Journal of Adolescent Health 65 (2019) 549–557

ELSEVIER

JOURNAL OF ADOLESCENT HEALTH

www.jahonline.org

Original article

Multi-Night Sleep Restriction Impairs Long-Term Retention of Factual Knowledge in Adolescents

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Article history: Received January 10, 2019; Accepted April 24, 2019

Keywords: Sleep restriction; Sleep deprivation; Declarative memory; Long-term memory; Learning; Encoding; Consolidation; Adolescents

A B S T R A C T

Purpose: Sleep deprivation is associated with increased forgetting of declarative memories. Sleep restriction across multiple consecutive nights is prevalent in adolescents, but questions remain as to whether this pattern of sleep impairs memory for material typically learned in the classroom and the time course of retention beyond a few days.

Methods: Adolescents aged 15–18 years (n = 29) were given 5 hours sleep opportunity each night for 5 consecutive nights (sleep restricted group; SR), simulating a school week containing insufficient sleep. After the fourth night of restriction, participants learned detailed facts about different species of arthropod across a 6-hour period. Retention was tested 30 minutes and 3 days after learning and contrasted with a control group (n = 30) who had 9 hours sleep opportunity every night of the study. A subset of participants (SR, n = 14; control, n = 22) completed a surprise test 42 days after learning.

Results: Memory was significantly impaired in the SR group relative to controls, with 26% increased forgetting at the 30-minute test ($t(57) = 2.54$, $p = .014$, $d = .66$), 34% at the Day 3 test ($t(57) = 2.65$, $p = .010$, $d = .69$), and 65% at the Day 42 test ($t(34) = 3.22$, $p = .003$, $d = 1.17$). Vigilance was also significantly impaired after 4 nights of restricted sleep ($p < .05$), but did not correlate significantly with memory ($p > .05$).

Conclusion: Long-term retention of classroom material is significantly compromised when adolescents learn after being sleep restricted, reinforcing the importance of keeping good sleep habits to optimize learning.

IMPLICATIONS AND CONTRIBUTION

Adolescent sleep is often insufficient during the school week when large amounts of information must be learned. This study documented poorer retention of factual information for up to 6 weeks when material was learned after successive nights of sleep restriction, reinforcing the message that adequate sleep before learning is important.

Many adolescents obtain insufficient sleep, tending to curtail sleep during the school week and to "catch-up" on weekends [1–3]. The National Sleep Foundation Sleep in America Poll found that 62% of teenagers (aged 14–17 years) obtained less than the recommended 8–10 hours per night [4,5]. Similarly, in Singapore, only 15% of adolescents reported obtaining sufficient sleep during the week, compared with 80% on weekends [6]. Several factors contribute to this growing trend [7,8], including delayed circadian phase [9], slowed accumulation of sleep pressure [10], and electronic media use [11]. Multiple consecutive nights of sleep restriction result in cumulative deficits in cognition, impaired mood [1], and poorer academic performance [12–14]. It is therefore critical to characterize these impairments, particularly those that influence the ability to learn and retain information in long-term memory. This is important to guide public policy on health and education and determine the efficacy

Conflicts of interest: The authors have no conflicts of interest to disclose.
Data availability: The datasets generated and analyzed during the present study are available from the corresponding author on reasonable request.

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https://doi.org/10.1016/j.jadohealth.2019.04.030

of measures to improve adolescent sleep such as delaying school start times [15].

There are several gaps in our understanding of how inadequate sleep impairs declarative memory (explicit memory for facts and events). Although many studies have investigated the effect of a single night of total sleep deprivation on long-term memory [16–20], to our knowledge, only three studies have assessed memory after the accumulation of sleep debt across several nights and have produced mixed results: in healthy adolescents, restricting sleep to only a 5-hour opportunity each night for 4 [21] or 7 [22] consecutive nights after learning had no negative impact on the overall retention of paired associates or a prose passage respectively. These findings suggest that the stabilization and integration of information into long-term memory (consolidation) may not be adversely affected by consecutive, multi-night sleep restriction. In contrast, when restricted sleep precedes learning, we recently found that 5 nights of only 5 hours sleep opportunity resulted in significantly reduced memory by 10% for incidentally encoded pictures in healthy adolescents [23]. This suggests that the capacity to attend to and form an enduring memory during encoding is impaired after sleep restriction and that encoding may be a more relevant mechanism influencing learning outcomes in adolescents.

Most studies of long-term memory and sleep involve memorizing individual, unrelated words, or pictures over a short space of time [23]. It is unclear if such findings generalize to the acquisition of complex factual knowledge over many hours of repeated study episodes, akin to classroom learning, which is critical to understand how sleep-related impairments translate to educational outcomes. Furthermore, prior studies have only tested memory at delays of a few days [21–23], but declarative knowledge must be retained for weeks and months to perform academically.

