motivation

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Purpose: Motivation is an important driver of behaviour, and several frameworks distinguish the willingness of individuals to invest cognitive versus physical effort to achieve a goal. One outstanding question is whether sleep loss lowers motivation within specific domains of effort, or has a global effect on motivation across multiple domains. Here, we investigated the effects of sleep restriction on the motivation to invest cognitive or physical effort in return for reward.

Materials and Methods: 24 healthy young adults (11 females) completed an effort-based decision-making task over two laboratory sessions – once while sleep restricted (three consecutive nights with a three-hour sleep opportunity), and the other while fully rested (nine-hour sleep opportunity on each night). In an initial reinforcement phase, participants were trained to ceiling performance across six levels of effort on separate cognitively and physically demanding tasks. Then, in the critical decision-making phase, participants revealed their preference for how much cognitive or physical effort they would be willing to invest for reward.

Results: Sleep restriction reduced the willingness to exert cognitive effort, but spared motivation in the physical domain. Furthermore, the reduction in cognitive motivation appeared to be a primary motivational deficit, which could not be attributed to differences in reward-likelihood of different levels of effort or the temporal structure of the task.

Conclusion: The results suggest that sleep restriction has a selective effect on cognitive over physical motivation, which has significant implications for real-world settings in which individuals must maintain high levels of cognitive motivation in the face of chronic sleep loss.

Keywords: sleep loss, cognitive effort, physical effort, effort-based decision-making

Introduction

Motivation is fundamental to daily life, and drives us to engage in effortful behaviour in pursuit of our goals – such as the cognitive effort invested by students and academics, and the physical effort invested by athletes and military personnel.¹⁻⁴ Chronic sleep loss can have a profound impact on daily function, with particular consequences for professions in which sleep loss is unavoidable (eg, healthcare, the military).^{5,6} It has long been recognised that the effect of sleep loss on performance may be driven, not only by its effects on cognitive and physical capacity,⁷⁻⁹ but also through its detrimental effects on motivational drive.¹⁰⁻¹⁵ Importantly, however, motivation is not a unitary construct, and several frameworks distinguish the motivation of individuals to invest effort in the cognitive vs the physical domains.¹⁶⁻¹⁸ An important question, therefore, is whether the effects of sleep loss are unique to specific domains of behaviour or generalise across them. However, this topical issue remains to be directly addressed.

The majority of studies that have examined the consequences of sleep loss on motivation have focused on its impact in the cognitive domain.^{10-12,19,20} Some sleep studies have simply asked the participants to report their willingness to engage in generally cognitively effortful behaviour, eg using a visual analog scale.^{20,21} However, a more sensitive approach developed in the neuroeconomic literature has been to quantify motivation as the willingness of individuals to

overcome different levels of effort costs in pursuit of rewards.^{17,22–27} Such an approach allows us to determine an individual's aversion to effort by fitting their choices to an “effort discounting” function.^{22,28–30} In the sleep literature, such effort discounting studies have tended to show that sleep loss seems to reduce the desire of individuals to engage in cognitively effortful behaviour.^{10,11,19}

However, an important unanswered question is the extent to which this reduction in cognitive motivation represents a primary motivational deficit, versus a secondary consequence of sleep loss on other cognitive functions. For example, previous studies have typically found that sleep loss hinders the capacity to complete cognitive tasks, and accentuates time-on-task decrements in task performance.^{9,11,19,31} Furthermore, many previous studies have manipulated effort by systematically varying the amount of time that individuals engage with each level of a task (eg, having to perform the psychomotor vigilance task for increasing periods of time).^{10,11,19} Given that sleep loss hinders the capacity to sustain cognitive performance, previous findings showing reduced willingness to engage in cognitive tasks under sleep restriction, could be, in part, explained by the desire to avoid task failure. Consequently, it is important to confirm that any apparent reduction in cognitive motivation is indeed driven by a greater aversion to effort itself, rather than simply a disinclination to engage in activities that are less likely to be successfully completed.²⁴

Surprisingly, much less work has examined the link between sleep and physical motivation.^{21,32} These limited data suggest that sleep loss similarly reduces the motivation to invest physical effort. However, these studies are limited in having focused on targeted populations of athletes, in less controlled environments (relying solely on measures of self-reported sleep quality and/or actigraphy), and using less sensitive measures of motivation (eg, a single visual analogue rating score of willingness to perform an effortful task). The impact of sleep loss on physical motivation is therefore unclear. Furthermore, no study has examined the consequence of sleep loss on both cognitive and physical motivation using comparable tasks in the same individuals.

In this study, we examined the effects of sleep restriction on the motivation to invest cognitive vs physical effort. We tested participants in a controlled laboratory setting over two counterbalanced sessions – once while fully rested, and once while sleep restricted – and required them to make decisions on the amount of cognitive or physical effort that they were willing to exert in return for reward.^{33,34} Importantly, our task was designed to control for potential effects of restricted sleep on variables that might influence participants' choices, including the capacity of individuals to perform each level of effort, and temporal factors.

