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The effects of insufficient sleep and adequate sleep on cognitive function in healthy adults

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ABSTRACT

Study objectives: Although sleep affects a range of waking behaviors, the majority of studies have focused on sleep loss with relatively little attention on sustained periods of adequate sleep. The goal of this study was to use an experimental design to examine the effect of both of these sleep patterns on cognitive performance in healthy adults.

Methods: This study used a randomized crossover design. Participants who regularly slept 7-9 hours/night completed two 6-week intervention conditions, adequate sleep (maintenance of habitual bed/wake times) and insufficient sleep (reduction in sleep of 1.5 hours relative to adequate sleep), separated by a 2-6 weeks (median = 43 days) washout period. Cognitive functioning was evaluated at baseline and endpoint of each intervention using the NIH Toolbox Cognition Battery. General linear models contrasted scores following each condition to the baseline of the first condition; the baseline of the second condition was included to evaluate practice effects.

Results: Sixty-five participants (age 35.9 ± 4.9 years, 89% women, 52% non-White race/ethnicity) completed study procedures. There was improvement in performance on the List Sorting Working Memory task after the adequate sleep condition that exceeded practice effects. Cognitive performance after insufficient sleep did not reach the level expected with practice and did not differ from baseline. A similar pattern was found on the Flanker Inhibitory Control and Attention task.

Conclusions: These findings contribute to our understanding of the complex interplay between sleep and cognition and demonstrate that consistent, stable sleep of at least 7 hours/night improves working memory and response inhibition in healthy adults.

Clinical Trial Registration: The manuscript reports on data from two clinical trials: Impact of Sleep Restriction on Performance in Adults (URL: https://clinicaltrials.gov/ct2/show/NCT02960776, ID Number: NCT02960776) and Impact of Sleep Restriction in Women (URL: https://clinicaltrials.gov/ct2/show/NCT02835261, ID Number: NCT02835261).

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Introduction

Sleep is a critical aspect of human health that has far-reaching effects on both physical and psychological functioning. Conditions in which individuals fail to obtain adequate sleep, such as insufficient sleep and insomnia, are increasingly common in modern society due to the ongoing demands of work, school, familial, and social obligations. Additionally, proliferation of artificial nighttime light and

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ubiquitous use of electronic devices that emit blue light affect regulation of sleep by the circadian system.[1] Chronic sleep disruption is associated with poor health outcomes that include mood disturbances, motor vehicle accidents, and medical conditions such as diabetes, hypertension, cardiovascular disease, and obesity.[2-6] This range of disturbance in waking neurobehavioral function highlights the insidious nature of an experience that is so regularly socially sanctioned in our everyday lives.

Cognitive functioning, which underlies nearly every aspect of our daily activities and is critical for optimal function, is another example of a health outcome affected by sleep. Such abilities include attention, learning and memory, language, working memory, and executive function. Executive function is a broad term used to encompass behaviors that support planning, performance monitoring, and/or purposeful action toward the achievement of an often complex goal.[7] Response inhibition, task switching, concept formation, mental flexibility, and problem-solving are aspects of executive function. A meta-analysis found that experimentally manipulated sleep restriction negatively affected performance on tests of sustained long-term attention, executive function, and memory, while studies focused on immediate short-term attention, impulse control, decision-making, and general intelligence reported mixed results.[8] With respect to task complexity, simple task performance may be more strongly affected by sleep loss than more complex task performance.[9] These findings may arise as a function of arousal; simple tasks are often associated with boredom and low arousal that is especially affected by sleep loss while complex tasks require more cognitive engagement and higher arousal that permit compensation for sleep loss. Finally, extreme sleep durations on either end of the spectrum (too much or too little sleep) have a negative impact on working memory, executive functions, and memory among older adults.[10]

Although previous studies focused on poor cognitive outcomes associated with sleep loss, few have examined the effects of sleep stability or consistent attainment of adequate sleep. Such research would expand our understanding of general sleep health and may help identify an important treatment goal to optimize well-being. Indeed, studies focused on inconsistency or variability in sleep infer the relative benefits of maintained stable sleep. For example, a systematic review[11] of sleep timing and consistency found that delayed sleep timing and inconsistent sleep patterns were associated with poor health outcomes that included cognitive function in the domains of attention, executive functions, learning, and memory. A 2017 study[12] of undergraduate students reported that highly variable sleep was associated with lower academic performance. Whiting and Murdock[13] highlighted the role of not only consistent sleep, but consistently insufficient sleep on cognitive outcomes. They showed that consistently short sleep duration was associated with poor attentional performance compared to more variable sleep durations. Notably, they focused on variability in total sleep duration rather than variability in sleep/wake times. These studies emphasize how important it is to consider an individual's typical or habitual sleep patterns when evaluating cognitive function.

