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Original Article

Multiple nights of partial sleep deprivation do not affect prospective remembering at long delays

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ABSTRACT

Prospective memory is defined as remembering to do something at a particular moment in the future and may be modulated by sleep. Here, we investigated whether multiple nights of partial sleep deprivation would affect the successful retrieval of intentions. Fifty-nine adolescents (mean age ± SD: 16.1 ± 0.6 years) were instructed to remember to press specific keys in response to the target words presented during a semantic categorization task in the future. Their memory was tested after five nights of either 5-h (sleep restriction group) or 9-h time-in-bed (control group). The average percentage of target words correctly responded to was small and did not significantly differ between the two groups (mean ± SEM for the sleep restriction group: 15.52 ± 6.61%; the control group: 23.33 ± 7.48%, $p = 0.44$). Thus, after the extended retention interval, prospective remembering was poor and did not appear to be affected by post-learning sleep restriction. These findings suggest a temporal boundary beyond which intentions fall below requisite levels of activation, potentially masking any benefits for retrieval conferred by sleep.

1. Introduction

Remembering to execute intended actions, such as remembering to pass a message to a friend when we see them, is an everyday task. To do so, we utilise prospective memory, which is defined as remembering to do something at a particular moment in the future [1]. Forgetting to perform intended actions may result in minor inconveniences (eg, a student forgetting to bring a pen to class) or more severe consequences (eg, a diabetic patient forgetting to inject insulin).

Recent work has shed light on the role of sleep in prospective remembering. While patients with obstructive sleep apnea and excessive daytime sleepiness report more prospective memory complaints [2], some studies have shown that insomnia patients perform better on prospective memory tasks compared to controls without insomnia symptoms [3,4]. Furthermore, older adults reporting short (<7 h) or long (>9 h) sleep durations have poorer prospective memory [4].

In healthy young adults, a 12-h period containing sleep relative to an equivalent period of wakefulness supports the consolidation of intentions [5,6]. Much less is known about whether sleep loss may impact prospective memory. Recent studies have found that 24 h of total sleep deprivation impairs the ability of young adults to remember to execute an intention in response to an event (eg, pressing a key upon encountering a target word [7]), as well as after a specified time (eg, pressing a key 20-min after a task began, [8]). However, the impact of *multiple* nights of *partial* sleep deprivation – the more commonly experienced form of sleep deprivation – remains to be examined.

Sleep curtailment is highly prevalent among adolescents with 75% of adolescents in the US [9] and more than 90% in some Asian countries [10,11] sleeping less than the recommended 8–10 h a night on school nights. Problems of short sleep and excessive daytime sleepiness extend into young adulthood, with 17–21% in both Western [12,13] and Asian countries [14,15] obtaining less than 6 h of sleep a night. Although the impact of curtailed sleep across multiple nights on various cognitive functions (such as sustained attention, working memory, and executive functions) are well documented for both adolescents and young adults [16–18], the effect on prospective memory has not been studied. Thus, we examined whether five nights of sleep restriction which simulated sleep curtailment in a typical school/work week would affect the execution of intentions previously encoded.

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2. Methods

2.1. Participants

Fifty-nine adolescents took part in the 11-day protocol of the Need for Sleep Study 3 (see Ref. [19] for further details). Participants were aged between 15 and 18 years (30 males, mean age ± SD: 16.1 ± 0.6 years). None reported any history of chronic medical conditions, psychiatric illness, or sleep disorders. They were not habitual short sleepers (average actigraphically assessed time-in-bed (TIB) < 6 h), consumed < five caffeinated beverages a day, and had not travelled across more than two time zones one month prior to the study. Participants and their parents provided written informed consent in compliance with the protocol approved by the National University of Singapore Institutional Review Board.