The Present Study

We addressed these issues with a novel factual knowledge task that included several learning sessions. Learning took place after either 4 nights of restricted sleep (5 hours time in bed [TIB]; sleep restricted (SR) group) or the recommended amount of sleep (9 hours TIB; control group; Figure 1). Participants learned detailed facts about arthropods across a 6-hour period and were tested with questions followed by a confidence rating (certain, somewhat certain and guess). Prior research indicates that memory impairment associated with sleep loss may recover over time [18–20]; therefore, we tested memory at two delays during the study (30 minutes and Day 3) and after 6 weeks in a subset of participants who returned for a debrief session. This design aimed to simulate a school week containing insufficient sleep, allowing measurement of the impact of a realistic sleep schedule on long-term memory for educationally realistic material. We predicted that retention would be impaired at all time points in the sleep restricted group. These effects were expected for confident memories (certain responses), which are least prone to noise introduced by guessing.

Methods

Participants

Sixty adolescents aged between 15–18 years were selected from a sample of volunteers recruited via online advertisements and visits to schools in Singapore. They reported having no psychiatric illness or sleep disorders, no history of chronic or medical conditions, no indication of obstructive sleep apnea (Berlin Questionnaire), consumed <5 caffeinated beverages a day, were not habitual short sleepers (>6 hours actigraphically assessed average TIB), and had not travelled across >2 time zones 1 month before the study. Participants and parents were briefed together, provided written informed consent, and received monetary compensation after completion, in accordance with a protocol approved by the National University of Singapore Institutional Review Board.

Participants were randomized into SR and control groups: equal numbers of males and females were randomly assigned to groups, and this was repeated until groups did not differ significantly on several screening factors (outlined below). One participant withdrew during the study for personal reasons, leaving 59 participants (30 males, 16.1 $\pm$ .6 years [mean $\pm$ standard deviation]). The SR ($n = 29$) and control ($n = 30$) groups did not differ in age, gender, consumption of caffeinated beverages, nonverbal intelligence, morning–eveningness preference, symptoms of chronic sleep reduction, levels of daytime sleepiness, subjective sleep quality, self-reported and actigraphically assessed sleep habits, or levels of anxiety and depression ($p > .19$).

Design

The 11-day protocol included several cognitive tests as part of the Need for Sleep 3 study [23,24]. The study simulated a school week containing inadequate sleep, flanked by 2 weekends with sleep extension (Figure 1A). Specifically, the SR group had 2 baseline nights (B1, B2) of 9 hours sleep opportunity (11:00 P.M. to 8:00 A.M.), followed by 5 nights (SR1–SR5) with only 5 hours sleep opportunity (1:00 A.M. to 6:00 A.M.), and, finally, 3 recovery nights of 9 hours sleep opportunity (R1–R3). Each 24 hours period of the study (e.g., SR1) began at midnight (12:00 A.M.), encompassing the nocturnal sleep period and the following day. All cognitive tests were completed by day R2—when both groups had undergone 2 recovery nights—except for the Day 42 test that took place during a debrief. The control group had 9 hours sleep opportunity (11:00 P.M. to 8:00 A.M.) for all nights of the protocol. Participants were monitored at all times and prevented from napping.

Materials

Factual knowledge task—learning. Participants learned factual information about six ant and six crab species [25]. This occurred in six blocks across the day separated by breaks: 3 hours 20 minutes of learning in total. Each 40-minute block contained all the information about either ants or crabs. The order of learning was counterbalanced across participants, and they were instructed not to discuss or look up information about arthropods during breaks.

Information was presented on approximately 80 slides containing numbered points and images (Figure 1B). To assist learning, some slides asked participants to write on paper what they could recall. The final slide of each block instructed participants to use any remaining time to recap the information. At the end of each block, participants completed ratings for subjective alertness (Karolinska Sleepiness Scale), focus, motivation, and ability (rated on 7-point scales; Supplementary Materials).

Factual knowledge task—tests. There were three test sets of 120 questions (60 ants and 60 crabs), matched for difficulty and counterbalanced across participants for the 30-minute, Day 3, and Day 42 tests. Participants answered questions in separate blocks for ants and crabs, separated by a 2-minute break, with order counterbalanced (i.e., ants or crabs first) and question order randomized. Questions included two-alternative forced choice answers followed by a confidence rating ("*Certain*," "*Somewhat Certain*," "*Guess*"; Figure 1B). An additional 60 questions were used in a pretest to establish prior knowledge of the materials.

In each trial, the question was displayed until a response was made using the keyboard arrow keys (or maximum of 10 seconds). Confidence ratings were displayed immediately until a response or when 2,000 ms had elapsed, followed by a 500 ms delay before the next trial. All stimuli were presented with E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA).

Psychomotor vigilance task. Participants performed three test batteries daily (10:00 A.M., 3:45 P.M., and 8:00 P.M.) that included the psychomotor vigilance task (PVT) to assess sustained attention. A counter appeared on screen at random intervals between 2,000 and 10,000 ms, and participants responded with the space bar as quickly as possible. Failure to respond within 10,000 ms initiated an alerting tone. The task was performed in a 10-minute continuous block. Lapses (responses >500 ms) and response speed (1/RT) were measured.