The goal of this study was to examine both insufficient sleep and adequate sleep and their respective effect on cognitive function in healthy adults using a randomized, crossover design. In addition, because our study design involved repeated cognitive assessments, we considered any changes in cognition in the context of practice effects. Such effects are observed when an individual demonstrates improved performance on cognitive tests with repeated task exposure due to procedural familiarity rather than any true cognitive change. In studies of cognitive function, practice effects are often disregarded, yet they remain critically important considerations for study design and interpretation of findings. The disentanglement of cognitive change due to an intervention or exposure as opposed to cognitive change due to practice effects is a necessary component of studies that seek to understand drivers of cognitive function. We hypothesized that individuals would demonstrate poorer cognitive test performance following a period of maintained insufficient sleep but not following a period of adequate sleep. We also hypothesized that these effects would persist above and beyond the effects of practice on the cognitive tasks. Our prior work examining cognitive test performance in individuals with insomnia[14] found improved performance on tests of processing speed and working memory in individuals with insomnia symptoms who underwent a blue light-blocking intervention. Thus, we further hypothesized that the effects from the current study would be strongest on tests of processing speed and working memory.

Participants and methods

Participants

Participants were recruited with electronic advertisements and were enrolled in two-parent studies (NIH R01HL128226-01A1, NCT02960776 and AHA 16SFRN27950012, NCT02835261, P.I.: M-P St-Onge) that examined the impact of sleep restriction on mood, cognition, and physical performance in adults. Participants were men and women, aged 20 years or older, who had a body mass index between 20 and 34.9 kg/m^2, were weight stable (± 2.5 kg) for at least 3 months prior to evaluation, nonsmokers for at least 3 years, and habitually slept between 7 and 9 hours/night without napping, on at least 70% of the nights during a 2-week screening period. This range of nightly sleep is recommended for optimal health for healthy adults.[15] Typical sleep duration was verified by a 2-week screening with actigraphy (ActiGraph xGT3X-BT, ActiLife LLC, Pensacola, FL) and sleep diaries. Women were not pregnant or breast-feeding and were not using hormonal contraception. The latter exclusion was related to the main goal of the parent studies that involved assessment of the impact of insufficient sleep on cardiometabolic risk factors, which could be affected by hormonal contraceptives. In addition, the heterogeneity of hormonal contraceptive types would make standardizing the timing of the intervention difficult. Exclusion criteria included questionnaire-based history of alcohol or substance abuse, excessive caffeine intake (≥300 mg/d, assessed using a questionnaire derived from the Caffeine Consumption Questionnaire[16]), presence of a medical condition, including diabetes, HIV, anemia, hyperthyroidism, any neurological disease, or any other unstable or uncontrolled medical condition (eg, hypertension, active malignancies, hypothyroidism), and any eating, sleeping, or depressive disorders. The latter were determined by normal scores on the Pittsburgh Quality of Sleep Index (PSQI ≤ 5),[17] Epworth Sleepiness Scale (< 12),[18] Berlin Questionnaire (low risk or none),[19] Sleep Disorders Questionnaire (no sleep disorders),[20] Beck Depression Inventory II (< 13),[21] Composite Scale of Morningness/Eveningness (≥ 31 or ≤ 69).[22] Of note, in order to increase enrollment in the parent study of postmenopausal women, those with PSQI > 5 could be included as long as they habitually slept between 7 and 9 hours/night without napping at least 70% of the nights during the screening period. History of alcohol or substance use was self-reported and did not utilize a validated questionnaire. Individuals taking antidepressants were excluded. Shift workers, individuals who traveled across time zones within 4 weeks of the study, individuals whose work required long-distance driving or operating heavy equipment, or individuals participating or planning to participate in a commercial diet or behavior modification program were also excluded from the study. This study was approved by the Columbia University Irving Medical Center Institutional Review Board and all participants provided informed written consent.

Study design

This study used a randomized, crossover design with two conditions (adequate sleep and insufficient sleep) of 6 weeks each (Fig. 1). During

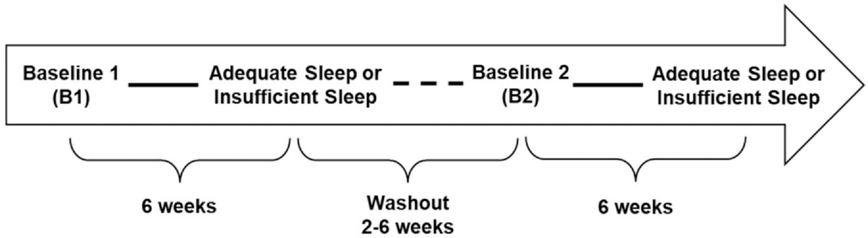

Fig. 1. Study design. Participants underwent study measures, including cognitive testing, at the baseline of the first condition (B1) before being randomized into a 6-week intervention of either adequate sleep or insufficient sleep. Assignment to study condition was counterbalanced. Following completion of a study condition, participants were evaluated with the same cognitive battery. Following a 6-week washout period, another assessment was conducted at the baseline of the second condition (B2) and then after 6 weeks of either adequate sleep or insufficient sleep. Models of cognitive test performance following insufficient sleep, adequate sleep, and at B2 compared with B1 performance permitted the evaluation of the effects of the intervention condition with respect to the expected change due to practice effects or repeated exposure to the cognitive instrumentation