Material and Methods

Participants

Data were collected as part of a larger study investigating the effects of sleep restriction on cognition. The final sample comprised 24 healthy adults (see Table 1), with no history of substance use, neurological or psychiatric disease. Participants were non-smokers, consumed less than 400mg of caffeine per day and reported habitual sleep of between 7 and 9 hours with a bedtime between 22:00 and 1:00 and wake times between 6:00 and 9:00. Additionally, participants had no history of night shift work within the past 12 months. Female participants taking hormonal contraceptives were included in the study. Extreme morning and evening types were excluded from the study based on criteria from the Morning and Eveningness Questionnaire.³⁵ This final sample did not include data from two additional participants, from whom data were partially lost due to technical issues. Including the available data from these participants did not alter the

Table 1 Participant Characteristics

Age	M= 26.8, SD = 5.2 Range: 21–45
Sex	11 Females 13 Males
Handedness	Right-handed: 19 Left-handed: 5

main findings. Data was collected between March 2018 and March 2021. Participants were recruited via online advertisements and compensated ~ AUD 2500.

Procedure

Participants completed two testing sessions in a closed laboratory environment. Each participant was admitted to a private, time-isolated, light, and temperature-controlled room. Light was maintained at 100 lux during wake periods and temperature maintained at 21° ($\pm$ 2°C). Each session lasted four nights (from a Sunday to a Thursday evening), and the sessions were separated by a nine-day interval. For one week prior to each session, participants maintained a regular sleep-wake schedule, based on their self-reported habitual sleep schedule, and verified with actigraphy and sleep diaries.

In one session (“Fully Rested”), participants were provided a nine-hour sleep opportunity each night. Timing was based on the at-home schedule, with time-in-bed increased equally at the start and end of the night, for those whose at-home schedule included <9 hours in bed. In the alternate session (“Sleep Restricted”), participants were provided a nine-hour sleep opportunity on their first night, but only a three-hour sleep opportunity on subsequent nights, commencing two hours after their “Fully Rested” bed time. Session order was counterbalanced across participants. The first night of the first session served as a sleep disorders screen. On the last day of each session, participants completed the experimental task four to six hours after habitual wake time, typically between 10 am and 2 pm (42 of 46 participants commenced the task between 10.57 am and 12.53 pm). Any given participant was tested at the same time of day in both testing sessions.

During the in-lab component participants were able to watch movies, play board games, and use a lab provided computer to work. Participants were not permitted to engage in any physical activity more vigorous than walking and there was no access to the internet. Activity was monitored by research staff and actigraphy. Meals and snacks with equivalent macronutrients were provided to participants at regular intervals. Participants were constantly monitored by research staff to ensure adherence to the protocol.

Effort-Based Decision-Making Task

We applied a cognitive and physical effort discounting paradigm, details of which have been previously reported.^{33,34} The paradigm consists of two phases. First, participants engaged in a Reinforcement Phase, in which they were trained on: (1) a cognitively effortful task, and (2) a physically effortful task, across separate, counterbalanced blocks. In the subsequent Choice Phase, we examined the willingness of individuals to exert cognitive or physical effort in return for reward. In both tasks, the stimuli were displayed on a 17-inch laptop monitor at a refresh rate of 60Hz positioned ~45cm from the participant. The cognitive effort task was implemented in Presentation software,³⁶ and the physical effort task in the Psychtoolbox package run in MATLAB.³⁷ Participants’ responses were registered with a standard computer keyboard for the cognitive task, and a hand-held dynamometer for the physical task (SS25LA, BIOPAC systems, USA).

Reinforcement Phase

The Reinforcement Phase for each task followed the same structure (Figure 1B and D). Each trial began with an effort cue (in the form of a pie chart presented for two seconds) indicating the amount of effort to be invested in that trial. Blue pie charts preceded cognitively effortful trials, and red pie charts physically effortful trials. These cues were followed by a period of effort exertion in the corresponding domain lasting 10 seconds, followed by a feedback display lasting two seconds indicating their success on that trial. For each task, participants completed three repetitions of each effort level delivered in a random order.

Cognitive Effort Task

The cognitive effort task required participants to monitor between one and six rapid-serial-visual-presentation (RSVP) letter streams for a target letter “T” (Figure 1A)^{33,34} The lowest effort level required participants to monitor one stream displayed at the centre of the screen. Higher effort levels required participants to simultaneously monitor between two to six streams, positioned equidistantly and equiangularly from fixation. Letter stimuli were displayed in Ariel 26-point font, and target letters could appear randomly in any stream. Each trial contained 24 frames, each of which lasted 416 ms, for a total trial duration of 10 seconds. The target was presented three times in each trial. A button-press response