Actigraphy

Participants wore an Actiwatch AW-2 (Philips Respironics, Inc., Pittsburgh, PA) during three phases: (1) screening period (1 week) of habitual term-time sleep, taking place 1–3 months before the study; (2) prestudy period (1 week) to verify compliance with the specified sleep schedule (11:00 P.M. to 8:00 A.M. daily); (3) the study period. Participants kept a sleep diary that was used to clean and verify the data. Data were collected at 30-second resolution and scored with Actiware software (version 6.0.2) at medium sensitivity. Actigraphy at this setting underestimates adolescent's total sleep time (TST) by ~30 minutes [26]; therefore, TIB was used for

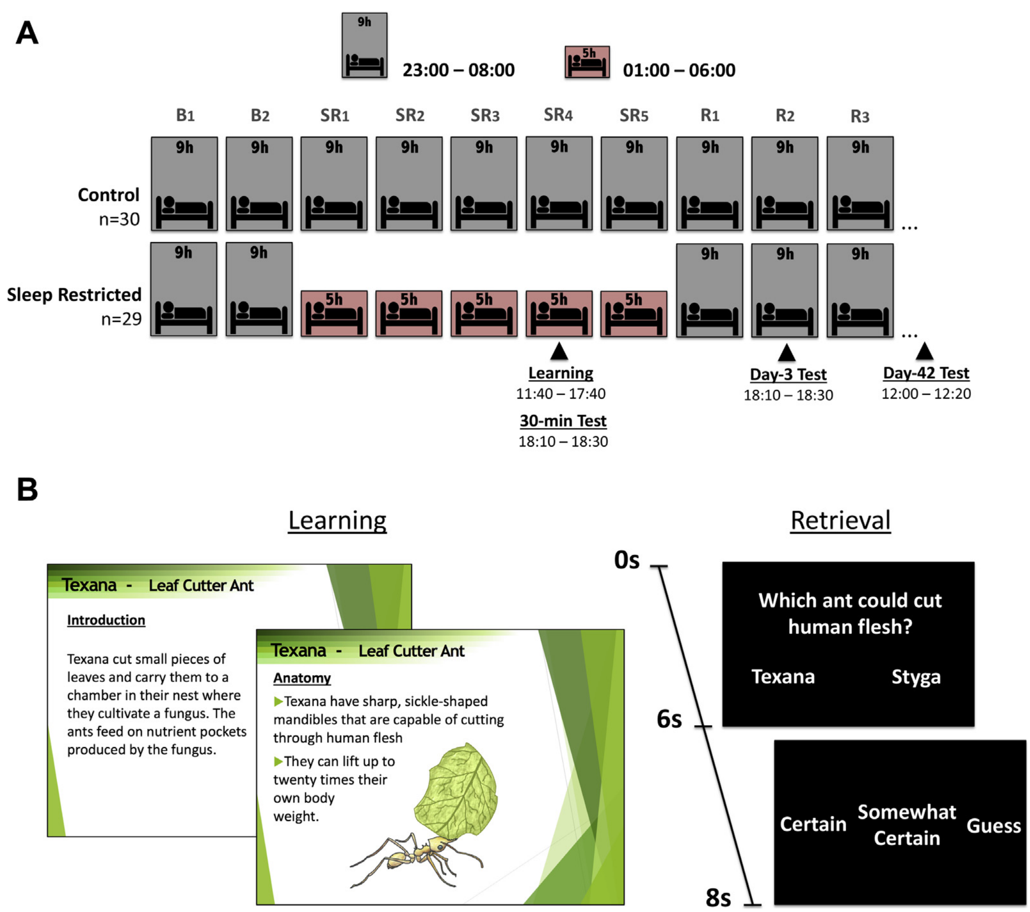

Figure 1. Study protocol and stimuli. (A) The experiment was part of an 11-day study that included 2 baseline days (B1, B2), a 5-day manipulation period (SR1–SR5) and 3 recovery days (R1–R3). Each 24-hour period of the study (e.g., B1) began at midnight (12:00 A.M.), encompassing nocturnal sleep and the daytime period that followed. The learning session and 30-minute test took place on manipulation day 4 (SR4), when the sleep restricted (SR) group had undergone 4 nights of 5 hours TIB. This was followed by an additional night of sleep restriction (5 hours TIB) for the SR group before 2 nights of recovery sleep (9 hours TIB) and testing on Day 3 (R2). The control group had 9 hours TIB throughout the protocol. A final test took place during a debrief on Day 42. The learning session began with a pretest to establish prior knowledge (not shown). Learning included six 30- to 40-minute blocks (three ants and three crabs) separated by 10-minute and 1-hour breaks. (B) Learning materials consisted of detailed information about each species presented on separate slides, including anatomy, habitat, and behaviors. Participants were tested using separate sets of 120 two-alternative forced choice questions for each test. Questions were followed by a confidence rating (Certain, Somewhat Certain, Guess).

screening and prestudy periods. TST values reported indicate relative group differences, but absolute values should be interpreted with caution.