the *adequate sleep condition*, participants were asked to maintain their habitual bed and wake times to achieve ≥7 hours of sleep/night. During the *insufficient sleep condition*, participants were asked to delay their bedtime by 1.5 hours/night while maintaining their habitual wake time. Delay in bedtime was the focus of behavioral change because it most closely mimics sleep timing differences observed in short and normal sleepers. Each condition was separated by a 2-6 weeks (median = 43 days) washout period, during which the participants returned to their regular sleep habits. The washout period was likely similar to the adequate sleep condition as participants were required to habitually sleep 7-9 hours/night without napping to meet study inclusion criteria. However, a potential difference between the adequate sleep condition and the washout period is that participants were not monitored during washout and it is possible that sleep bed and wake times were more variable. Adherence to sleep schedules was verified with an actigraph monitor (xGT3X-BT) using the Cole-Kripke algorithm[23] in the ActiLife software and a sleep diary for the duration of each study condition. Data from the nightly sleep diary was used to enhance bed and waketime estimates produced by the ActiLife software prior to automated scoring. Actigraphy and sleep diaries were reviewed with the research assistant at weekly study visits. Adherence to sleep schedules was an important indicator of sleep consistency over each study condition.

Cognitive assessment

Cognitive performance was measured with the NIH Toolbox Cognition Battery, a widely used computer-administered measure that is a reliable and valid assessment of cognitive functions.[24-26] The Toolbox was administered in the laboratory at baseline and endpoint of each intervention condition (total of 4 assessments). All subtests in the battery have equivalent alternate forms. Raw scores can be adjusted by age and education. All subtests have an introductory module and practice session to ensure task comprehension. In addition, the battery is supervised by a trained research assistant who monitors task adherence and completion and answers any questions as they arise. Total time to complete the battery was approximately 30 minutes. *Quality of education* was estimated with the Picture Vocabulary test, a measure of receptive vocabulary that requires the participant to select a picture from an array of 4 images that most closely matches the meaning of a target word. The Picture Vocabulary test uses a computer-adaptive test administration in which the number and difficulty level of items a participant is exposed to varies as a function of their performance to estimate an ability level. Vocabulary tests are frequently used to estimate educational quality and/or premorbid ability in the case of injury. *Processing speed* was measured with the Pattern Comparison Processing Speed test, in which participants are presented with two pictures and are asked to indicate whether the pictures are the same or not the same. Participants respond to as many picture sets as possible in an 85-second interval. *Working memory* was assessed using the List Sorting Working Memory test in which participants remember and sequence a series of different stimuli to a target criterion category. There are two conditions consisting of one list (either food or animals) or two lists (both food and animals). *Executive function* and *attention* were measured with two tests: (1) the Dimensional Change Card Sort test, a measure of cognitive flexibility, in which participants sort bivalent pictures (eg, yellow balls and blue trucks) that vary along two dimensions (eg, either color or shape) to a target cue word, and (2) the Flanker Inhibitory Control and Attention test, in which participants focus on a target stimulus while inhibiting attention to other nearby stimuli. In the Dimensional Change Card Sort test, participants complete 30 test items while in the Flanker Inhibitory Control and Attention test, participants complete one block of 20 trials. Questionnaires and cognitive tasks were completed by all participants in the morning.

Statistical approach

Descriptive statistics were generated for participants and compared between individuals who were randomized first to the adequate sleep condition and those who were randomized first to the insufficient sleep condition with t tests for continuous variables and a Chi-square test for proportional variables. Performance on the Picture Vocabulary test was used to estimate participants' quality of education and to gauge the range of cognitive function on baseline cognitive measures. In addition, we summarized the average nightly sleep duration derived from actigraphy data with descriptive statistics (mean, sd, range, and coefficient of variation [CV]).

Repeated measures analyses of variance were used to contrast cognitive test performance following each intervention condition to the baseline of the first condition (B1) (Fig. 1). Separate models were run for each cognitive outcome. To examine whether the differences between cognitive test performance following each intervention condition and B1 were greater than what would be expected due to practice or previous test exposure, we included the baseline of the second condition (B2) in statistical models. For statistical analyses, participant visit was treated as a within-subjects factor and reordered such that the first visit was B1, the second visit was B2, the third visit was following the adequate sleep condition, and the fourth visit was following the insufficient sleep condition. The statistical analysis compared demographically adjusted (with a normative mean and standard deviation of 100 and 15, respectively) cognitive test scores at each visit relative to B1. Effect sizes comparing performance at each visit with B1 were estimated with Cohen's d and 95% confidence intervals (95%CI). Additionally, we conducted planned comparisons using paired sample t tests that directly contrasted cognitive test performance following the adequate sleep condition to performance following the insufficient sleep condition to test the hypothesis that insufficient sleep negatively affects cognition more than adequate sleep.