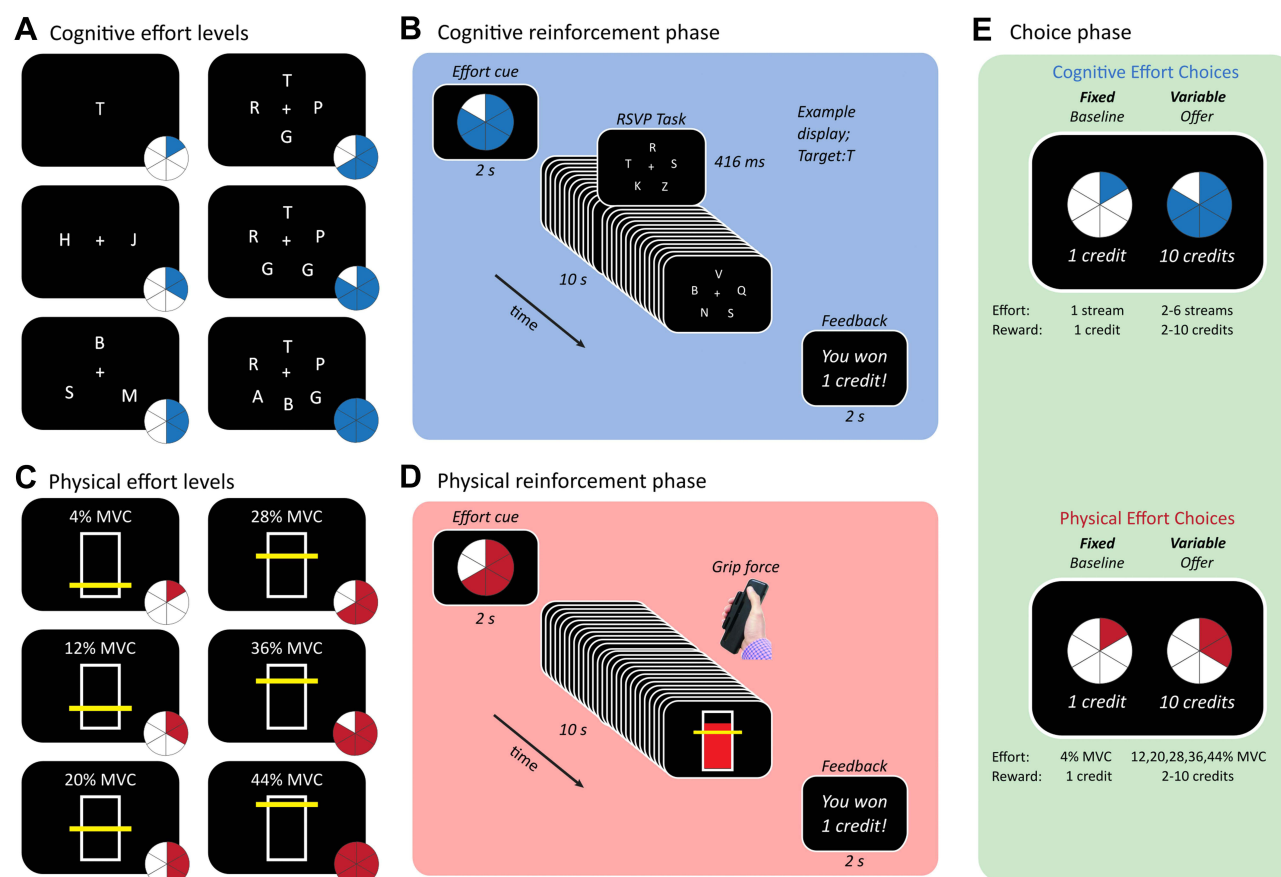


Figure 1 Experimental task. **(A and B)** Cognitive effort task required participants to monitor 1–6 streams of letters rapidly presented on the screen. **(C and D)** Physical effort task required sustaining target handgrip force (4–44% MVC). In the training phase, participants completed different effort levels presented in random order, in cognitive and physical domain (counterbalanced order). **(E)** In the choice phase, participants indicated their preferences between the fixed low-effort/low-reward baseline on the left and a variable high-effort/high-reward offer on the right.

qualified as a hit if it occurred within 833ms of target presentation. Participants were rewarded with one credit if they were able to complete each trial above a threshold level of performance (>1 hit, <3 false alarms).

Physical Effort Task

The physical effort task required participants to exert one of six levels of force on a hand-held dynamometer using their dominant hand (Figure 1C). At the beginning of each session, we determined individuals' maximum voluntary contraction (MVC) as the maximum of three consecutive ballistic squeezes with their dominant hand. We then defined the six effort levels for each individual as a function of their MVC (4, 12, 20, 28, 36, 44% MVC). On each trial, the target effort level was depicted by a yellow horizontal line on a vertical bar, which provided participants with real-time feedback on their generated force. To succeed, participants had to maintain their force above the target effort level for $\geq 50\%$ of the 10-second duration of the trial.