Procedure

The study took place inside a boarding school in Singapore during a school holiday period. Participants' activities were strictly monitored throughout the protocol. A minimum of two experimenters monitored participants in a classroom during testing, and a common room during free periods where participants could socialize, play games, study, or engage in light exercise. The SR group engaged in these activities during the early morning and late evening periods when the control group slept. Groups were permitted to mix except during sleep periods when they were separated into twin-share bedrooms on different floors of the boarding school. Participants were provided with individual laptops in a classroom for the factual knowledge task. This began on Day SR4 with a briefing to introduce the types of information to be learned and questions that would be asked (11:00 A.M.), followed by the pretest (11:20 A.M.). Participants then performed the first (11:40 A.M. to 12:20 P.M.) and second (12:30 P.M. to 1:10 P.M.) learning blocks. A 1-hour lunch break was followed by the third (2:10 P.M. to 2:40 P.M.) and fourth (2:40 P.M. to 3:10 P.M.) blocks. Another 1-hour break was followed by the fifth (4:10 P.M. to 4:50 P.M.) and sixth blocks (5:00 P.M. to 5:40 P.M.). The 30-minute test took place from 6:10 P.M. to 6:30 P.M.. Throughout the day, participants also performed three PVT's (10:15 A.M., 4:00 P.M., and 8:15 P.M.) in the same testing room.

The Day 3 test took place following the administration of the PVT (4:00 P.M.) on Day R2 (18:00) when both groups had obtained 2 nights of 9 hours sleep opportunity. Finally, participants were administered a surprise Day 42 test (12:00 P.M.) while attending a debrief.

Statistical analysis

Memory scores were calculated for "certain," "somewhat certain," and "guess" responses separately by subtracting incorrect from correct responses. "Overall memory" was based on all correct responses, including trials where no certainty response was recorded. Separate 2 × 2 mixed analysis of variance (ANOVA) with the factors group (SR and control) and delay (30 minutes and Day 3) were performed using these four measures. A subset of participants returned for the Day 42 test, where groups were compared with independent *t*-tests. Mixed ANOVA were also used for subjective measures and PVT (Supplementary Materials).

Independent *t*-tests compared groups for memory, PVT (lapses and response speed), pretest knowledge, and actigraphy. Mann–Whitney *U* tests were used where the Shapiro–Wilk's test indicated a non-normal distribution. False discovery rate correction [27] was performed for measures where there was no clear a priori hypothesis. Spearman's Rho correlations explored the relationship between memory and other measures. Effect sizes indicated by partial eta squared (η_p^2) and Cohen's d (d). All statistical tests were two tailed, significance level $p < .05$. All means presented in the text ± standard deviation.

Results

Factual knowledge task—tests

The pretest showed there were no group differences in prior knowledge ($t(57) = .18$, $p = .86$). For responses rated as certain in the postlearning tests, a 2 × 2 mixed ANOVA with group (SR and control) and delay (30 minutes, Day 3) as factors showed a significant main effect of group ($F(1, 57) = 9.81$, $p = .003$, $\eta_p^2 = .14$) and delay ($F(1, 57) = 7.47$, $p = .008$, $\eta_p^2 = .12$) with no interaction ($F(1, 57) = .08$, $p = .77$). As predicted, planned comparisons revealed significantly worse memory for the SR group relative to controls for the 30-minute test ($t(57) = 2.54$, $p = .014$, $d = .66$) and Day 3 test ($t(57) = 2.65$, $p = .010$, $d = .69$; Figure 2A). Using control group retention at each test as normative performance, sleep restriction produced 26% less retention of learned materials at the 30-minute test and 34% less at the Day 3 test.

Somewhat certain responses showed no significant main effects or interactions (group, $F(1, 57) = 1.72$, $p = .20$; delay, $F(1, 57) = .92$, $p = .34$; group × delay, $F(1, 57) = .69$, $p = .41$). Guesses also showed no significant effects (group, $F(1, 57) = 3.46$, $p = .07$; delay, $F(1, 57) = .24$, $p = .63$; group × delay, $F(1, 57) = .46$, $p = .50$).