In a secondary set of analyses, we used paired sample *t* tests to contrast the mean cognitive scores in each condition with their respective baseline assessments (eg, for participants randomized to the adequate sleep condition first, we used B1 as the comparator for that condition, but for individuals randomized into the adequate sleep condition second, we used B2). In addition, we used bivariate correlations to examine the relationship between continuous sleep measures (average sleep duration and CV in sleep duration) from the 2-week screening period and the primary cognitive variables of interest at baseline in order to more fully characterize these relationships using sleep as a continuous variable.

Results

Sixty-five participants completed study procedures from both parent studies and were included in our sample. Demographic characteristics comparing participants randomized first to the adequate sleep condition compared with those randomized first to the insufficient sleep condition are presented in Table 1. The two groups did not differ in age, gender distribution, ethnicity, race, or on performance of the Picture Vocabulary test, which was in the expected average range of estimated quality of education based on the education level of the entire sample. We used actigraphy data to calculate the average amount of sleep during the 2-week screening period and during each 6-week condition within each adequate sleep and insufficient sleep condition. Participants, on average, slept 455.0 (sd = 22.86, range 390-528) minutes during the screening period, 445.7 (sd = 30.02, range 321-497) minutes during the adequate sleep condition, and 369.4 (sd = 24.45, range 301-422) minutes during the insufficient sleep condition. The CV for total sleep time was calculated for each participant in each condition. The mean CV during the screening period was 0.10 (sd = 0.038) with a range of 0.02-0.23. The mean CV during the adequate sleep condition was 0.10 (sd = 0.047) with a range of 0.04-0.26. The mean CV during the insufficient sleep condition was 0.10 (sd = 0.044) with a range of 0.04-0.25. These values did not differ from each other meaningfully, $F(2108) = 0.36$, $p = .69$. These analyses reveal relatively consistent sleep within each condition that does not differ among conditions.

Omnibus statistics for separate repeated measures analyses of variance models are shown in Table 2. Performance on the *List Sorting Working Memory test* markedly improved after the adequate sleep condition ($t(55) = 4.54$, $p < .001$, Cohen's $d = 0.61$, 95%CI: 0.01-0.89) compared with B1, which exceeded the practice effects observed by contrasting B1 with B2 ($t(55) = 3.30$, $p = .002$, $d = 0.45$, 95%CI: 0.16-0.72) (Table 2 and Fig. 2). Performance after the insufficient sleep condition was no different than the level of improved performance expected with practice and was not significantly different from B1 ($t(51) = 2.07$, $p = .06$, $d = 0.29$, 95%CI: 0.009-0.57). To test whether this observation was driven by the order of intervention, we divided the sample by whether participants were randomized first into the adequate sleep condition or into the insufficient sleep condition and repeated the identical analysis separately in each group. Although the effect was more reliable among the group randomized into the insufficient sleep condition first ($F(3,72) = 3.26$, $p = .02$) than in the group randomized into the adequate sleep condition first ($F(3,63) = 1.89$, $p = .14$), the pattern of results was identical. That is, both groups showed marked improvement in performance on a working memory task following the adequate sleep condition ($p = .005$ and $p = .032$, respectively) and numerically lower performance than would be expected with practice following the insufficient sleep condition that did not differ from B1 ($p = .18$ and $p = .20$, respectively).

For the *Flanker Inhibitory Control and Attention* test, the pattern of performance was similar to that of the List Sorting Working Memory task, where the magnitude of improvement was greatest following the adequate sleep condition ($t(55) = 4.61$, $p < .001$, $d = 0.61$ 95%CI: 0.32-0.90) compared to B1, followed by relatively smaller improvements for the practice effect ($t(50) = 2.10$, $p = .03$ $d = 0.30$ 95%CI: 0.03-0.57) and the insufficient sleep condition ($t(50) = 3.28$, $p = .002$, $d = 0.46$ 95%CI: 016-0.74).

For the *Pattern Comparison Processing Speed* test, while participants performed best following the adequate sleep condition, performance following the insufficient sleep condition was comparable to expected practice effects and performance at all three study visits was better than B1. That is, the magnitude of the practice effect, B2 vs. B1 ($t(53) = 6.13$, $p < .001$, $d = 0.83$ 95%CI: 0.52-1.14) was similar to those following the adequate sleep condition ((t54) = 6.03, $p < .001$, $d = 0.81$ 95%CI: 0.50-1.11) and following the insufficient sleep condition ($t(50) = 6.07$, $p < .001$, $d = 0.85$ 95%CI: 0.52-1.16).