Choice Phase

In the critical Choice Phase, we quantified participants' motivation to exert cognitive or physical effort for a given reward. In each trial, participants chose between a fixed low-effort/low-reward baseline and a variable high-effort/high-reward offer within the same domain. The fixed baseline was the opportunity to perform the lowest level of effort (Level 1) in return for the lowest reward (1 credit). The variable offer was the opportunity to perform higher levels of effort (levels 2–6) for higher rewards (2, 4, 6, 8, 10 credits). The entire Effort $\times$ Reward space (5×5) was sampled three times in each of the two domains, for a total of 150 trials. Trials were self-paced, participants on average took 5–10 minutes to complete this phase. In keeping with previous studies, we reduced the impact of fatigue accumulation on

decision-making by requiring participants to simply indicate their preferred option without executing their choices. In addition, they were explicitly told they should select the option that was most preferable to them, but that the points themselves did not alter remuneration. This protocol is consistent with previous studies and has been shown to be sensitive to changes in motivation.^{33,34,38–40}

Statistical Analysis

The outcomes of interest were participants' performance in the Reinforcement Phase, and their decisions to engage in effortful behaviour in the Choice Phase. In the Reinforcement Phase, we examined the effect of sleep restriction on performance with within-subjects repeated-measures ANOVAs on the factors of Sleep Condition (fully rested vs sleep restricted) and Effort Level (1–6). We quantified performance in the cognitive effort task as a function of d' ($Z_{\text{Hit Rate}} - Z_{\text{False Alarm Rate}}$).⁴¹ We used a log-linear correction for extreme values of hits or false alarms.⁴² Performance in the physical effort task was measured as the proportion of time that participants were able to meet or exceed the target effort level on each trial.

In the Choice Phase, we examined the effect of sleep restriction on the proportion of trials that individuals chose the more effortful offer relative to baseline. This was accomplished with a four-way repeated-measures ANOVA on the factors of Sleep Condition (fully rested, sleep restricted), Task Domain (cognitive, physical), and the Effort (2–6) and Reward (2–10) levels associated with the more effortful option. We applied Greenhouse–Geisser corrections for violations of sphericity. All significant main effects or interactions were decomposed with pairwise comparisons corrected for multiple comparisons with a Bonferroni adjustment. We calculated effect sizes using η_p^2 (partial eta-squared), a commonly used measure of effect size.⁴³ η_p^2 shows the amount of total variance in the dependent variable that is explained by an independent variable while the effects of other variables and interactions are partialled out.

Further, we conducted a control analysis to examine whether participants' choices were influenced by their capacity to perform the corresponding effort level. For each participant in each session, we used a logistic regression to predict choices as a function of Cognitive Effort, Reward, and the d' for that effort level in the Reinforcement Phase. We then compared the standardised regression coefficients for each factor to zero using a non-parametric Wilcoxon signed-rank test.

Data were analysed using MATLAB Version 2018b³⁷ and JASP Version 0.11.1.⁴⁴

Results

Reinforcement Phase: The Effects of Sleep Restriction on Performance

First, we examined data from the Reinforcement Phase to probe for differences in performance between the fully rested and sleep restricted conditions.

Cognitive Effort Task

The Sleep Condition x Effort ANOVA revealed a significant main effect of Effort, such that increasing effort was associated with a decrement in d' ($F(3.8, 86.3) = 6.42, p < 0.001, \eta_p^2 = 0.22$). However, this was qualified by a significant Sleep x Effort interaction (Sleep x Effort, $F(5, 115) = 3.25, p = 0.009, \eta_p^2 = 0.12$; Sleep, $F(1, 23) = 0.13, p = 0.719, \eta_p^2 = 0.01$). Decomposing this interaction indicated a lower d' when sleep restricted vs fully rested at effort level 5, but the reverse pattern at level 6 (Figure 2A). Regardless, in both sessions, reinforcement rates were at ceiling, indicating that every participant was able to complete every level of effort to be rewarded on every trial (Figure 2B).

Physical Effort Task

A repeated measures ANOVA on Sleep Condition and Effort (1–6) revealed a significant main effect of Effort, such that higher effort levels led to less time being spent above the target force ($F(2.2, 51.5) = 55.42, p < 0.001, \eta_p^2 = 0.71$) (Figure 2C). Neither the main effect of Sleep nor the Sleep x Effort interaction were significant (Sleep, $F(1, 23) = 0.74, p = 0.399, \eta_p^2 = 0.03$; Sleep x Effort, $F(1.9, 43.9) = 0.10, p = 0.896, \eta_p^2 = 0.00$). Similarly, the ANOVA on average reinforcement rates showed a significant main effect of Effort ($F(5, 115) = 2.32, p = 0.048, \eta_p^2 = 0.09$), with a small decrement in reinforcement rates at the highest effort levels (Figure 2D). Importantly, however, the main effect of Sleep