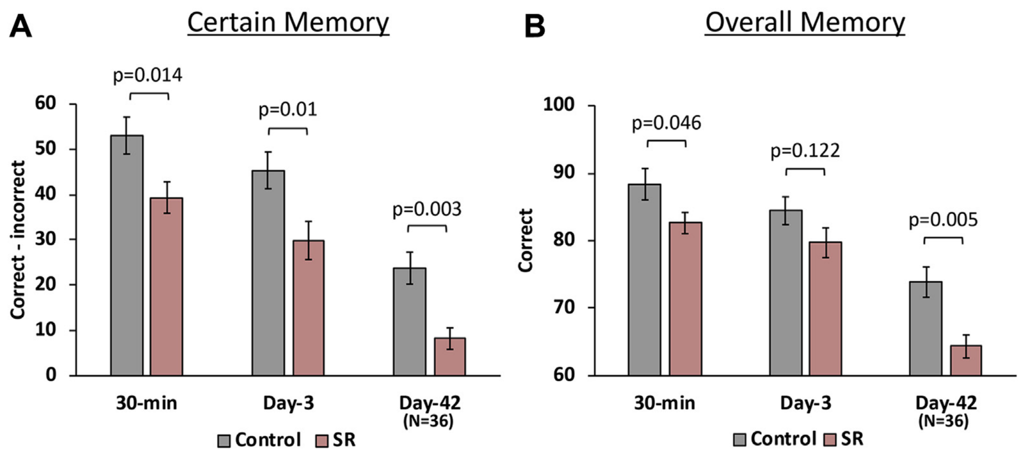

Figure 2. Long-term retention of knowledge was impaired after sleep restriction. (A) Certain memory (correct-incorrect) was significantly worse in the SR group relative to controls at 30 minutes, Day 3, and Day 42. (B) For overall memory (total correct out of 120 questions), the SR group were significantly impaired on the 30-minute and Day 42 tests, but the deficit on Day 3 failed to reach significance. Mean ± standard error of the mean.

Overall memory was similar to certain memory scores, with a significant main effect of group ($F(1, 57) = 4.99$, $p = .029$, $\eta_p^2 = .08$), no effect of delay ($F(1, 57) = 3.84$, $p = .06$) and no interaction ($F(1, 57) = .08$, $p = .78$; Figure 2B). The SR group had significantly worse memory than controls at the 30-minute test ($t(57) = 2.03$, $p = .047$, $d = .53$), but not the Day 3 test ($t(57) = 1.57$, $p = .12$).

A third surprise test was administered 6 weeks after learning with a subset of participants who returned for a debrief (SR, n = 14; control, n = 22). Independent *t*-tests showed significantly worse memory at Day 42 for the SR group for certain responses ($t(34) = 3.22$, $p = .003$, $d = 1.17$) and overall memory ($t(34) = 3.04$, $p = .005$, $d = 1.10$), but not somewhat certain ($t(34) = .44$, $p = .67$) or guesses ($t(34) = 1.69$, $p = .10$). Relative to control group performance for certain responses, sleep restricted participants retained 65% less of the learned material.

Subjective measures

Subjective alertness was significantly lower in the SR group across all blocks ($p < .01$), whereas focus was significantly lower in the SR group during blocks 3, 4, and 5 ($p < .01$; Figure 3; Supplementary Materials). Motivation was significantly lower in the SR group across all blocks ($p < .05$) except the final block ($p = .39$). The SR group felt they were significantly less able to perform during all blocks ($p < .05$) except the final block ($p = .09$). There were no significant correlations between memory (30-minute and Day 3 tests) and each subjective measure (mean of all six blocks) in the control group ($p > .05$). In the SR group, Day 3 memory correlated significantly with motivation (r = .41, $p = .026$) and ability (r = .46, $p = .012$). Thus, higher levels of motivation and ability were associated with better memory, although these do not survive false discovery rate correction. Taken together, this suggests that SR participants were less alert, less able to focus, less motivated, and aware that they were not performing optimally.

Psychomotor vigilance

As expected, the SR group made significantly more lapses and had slower response speed during PVT's performed at 10:15 A.M., 4:00 P.M., and 8:15 P.M. on the day that learning took place ($p < .05$; Figure 4; Supplementary Materials). There were no significant correlations between memory and attention measures at either delay for the control or SR group ($p > .05$). This indicates a dissociation between the effects of restricted sleep on vigilance and memory within participants, although at a group level, both domains were similarly impaired. A PVT performed shortly before the Day 3 memory test (4:00 P.M.)