Performance on the *Dimensional Change Card Sort* test did not differ across the four study visits (Table 2). For this test, there were very small practice effects ($t(53) = 0.71$, $p = .47$, $d = 0.09$, 95%CI: −0.36 to 0.17) as well as following habitual ($t(55) = 0.53$, $p = .59$, $d = 0.07$, 95%CI: −0.19 to 0.33) and insufficient sleep ($t(50) = 0.32$, $p = .74$, $d = 0.04$, 95%CI: −0.22 to 0.32) conditions.

Post hoc contrasts (Table 2, caption) were consistent with these observations, showing statistically trending and numerically better performance on the List Sorting Working Memory test and the Flanker Inhibitory Control and Attention test after the adequate sleep condition compared with the insufficient sleep condition. Similarly, the secondary analyses that contrasted performance after each sleep condition with its respective baseline showed marked improvement following sustained adequate sleep and very little change following insufficient sleep (Table 3). Finally, additional secondary analyses are summarized in Supplementary Table 1, which depicts bivariate correlations between continuous sleep measures (average sleep duration and CV in sleep duration) from the 2-week screening period and the primary cognitive variables of interest at baseline.

From a clinical perspective, performance on all four cognitive measures can be appreciated through examination of the mean score, which is expressed as a standardized score with a mean of 100 and standard deviation of 15. Table 2 indicates that performance for the List Sorting Working Memory and Dimensional Change Card

Table 1
Baseline characteristics of participants randomized first to the adequate sleep condition vs. those randomized first to the insufficient sleep condition

		Adequate sleep condition first	Insufficient sleep condition first	Total sample	Statistic
N		32	33	65	-
Age, mean years (SD)		34.0 (13.2)	37.8 (13.8)	35.9 (13.6)	$t(63) = 1.12$, $p = .26$
Gender, n (%) woman		28 (87.5%)	30 (90.9%)	58 (89.2%)	$\chi^2(1) = 0.19$, $p = .68$
Hispanic/Latinx ethnicity, n (%)		6 (18.7%)	10 (30.3%)	16 (24.6%)	$X^2(1) = 1.16$, $p = .28$
Race, n (%)	White	17 (53.1%)	14 (42.4)	31 (47.7)	$X^2(4) = 1.42$, $p = .84$
	Black	9 (28.1%)	9 (27.3%)	18 (27.7)	
	Asian	4 (12.5%)	7 (21.2%)	11 (16.9)	
	Other	1 (3.1%)	2 (6.1%)	3 (4.6)	
	Not reported	1 (3.1%)	1 (3.0%)	2 (3.1)	
Picture Vocabulary test (age-corrected standard score)		109.88 (9.29)	110.85 (8.23)	110.37 (8.71)	$t(63) = 0.44$, $p = .65$

Table 2
Cognitive performance at the four study visits

	Baseline 1 (B1)	Baseline 2 (B2)			Adequate sleep condition			Insufficient sleep condition			Omnibus statistic
	Mean (SD)	Mean (SD)	Cohen's *d*	*p*-value	Mean (SD)	Cohen's *d*	*p*-value	Mean (SD)	Cohen's *d*	*p*-value	
List Sorting Working Memory	102.77 (12.19)	106.87 (11.99)	0.45	.002	108.71 (11.14)	0.61	< .001	106.27 (12.49)	0.29	.063	F(3138) = 5.15, *p* = .002
Pattern Comparison Processing Speed	101.77 (23.20)	116.89 (21.49)	0.83	< .001	117.58 (19.29)	0.81	< .001	117.39 (20.78)	0.85	< .001	F(3135) = 20.79, *p* < .001
Dimensional Change Card Sort	101.62 (18.97)	98.80 (15.97)	0.09	.47	102.16 (17.70)	0.07	.59	101.84 (16.04)	0.04	.74	F(3138) = 0.86, *p* = .46
Flanker Inhibitory Control and Attention	88.58 (14.88)	91.74 (12.32)	0.30	.029	94.64 (12.44)	0.61	< .001	92.96 (12.43)	0.46	.002	F(3138) = 6.05, *p* < .001

Values are presented as mean (SD) demographically-adjusted standard scores. Cohen's *d* (effect size) and *p*-values refer to contrasts with Baseline 1. *Post hoc* contrasts showed better performance on the List Sorting test (t(46) = 1.57, *p*[one sided] = .06, *p* = .12, Cohen's *d* = 0.23) and the Flanker test (t(46) = 1.62, *p*[one sided] = .05, *p* = .11, Cohen's *d* = 0.24) after the adequate sleep condition compared with after the insufficient sleep condition, but no difference on the Dimensional Change Card Sort (t(46) = 0.46, [one sided] = .32, *p* = .64, Cohen's *d* = 0.06) or Pattern Comparison tests (t(45) = 0.60, *p*[one sided] = .27, *p* = .54, Cohen's *d* = 0.08).