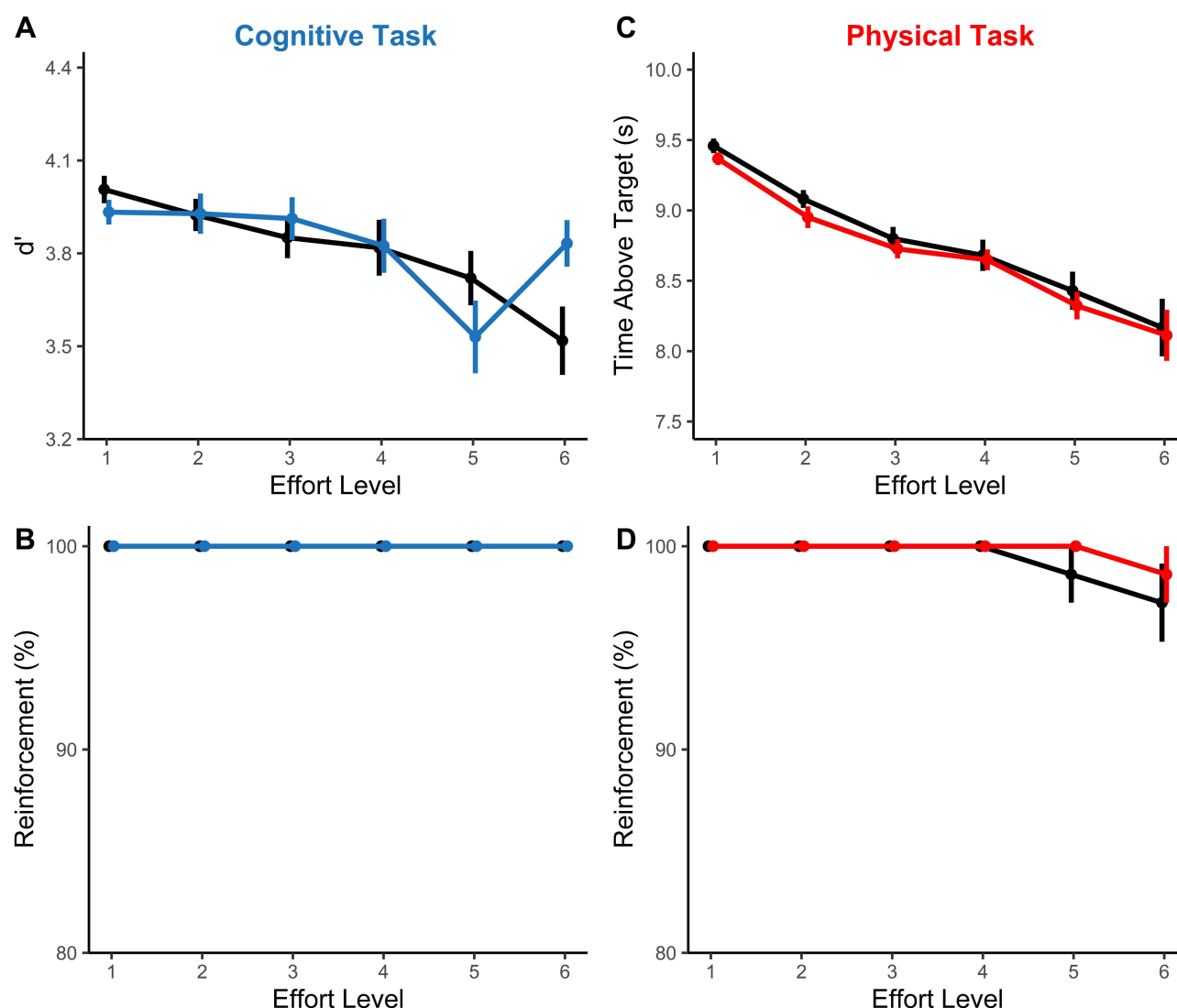


Figure 2 Performance in the cognitive and physical effort tasks during the Reinforcement phase. Fully rested condition is shown in black and sleep restricted condition is shown in blue (cognitive task) or red (physical task). **(A)** Performance in the cognitive task, quantified as d' , declined as a function of effort but was not consistently impaired under sleep restriction. **(B)** The reinforcement rates in the cognitive task were at ceiling level across both testing sessions. **(C)** Performance in the physical task, quantified as the time spent maintaining force above the target effort level, decreased as a function of effort. However, this decrease was unrelated to the sleep manipulation. **(D)** Finally, there was a slight decrement in the reinforcement rates in physical task at the highest effort levels, but this effect was similar across both sleep conditions.

and the Sleep $\times$ Effort interaction were not significant (Sleep: $F(1, 23) = 1.00$, $p = 0.328$, $\eta_p^2 = 0.04$; Sleep $\times$ Effort $F(5, 115) = 0.39$, $p = 0.855$, $\eta_p^2 = 0.02$).

We also confirmed that there was no statistically significant difference between MVCs in the Fully Rested versus Sleep Restricted condition ($t(23) = 0.69$, $p = 0.50$).

In summary, there were no consistent differences in behaviour between the fully rested and sleep restricted conditions during the Reinforcement Phase of the task.

Choice Phase: The Effects of Sleep Restriction on Motivation

To address our principal question of whether sleep restriction differentially affected the willingness to exert cognitive vs physical effort, we examined the proportion of trials in which individuals chose the more effortful offer relative to baseline (Figure 3). We conducted a four-way ANOVA on the factors of Sleep Condition, Domain, Effort and Reward. The critical result was revealed by a significant three-way interaction between Sleep Condition $\times$ Domain $\times$ Effort ($F(4, 92) = 4.96$, $p = 0.001$, $\eta_p^2 = 0.18$). Decomposing this interaction revealed that sleep restriction only reduced the motivation to exert effort