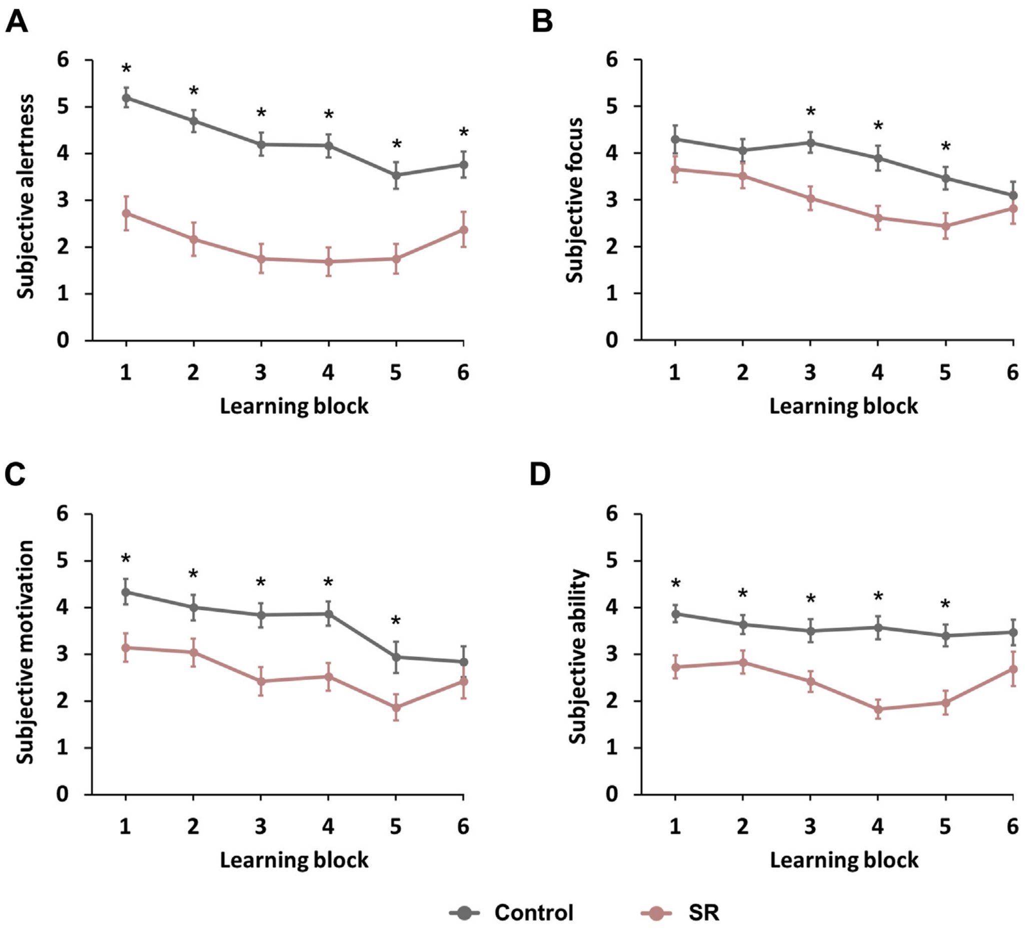

Figure 3. Subjective ratings for performance during learning. Higher scores indicate a higher level of (A) alertness (9-point scale), (B) focus on the task, (C) motivation to learn, and (D) ability to learn (7-point scales). The SR group reported consistently lower levels for all measures. Mean ± standard error of the mean. *$p < .05$.