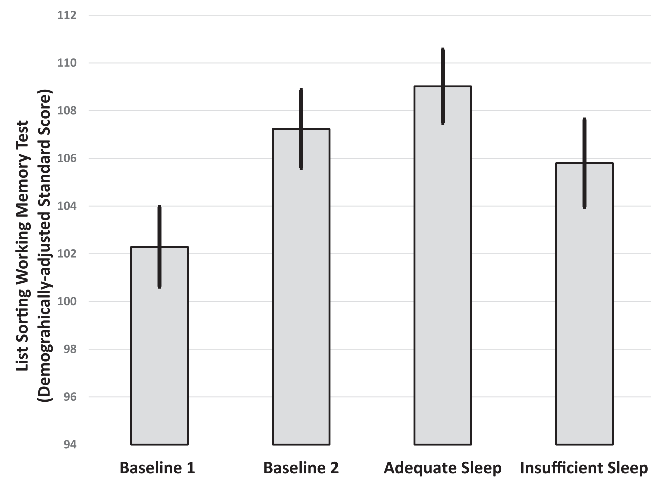

Fig. 2. Differences in performance on the List Sorting Working Memory test across the four study visits. The improved score from the baseline of the first condition (B1) to the baseline of the second condition (B2) indicates a practice effect. Following the adequate sleep condition, participants showed greater improvement than what would be expected with practice. However, following the insufficient sleep condition, participants did not improve as much as would be expected with practice; there were no statistical differences between B1 and performance following the insufficient sleep condition. Values plotted are means (SE) derived from the repeated measures analysis of variance models

Sorting tests largely remained within the clinically average range across all four study visits. For the Flanker Inhibitory Control and Attention test, performance was within the lower end of the average range at baseline but improved to a solidly average range with practice and this clinically significant improvement persisted in both the adequate and insufficient sleep study conditions. For the Pattern Comparison Processing Speed test, performance was within the clinically average range at baseline but improved to the clinically above-average range with practice. This effect persisted with both the adequate and insufficient sleep study conditions.

Discussion

Using a randomized, experimental design in healthy adults, we demonstrated that consistent maintenance of adequate sleep had a positive impact on working memory, or the ability to hold information temporarily in mind while executing complex task demands. Additionally, in the context of a consistently insufficient period of sleep, individuals failed to benefit from practice on a test of working memory to the same degree as they did during a consistently adequate period of sleep. This pattern of results was similar for a test of response inhibition and attention with consistent small to medium effect sizes. These findings are an important contribution to our understanding of the complex interplay between different aspects of sleep quality and quantity (ie, both insufficient sleep as well as the stable maintenance of adequate sleep patterns) on cognitive function and suggests that consistent, stable sleep of at least 7 hours a night can improve working memory and response inhibition in healthy adults.

Based on prior work in an independent sample,[14] we hypothesized that manipulating sleep duration would affect the cognitive functions of processing speed and working memory. This hypothesis was partially supported in that we found that adequate sleep intervention improved working memory beyond a practice effect, although insufficient sleep had little effect on cognitive function in this sample. Contrasts of working memory performance between different study conditions revealed consistent small to medium effect sizes irrespective of statistical significance. Similarly, we found that adequate sleep intervention improved performance on a task of

Table 3
Cognitive test scores contrasted after each sleep condition with each condition's respective baseline condition

	Adequate sleep condition				Insufficient sleep condition			
	Baseline	Follow-up	Statistic	Cohen's *d*	Baseline	Follow-up	Statistic	Cohen's *d*
List Sorting Working Memory	104.64 (12.82)	108.71 (11.14)	$t(55) = 2.74$, $p = .008$	0.36	104.37 (10.48)	106.27 (12.49)	$t(50) = 1.21$, $p = .22$	0.17
Pattern Comparison Processing Speed	106.67 (21.03)	117.58 (19.29)	$t(54) = 4.52$, $p < .001$	0.61	108.31 (25.78)	117.39 (20.78)	$t(50) = 3.71$, $p < .001$	0.52
Dimensional Change Card Sort	100.87 (16.03)	102.16 (17.70)	$t(55) = 0.68$, $p = .49$	0.67	90.49 (14.07)	101.84 (16.04)	$t(50) = 4.78$, $p < .001$	0.67
Flanker Inhibitory Control and Attention	88.55 (12.92)	94.64 (12.44)	$t(55) = 3.98$, $p < .001$	0.53	90.49 (14.07)	92.96 (12.43)	$t(50)1.82$, $p = .07$	0.25

Cohen's d and *p*-values reflect the effect size and significance, respectively, of the simple contrast between baseline and follow-up for each respective sleep condition.