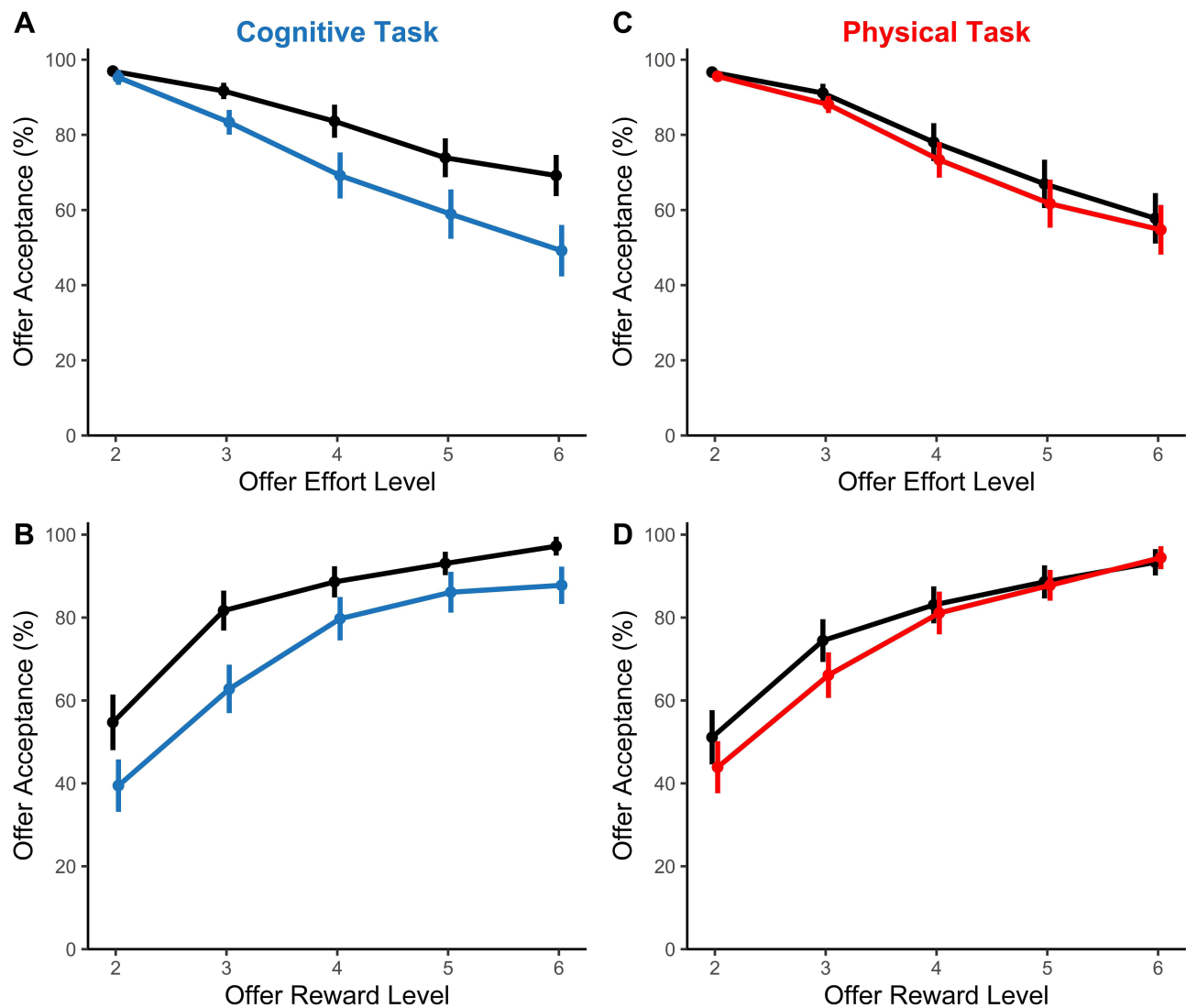


Figure 3 The effects of sleep restriction on motivation. Fully rested condition is shown in black and sleep restricted condition is shown in blue (cognitive task) or red (physical task). The percentage of trials in which the high-effort/high-reward offer was chosen are plotted as a function of (A and C) effort, and (B and D) reward, for the (A and B) cognitive effort task, and the (C and D) physical effort task. Offer acceptance rates are plotted as group means, with error bars indicating one standard error. (A) Sleep restriction impaired cognitive motivation, with a more pronounced effect at the highest levels of effort and (B) across all levels of reward. (C) In contrast, sleep restriction did not change the willingness to invest any level of physical effort, (D) at any level of reward.

within the cognitive domain, but not the physical domain. Furthermore, the effect of motivation on the cognitive domain was manifest at all but the lowest level of effort (level 2, $p = .443$, levels 3–6, all p -values ≤ 0.040).

The only other significant set of results was independent of the sleep manipulation. A significant Effort $\times$ Reward interaction simply reflected the expected finding that effort discounting was greatest at the lowest levels of reward (when individuals were more sensitive to effort), and minimal at the highest levels of reward (when the rewards outweighed all effort costs) ($F(4.3, 98.0) = 11.83$, $p < 0.001$, $\eta_p^2 = 0.33$). There was a trend towards Sleep Condition modulating this interaction (Sleep $\times$ Effort $\times$ Reward, $F(5.6, 127.7) = 2.15$, $p = 0.057$, $\eta_p^2 = 0.09$).