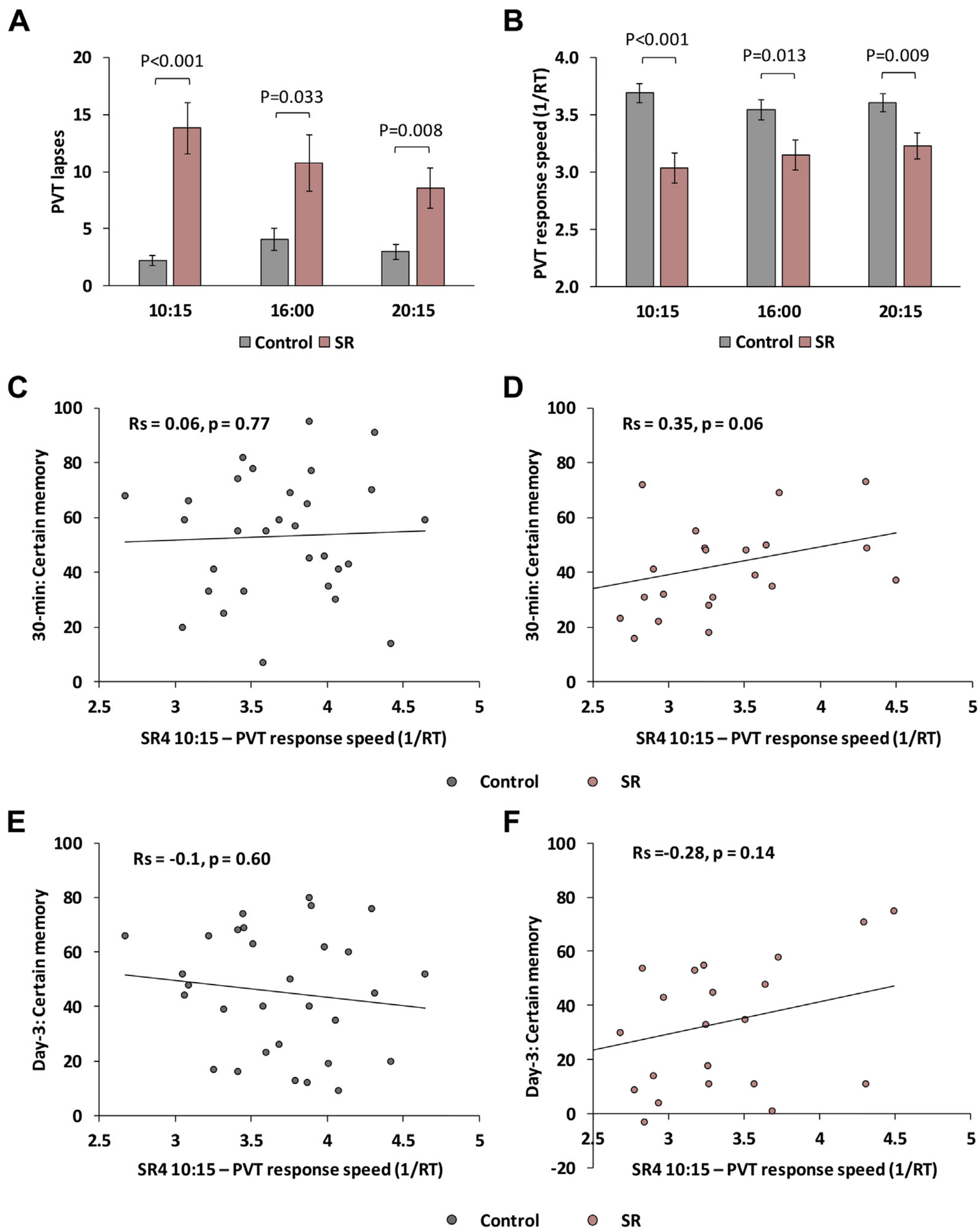

Figure 4. Psychomotor vigilance was impaired after sleep restriction and did not correlate with memory. (A) PVTs performed shortly before learning began on Day SR4 (10:15 A.M.), midway through the learning session (4:00 P.M.), and shortly after the 30-minute test (8:15 P.M.) showed significantly more attentional lapses after 4 nights of sleep restriction relative to controls. (B) Response speed was also significantly slower for the SR group during all three learning session PVTs. (C) PVT response speed on the morning that learning occurred (SR4) did not correlate significantly with certain memory at the 30 minute test in the control group or (D) the SR group, nor with certain memory at the Day 3 test in (E) the control group or (F) the SR group. Mean ± standard error of the mean. PVT, psychomotor vigilance task.

showed no significant group differences for lapses or response speed ($p > .05$), indicating that vigilance levels were similar between the two groups and unlikely to account for differences in memory performance.

Actigraphy

Participants' term-time sleep habits showed shortened weekday sleep (TIB = 6.75 ± .92 hours, TST = 5.38 ± .87) and weekend extension (TIB = 8.33 ± .92 hours, TST = 6.67 ± .86 hours). In the prestudy period, participants adhered to the sleep schedule (11:00 P.M. to 8:00 A.M.), and groups did not differ significantly for TIB (control: 8.79 ± .27 hours, SR: 8.79 ± .43 hours) or TST (control: 7.49 ± .53 hours, SR: 7.41 ± .65 hours; $p > .05$). This TST is below the recommended 8–10 hours [4], although actigraphy tends to underestimate adolescent TST by ∼30 minutes [26]; therefore, participants likely obtained ∼8 hours TST during this period and could be considered well rested.

During the study, sleep duration was altered in line with our experiment design (Table 1), with no group differences at baseline (B1, B2) and significantly reduced sleep during the restriction period (SR1–SR5). On the first recovery night, the SR group had significantly greater TST than controls ($p < .001$). There were no significant group differences in TST on the second recovery night ($p > .05$).

Discussion

We examined the impact of sleep restriction in adolescents on the long-term retention of educationally realistic materials by comparing teenagers with restricted sleep (5 hours sleep opportunity for 5 consecutive nights) to those obtaining the recommended amount (9 hours sleep opportunity) during a simulated school week. We found significantly reduced retention of factual knowledge after 4 nights of restricted sleep, and this deficit was still evident when tested 6 weeks later.

These findings show that multi-night sleep restriction is detrimental to long-term memory; therefore, improving adolescent sleep (e.g., by delaying school start times [15]) may be an effective way to enhance educational outcomes. These findings add to our prior work where the incidental encoding of pictures was impaired after 5 nights of sleep restricted to 5 hours TIB [23]. First, we showed that as little as 4 successive nights of insufficient sleep are necessary to significantly impair memory. Second, deficits occurred in the learning of detailed and interrelated factual knowledge. Third, large group differences remained when memory was tested 6 weeks after learning. This contrasts with several prior studies, where impairments to memory when a night of total sleep deprivation followed learning were no longer present when tested at delays of 6 days [20] and up to 6 months [18,19]. A key distinction is that this prior work assessed consolidation only, which appears to have the capacity to recover from sleep loss over time [20], whereas our protocol examined deficits to encoding, which may not. In addition, our complex stimuli acquired across long learning blocks (3 hours 20 minutes in total) differ from the briefly studied memoranda typically used. This deeper form of learning may be easier to retain at longer delays and facilitate the observation of differences between conditions.

The size of observed impairments paints a sobering picture—26% and 34% increased forgetting at 30-minute and Day 3 tests respectively—especially considering that our 5 hours TIB manipulation was similar to habitual sleep length observed in our adolescent sample and prior work [1,23]. Importantly, this impairment remained 6 weeks later, although the increased deficit of 65% cannot be interpreted as an increase over time because only a subset of participants performed this test.