response inhibition and attention beyond a practice effect in a pattern of findings supported by small to medium effect sizes. An intervention focused on maintenance of insufficient sleep did not negatively impact performance on this task. Working memory is a common focus of sleep research given its critical support of a wide range of everyday activities that require multitasking and effective achievement of complex goals. Response inhibition is an aspect of executive function that underlies activities that require self-control, performance monitoring, and resisting the urge to impulsively respond to a stimulus. While some prior studies found that sleep loss impairs working memory,[27-29] others did not.[30] For example, a study of adolescents and young adults who underwent 1-week of chronic sleep restriction (5 school days of 6 hours/night) found no impact on the accuracy of working memory performance, although declines were observed in reaction time.[27] Several studies have shown that sleep loss and sleep deprivation adversely affects performance on tests of response inhibition. One study demonstrated a speed/accuracy tradeoff where participants undergoing 34.5 hours of wakefulness responded more slowly to a test of response inhibition compared to baseline testing, but were not less accurate.[31] Other studies have reported decreased response inhibition in those with insomnia and sleep restriction.[32,33] With respect to the latter, performance improved with recovery sleep, but not to levels observed at a baseline assessment. A recent meta-analysis[8] examined results from 61 studies that used experimentally manipulated insufficient sleep and found that such sleep loss had a detrimental effect on cognitive function across the domains of sustained attention, memory, and executive function. These findings were largely supported by a meta-review[34] that found that sleep deprivation negatively affects attention and memory, but not other cognitive domains. A recent study[35] examined cognitive performance in healthy adults who underwent 21 days of chronic sleep restriction (either 5 hours or 5.6 hours time in bed) followed by 9 nights of recovery sleep. Results indicated that participants demonstrated persistent deficits in vigilance even after sleep recovery. An assessment of cognitive function following 6 weeks of chronic sleep restriction (5 hours on weekdays/8 hours on weekends) revealed poorer performance on tests of spatial orientation and vigilance that did not improve with the two nights of weekend recovery sleep.[36] In contrast, an experimental design involving both variable and stable short sleep schedules found that variability in sleep that allows for recovery sleep may confer a benefit to performance on tests of vigilance and processing speed when compared to consistently short sleep schedules.[37] Taken together, these studies suggest that cognitive dysfunction associated with sleep restriction may persist despite opportunities for sleep recovery, but this may depend on sleep schedule variability. An important difference between our study and those in the existing literature is that our sample comprised adults without known clinical sleep disorders who habitually slept between 7 and 9 hours each night. Moreover, in our study, participants experienced a period of insufficient sleep that was induced by delaying bedtime by 1.5 hours, resulting in a smaller sleep restriction than that reported in studies included in Lowe et al[8] meta-analysis. Although our study participants experienced an extended condition of 6 weeks of insufficient sleep as part of the experimental design, it is possible that a more prolonged period or a more significant degree of sleep loss is necessary to produce changes in cognitive function in nonclinical populations. Another nuance of our findings is that participants were identified as having good sleep prior to enrollment, and yet they still demonstrated improvements in working memory and response inhibition performance beyond the practice effect in the adequate sleep intervention condition. We speculate that this effect is likely because although they were habitually good sleepers outside the context of the study, the intervention encouraged a sustained period of consistently good sleep that conferred a benefit on this cognitive task.

An important finding emerged from our study that expands our understanding of both positive and negative impacts of sleep on cognitive function. Our experimental design included 6-week conditions of insufficient sleep as well as adequate sleep. Although prior sleep investigations broadened our appreciation for the potentially harmful effects of sleep loss on a wide range of waking behaviors, few examined the potentially beneficial impact of sustained periods of consistent, adequate sleep on cognitive function. We found that performance on a test of working memory improved following a sustained period of adequate sleep compared to baseline functioning. In addition, individuals failed to benefit from practice effects following a period of insufficient sleep to the same degree that they did following the adequate sleep condition. The pattern of results was similar for a test of response inhibition, an important component of executive functioning and social interactions. Of note, performance on this test was on the clinically lower end of average at baseline and it improved to the average range across all three subsequent study conditions, including insufficient sleep. This may be because individuals performed relatively lower at baseline than the other tests and therefore benefited more from repeated exposures irrespective of intervention condition. Overall, these findings support the notion that stable, consistent periods of adequate sleep are beneficial for our optimized daily functioning and suggest that variability in sleep is a major barrier toward achievement of this goal.