Other main effects and interactions were either not significant or captured by the higher-order interactions above (Sleep, $F(1, 23) = 3.79$, $p = 0.064$, $\eta_p^2 = 0.14$; Domain, $F(1, 23) = 0.03$, $p = 0.858$, $\eta_p^2 = 0.00$; Effort, $F(4, 92) = 62.30$, $p < 0.001$, $\eta_p^2 = 0.73$; Reward, $F(4, 92) = 45.47$, $p < 0.001$, $\eta_p^2 = 0.66$; Sleep $\times$ Domain, $F(1, 23) = 7.51$, $p = 0.012$, $\eta_p^2 = 0.25$; Sleep $\times$ Effort, $F(1.98, 45.6) = 1.93$, $p = 0.156$, $\eta_p^2 = 0.08$; Sleep $\times$ Reward, $F(1.9, 43.2) = 2.87$, $p = 0.071$, $\eta_p^2 = 0.11$; Domain $\times$ Effort, $F(1.3, 30.8) = 0.34$, $p = 0.629$, $\eta_p^2 = 0.01$; Sleep $\times$ Domain $\times$ Reward, $F(2.8, 64.4) = 0.58$, $p = 0.617$, $\eta_p^2 = 0.03$; Sleep $\times$ Domain $\times$ Effort $\times$ Reward ($F(6.9, 159.3) = 0.91$, $p = 0.562$, $\eta_p^2 = 0.04$).

Overall, these data indicate that sleep restriction had a differential effect on the willingness to exert effort in the cognitive domain, and not in the physical domain. In order to compare our results with those of previous effort discounting studies, we also fit participants' choices to commonly applied computational models of effort discounting. These data reaffirm the differential impact of sleep restriction on changing patterns of cognitive effort discounting, while having no effect on effort discounting in the physical domain. Details of these analyses are presented in the [Supplementary Information, Figures S1 and S2](#).

Control Analyses

The previous findings suggest that individuals had a lower motivation to invest cognitive effort when sleep restricted vs fully rested, which could be interpreted as evidence that sleep restriction leads to a heightened aversion to cognitively effortful behaviour. In principle, an alternate explanation could be that participants were disinclined to engage in greater effort due to a lower likelihood of completing those levels successfully. Importantly, this could not be the case here, as reinforcement rates in the cognitive effort task were at ceiling across all effort levels in both tasks ([Figure 2B](#)). Similarly, there was no consistent pattern of difference in performance (d') in the fully rested vs sleep restricted conditions.

Nevertheless, in a control analysis, we formally verified that cognitive effort choices were not influenced by individuals' capacity to perform the corresponding effort level. Importantly, performance in the cognitive task, quantified as d' for a given effort level, did not significantly explain individuals' choices in either sleep condition (fully rested: $Z = -1.17$, $p = 0.241$; sleep restricted: $Z = 0.14$, $p = 0.886$). As expected, effort and reward both had significant effects on choice (fully rested: Effort, $Z = -3.69$, $p = 0.002$; Reward, $Z = 3.97$, $p = 0.001$; sleep restricted: Effort, $Z = -4.11$, $p < 0.001$; Reward, $Z = 4.17$, $p < 0.001$).

Discussion

Increasing evidence suggests that the motivation to engage in cognitively and physically effortful behaviour is dissociable.^{22,28,33} However, the question of whether the effect of sleep loss is limited to particular domains of behaviour has not been addressed. Our main finding was that sleep restriction reduced the willingness of individuals to invest cognitive effort, but spared their willingness to engage in physically effortful behaviour. Importantly, the effects of sleep restriction on cognitive motivation could not have been driven by reduced capacity of individuals to perform each level of the cognitive effort task. This finding of a behavioural dissociation in the effect of sleep restriction on cognitive and physical motivation may have significant implications for those whose professions rely on optimal cognitive performance in spite of chronic sleep loss. In contrast, those occupations relying more heavily on physical effort may not see the same decrement in motivation to perform more physically demanding tasks during sleep loss.

Our findings clarify the interpretation of recent studies which have reported that sleep loss decreases the willingness of individuals to engage in cognitively effortful tasks.^{10,11,19} In interpreting the effects of sleep loss on cognitive motivation, it is important to distinguish choices based on the aversiveness of effort itself versus the capacity of individuals to adequately perform the corresponding action. More effortful actions are typically associated with a performance decrement, as shown both in our data ([Figure 2A](#)), and those of previous studies.^{11,19} It is therefore important to determine whether the choice to engage in the less effortful option is indeed due to an aversion to higher effort, rather than simply a desire to avoid engaging in options that the individual is less capable of completing. Importantly, participants in our task were able to accomplish all levels of cognitive effort at ceiling performance ([Figure 2B](#)). Furthermore, control analyses indicate that performance in the cognitive effort task could not account for the reduction in cognitive motivation caused by sleep restriction.