Although our primary aim was to assess memory in the naturalistic context of a typical school week, rather than determine which specific memory processes were responsible, our data permit speculation on the underlying mechanisms affected by SR. The poorer performance of the SR group in the 30-minute test can reasonably be attributed to a deficit during encoding, although it is difficult to separate contributions of encoding mechanisms and those of attention. Decline in vigilance after sleep deprivation is a robust finding [28], and it is likely that lapses in attention contributed to performance detriments during our long blocks of learning. We found the expected decrease in vigilance and subjective alertness after sleep restriction [1], but these factors did not significantly correlate with memory. As such, the memory findings here may be more specifically attributed to a degradation of encoding capacity, consistent with prior demonstrations of impaired encoding after a night of total sleep deprivation [16,17] or several nights of sleep restriction [23].

In addition, motivation influences performance of even the simplest cognitive tasks [29], and this may be exaggerated across a long learning period. Although we did not measure or manipulate motivation objectively, our subjective measure showed a modest relationship with memory in the SR group, indicating that decreased motivation may have contributed to impaired learning.

It is possible that recollection at Day 3 and Day 42 may have been influenced by impaired consolidation because the SR group

Table 1
Sleep characteristics across baseline, manipulation, and recovery nights (assessed with actigraphy)

	Control (mean ± SD)	SR (mean ± SD)	p value
	n = 30	n = 29	
Prelearning sleep			
Baseline (B1, B2)			
TIB	8.99 ± .04	8.99 ± .03	.748
TST	7.56 ± .54	7.59 ± .50	.829
Manipulation (SR1–SR4)			
TIB	9.00 ± .03	5.00 ± .01	<.001
TST	7.44 ± .52	4.35 ± .29	<.001
Postlearning sleep			
Manipulation (SR5)			
TIB	9.00 ± .01	5.01 ± .01	<.001
TST	7.55 ± .47	4.49 ± .25	<.001
Recovery (R1)			
TIB	9.01 ± .04	8.99 ± .04	.108
TST	7.34 ± .41	7.96 ± .41	<.001
Recovery (R2)			
TIB	9.01 ± .02	9.01 ± .02	.71
TST	7.62 ± .53	7.58 ± .53	.844

p values correspond to independent samples t-tests.
SD = standard deviation; SR = sleep restricted; TIB = time in bed (hours); TST = total sleep time (hours).

underwent an additional night of restricted sleep after the 30-minute test. Prior studies exploring the long-term effects of sleep deprivation on memory consolidation would suggest this is unlikely: declarative memory consolidation was not impaired after sleep of less than 4 hours on a single night [30–32] or 5 hours TIB over several consecutive nights [21,22]. This has been suggested to be a result of the relative preservation of slow-wave sleep during sleep restriction [21,33]. Moreover, memory impairments associated with the loss of a full night of sleep appear to dissipate after subsequent recovery sleep has been obtained [20]. We did not observe an interaction between 30-minutes and Day 3 tests that would be indicative of an additional impairment to consolidation in the SR group. This null finding should be interpreted with caution however, as we cannot rule out a contribution of consolidation to memory deficits at 3 days and 6 weeks.

A further consideration is the impact of interference on memory [34], where experiences of the SR group during the extra 4 hours of wakefulness each day may have interfered with factual knowledge learning, both before and after learning. This could be explored in future studies by manipulating the types of activities engaged in during wake periods.

We observed that groups had similar vigilance after 2 recovery nights, and sleep duration did not differ on the second recovery night, which may suggest that weekend sleep permitted adolescents to "catch up" on lost sleep. However, we advise caution in this interpretation because prior studies have shown incomplete recovery of vigilance under similar levels of insufficient sleep in adolescents [1], and this pattern of restriction and recovery has also been associated with negative outcomes for metabolic health [35].

To summarize, we show that the capacity to acquire detailed factual knowledge is significantly impaired when learning takes place after only 4 nights of inadequate sleep. This memory impairment was apparent at 3 days and up to 6 weeks after learning, illustrating the negative impact of curtailing sleep during the school week when students most need to acquire and retain new knowledge.

Acknowledgments

The authors thank Bindiya Lakshmi Raghunath, Karen Sasmita, Su Mei Lee, Jesisca Tandi, Lee Xuan Kai, Cher Wei Shan, Lydia Teo Manling, Chong Shin Wee, Nicholas Chee, Shirley Koh, Teo Teck Boon, and Vaisakh Puthusseryppady for assistance in data collection. They also thank Nanyang Girls boarding school for use of their facilities. J.N.C. affirms that this list includes all who contributed significantly to the work.

Authors' contributions: J.N.C., M.W.L.C., and K.F.W. designed the study; J.N.C. and K.F.W. collected data; J.N.C. and K.F.W. conducted data analysis; J.N.C., M.W.L.C., and K.F.W. wrote the article.

Funding Sources

This work was supported by the National Medical Research Council Singapore (STaR/0015/2013) and the Far East Organization.

Supplementary Data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jadohealth.2019.04.030.

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