With respect to general health, sleep variability is associated with increased risk for metabolic syndrome, type 2 diabetes, glucose regulation, and adiposity.[38] With respect to cognitive function, a review by Chaput and colleagues[11] found that highly variable sleep was associated with poorer general cognitive function. Another study[12] of young adult college students calculated a sleep regularity index using assessments of circadian condition and light exposure obtained from salivary dim-light melatonin onset and wrist-worn photometry. They found that individuals with highly variable sleep had delayed circadian rhythms as well as lower overall academic performance. These findings differ from ours in that we did not experimentally introduce sleep variability. However, they do suggest that we may have observed more negative effects of insufficient sleep on cognitive performance if that condition of the study also included variability in sleep. This is an important area of future research. Taken together, many reports of sleep variability include recommendations highlighting the importance of stable adequate sleep. Our study strongly supports such a recommendation through demonstration of improvements in working memory following an intervention that ensured a prolonged period of adequate sleep, thus providing experimental evidence that maintenance of stable adequate sleep behavior improves cognitive ability.

Another central aspect of our study design was that we included cognitive assessments both before and after each intervention condition, which provided a unique opportunity to examine practice effects. Practice effects can occur within different paradigms, but in neuropsychology, they refer to improvements in task performance with repeated test administration that are primarily due to familiarity with the test items or approach to testing rather than an actual improvement in cognitive ability. Such effects are not consistently examined in the literature or in experimental designs involving cognitive outcomes, likely due to time restrictions or failure to fully appreciate this phenomenon, yet these practice effects may obscure meaningful signal. In our study, for example, the practice effects we observed were of a clinically meaningful magnitude (see Table 2), sometimes improving average performance on a task to above average performance. We used the initial assessment prior to the first randomization condition as an indicator of a true baseline, or first exposure to the tasks. We used the initial assessment prior to the second randomization condition, which followed a 6-week washout period, as an indicator of practice effects. Our statistical models thus accounted for both baseline and practice effects as we examined the impact of each intervention condition on cognitive performance. On a test of working memory, we found improvement following adequate sleep above and beyond what we would expect given the observed practice effects. However, following insufficient sleep, we found no difference from the baseline assessment as well as a failure to improve performance given the observed practice effects. In other words, consistent, adequate sleep leads to a relatively large improvement in working memory cognitive test performance that goes beyond the effect of practice, whereas insufficient sleep results in lower test scores than would be expected by practice. Under both conditions, participants still benefit from practice (and the effect of either experimental manipulation is not as large as the practice effect itself), but the pattern of findings with respect to working memory clearly points to a positive impact of sustained, adequate sleep. A study by Casement and colleagues[39] reported a similar pattern of findings in young adults living in a controlled hospital environment who underwent both insufficient sleep (4 hours/night for 12 days) and adequate sleep (8 hours/night for 12 days) interventions. Working memory was assessed on the first 9 days of each condition and researchers found improvements in performance with repeated practice in the adequate sleep period while the insufficient sleep period appeared to prevent this improvement. Overall, our inclusion of practice effects in this study provides an important nuance to the interpretation of findings that is critical for any future investigation that examines cognitive outcomes in the context of sleep disturbance.

A strength of our study is that we used an insufficient sleep design that entailed a 1.5 hours onset delay from a typical adequate sleep routine, which is consistent with what individuals commonly report experiencing in their daily lives, whereas other studies may delay sleep bedtime to a greater degree to induce insufficient sleep. Our approach lends a naturalistic framework to our experimental design that may be more generalizable to the general population. Another strength of our study is that our sample comprised 52% individuals from racially and ethnically underrepresented groups. Inclusion of individuals with a range of racial and ethnic backgrounds is an important step toward ensuring equal representation and generalization to the broader population. However, a limitation of our study is that our sample was majority women (89%), yet our study design excluded women who were using hormonal contraception, thereby restricting generalizability. This exclusion criteria was in alignment with the study goals of the parent studies of our sample, but future studies should endeavor to include a more generalizable sample with respect to gender and associated characteristics. Another important consideration is that while our insufficient sleep intervention required a delay in bedtime, we were not able to consider chronotype or differences in the relative proportions NREM or REM sleep that may depend on the time of night. Future studies may incorporate such measurements to more fully explore their impact.

Using an experimental design, we found improvements in cognitive performance on tests of working memory and response inhibition following sustained adequate sleep that were greater than we would expect given observed practice effects. Our findings bring attention to the critical need to include measures of practice effects in any study investigating cognitive change. In addition, these patterns of performance highlight the important consideration of both sleep loss and sleep stability, particularly maintenance of adequate sleep over prolonged periods of time. These findings may serve as motivators for change for sleep intervention programs that seek to improve cognitive outcomes.

Author contributions

Molly Zimmerman: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Giada Benasi**: Data curation, Writing – original draft, Writing – review & editing. **Christiane Hale**: Investigation, Data curation. **Justine Cochran**: Investigation, Data curation. **Lok-Kin Yeung**: Investigation, Data curation. **Adam Brickman**: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Marie-Pierre St-Onge**: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. All authors have seen and approved the manuscript.

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Declaration of conflict of interest

The authors have no conflicts of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.sleh.2023.11.011.

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