Relatedly, previous studies have typically been manipulated effort by increasing the time it takes to complete a cognitive task (although see²⁰). Considering that sleep loss has been found to accentuate the time-on-task decrements in cognitive performance,^{11,19} reduced willingness to perform longer cognitive tasks under sleep restriction could be due to concerns about being able to sustain the required performance level. An important feature of our cognitive task was that we were able to manipulate attentional load while holding trial duration constant. Our results therefore serve to increase the specificity of prior findings, by showing that the effect of sleep loss on cognitive motivation likely represents a primary motivational deficit, rather than one driven by concerns about task performance.

In contrast to cognitive effort, relatively few studies have examined the question of how sleep loss affects motivation in the physical domain. Those that have suggest that a reduction in sleep quality or quantity lowers the motivation to engage in physically effortful behaviour.^{21,32} These reports may seem at odds with our results, which showed that sleep restriction had relatively little impact on motivation in the physical domain. However, key methodological differences between the current study and previous literature may explain the inconsistent results. Firstly, these earlier studies all utilised targeted groups of athletes, as opposed to the non-selective group of young adults recruited here. Unsurprisingly, previous work has shown that athletes have a higher motivation to invest physical effort relative to non-athletes.²⁸ Thus, this apparent discrepancy could simply reflect an effect of sleep loss on physical motivation in cohorts that merely had a greater capacity to demonstrate such effects in the first place. Secondly, previous work on physical motivation has relied on subjective reports of sleep quality and quantity, in contrast to the highly controlled manipulation of sleep restriction we implemented here. Thus, it will be important for future work to directly address our speculation that an individual's baseline level of physical motivation affects their response to physical effort under sleep restricted conditions.

Our findings contribute to accumulating evidence from both behavioural tasks and neurophysiological studies that cognitive and physical motivation are dissociable.^{22,28,33,45} For example, studies in neurological disease indicate that certain patient groups can have selective impairments that primarily affect a single domain of motivation,³³ although other patient groups may demonstrate more global deficits.^{34,38} Furthermore, recent studies indicate that the neural correlates of motivated behaviour comprise a network of regions, with some areas, such as amygdala, that are sensitive to individual domains of effort,^{22,46,47} and other regions that are more domain-general, including the medial prefrontal cortex and ventral striatum.^{18,48–51} Across many of these studies, it is clear that individuals vary widely in their motivation across the cognitive and physical domains. A logical extension of this work is to consider how sleep loss modulates neural activity across those areas involved in motivated behaviour – a question that is beginning to be addressed.¹¹

Limitations

In this study, we operationalised cognitive effort specifically in terms of sustained attention. This is a logical approach, given the sensitivity of attention and arousal to sleep loss.^{19,31,52} However, cognitive effort can be operationalised in many different ways, and many studies have focused on cognitive tasks requiring divided attention,^{11,19,31} memory,⁵³ language,¹⁰ or arithmetic.²⁰ We predict therefore that our findings should generalise to other cognitive tasks and operational settings that are primarily reliant on sustained attention. However, given the impact of sleep loss varies across cognitive domains,^{54–57} the extent to which cognitive motivation is diminished in other types of cognitive tasks remains to be empirically demonstrated.

Similarly, grip force is a common^{27,58–62} but not the only way to manipulate physical effort in an experimental setting.^{21,32,63–66} Of note, endurance tasks (eg running, cycling) appear to be more susceptible to the detrimental effects of sleep restriction than brief, strength-dependent tasks (eg weight-lifting).^{64,66,67} Our task required sustaining grip force for 10 seconds. It remains to be determined to what extent our findings generalise to tasks that require maintaining physical effort for longer periods.

Conclusion

In conclusion, this study demonstrates a selective effect of sleep restriction on reducing cognitive vs physical motivation. Our data provide a compelling demonstration that sleep loss results in a primary deficit in cognitive motivation due to a heightened aversion to effort, while sparing motivation in the physical domain. These findings have significant implications for academic and professional settings that characteristically require maintaining high levels of cognitive motivation in the face of chronic sleep loss – such as in students and medical professionals. The detrimental effects of sleep loss on cognitive and physical performance are well recognised. Our data emphasise the importance of sleep, not only to optimise cognitive performance, but also to maintain the motivation to do so.

Abbreviations

MVC, maximum voluntary contraction; RSVP, rapid-serial-visual-presentation.

Data Sharing Statement

Data that support the findings of this study data are available from the corresponding authors upon reasonable request.

Ethics Approval and Consent to Participate

The study was approved by the Monash University Human Research Ethics Committee (Project ID 8032) and was conducted in accordance with relevant guidelines and regulations. All participants provided written informed consent. The study complied with the Declaration of Helsinki.

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Author Contributions

M.J., S.D. and T.C. were involved in study design. M.J. and J.B. collected the data. M.J. and T.C. analysed the data. All authors contributed to writing the manuscript. All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

Professor Sean PA Drummond reports grants from Office of Naval Research Global, during the conduct of the study; advisory board via Monash University for Avecho and Philia Labs, member of Data and Safety Monitoring Board for Zelda Therapeutics, outside the submitted work. The authors report no other conflicts of interest in this work.

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