Participants were randomized into sleep restriction (SR; n = 29) and control groups (n = 30). The groups did not differ in age, gender distribution, consumption of caffeinated beverages, body mass index, a test of non-verbal intelligence (Raven's Advanced Progressive Matrices; [20]), levels of anxiety (Beck Anxiety Inventory; [21]) and depression (Beck Depression Inventory; [22]), morningness-eveningness preference (Morningness–Eveningness Questionnaire; [23]), levels of excessive daytime sleepiness (Epworth Sleepiness Scale; [24]), symptoms of chronic sleep reduction (Chronic Sleep Reduction Questionnaire; [25]), or subjective sleep quality (Pittsburg Sleep Quality Inventory; [26]) ($p > 0.21$; Table 1). The two groups also did not differ in sleep habits as assessed by actigraphy 1–3 months prior to the commencement of the study ($p > 0.16$; Table 1).

2.2. Study protocol

One week prior to the study, participants adhered to a 9-h TIB sleep schedule (23:00–08:00) at home. This was intended for circadian entrainment as well as for minimizing any effect of prior sleep restriction on sleep and cognitive performance. Participants resided in a boarding school in the following eleven days. The protocol began with two baseline nights (23:00–08:00), followed by a five-night sleep opportunity manipulation period in which the SR group had 5-h TIB (01:00–06:00) and the control group had 9-h TIB (23:00–08:00). The protocol ended with three nights of recovery sleep of 9-h TIB (23:00–08:00).

The intention encoding session of the prospective memory task took place after the second baseline night at 15:35, while the intention retrieval session was conducted at 15:50 the day after the fifth night of the sleep opportunity manipulation. Subjective sleepiness and sustained attention were also measured during the encoding and the retrieval sessions.

2.3. Prospective memory task

In order to approximate an everyday situation of prospective remembering, the prospective memory task [6] was embedded in an ongoing activity. Here, we used a semantic categorization task as the ongoing task. This task consisted of 150 trials. In each trial, a word was presented in lower case to the left on a computer screen, and participants had to determine if it was a member of the category word presented in capital letters to the right ('hockey SPORT'). For 'yes' and 'no' answers, participants pressed '1' and '2' on the keyboard respectively. Performance on the ongoing task was

Table 1
Characteristics for the sleep restriction and control groups.

	Sleep Restriction		Control		t/χ^2	p
	Mean	SD	Mean	SD		
n	29	–	30	–	–	–
Age (y)	16.07	0.59	16.10	0.64	0.19	0.85
Gender (number of males)	14	–	15	–	0.02	0.55
Caffeinated drinks per day	0.50	0.77	0.35	0.53	0.88	0.38
Body mass index	19.90	4.26	20.04	3.46	0.19	0.85
Raven's Advanced Progressive Matrices score	8.90	1.47	8.83	1.91	0.14	0.89
Beck Anxiety Inventory score	9.17	6.88	8.00	5.50	0.72	0.47
Beck Depression Inventory score	8.97	6.10	8.57	5.82	0.26	0.80
Morningness–Eveningness Questionnaire score	52.28	8.52	53.30	6.42	0.52	0.60
Epworth Sleepiness Scale score	6.97	3.49	6.73	2.78	0.28	0.78
Chronic Sleep Reduction Questionnaire						
Total score	34.86	5.14	35.23	5.25	0.27	0.79
Shortness of sleep	13.00	2.15	13.13	2.24	0.23	0.82
Irritation	6.93	2.30	6.37	1.67	1.08	0.28
Loss of energy	7.48	1.48	8.10	2.19	1.26	0.21
Sleepiness	7.45	1.78	7.63	1.59	0.42	0.68
Pittsburgh Sleep Quality Index						
TIB on weekdays (h)	6.86	0.86	6.63	1.00	0.95	0.35
TIB on weekends (h)	8.19	0.86	8.31	0.90	0.52	0.60
TIB on average (h)	7.34	0.73	7.14	0.80	1.01	0.32
TST on weekdays (h)	5.99	0.97	5.85	0.94	0.54	0.59
TST on weekends (h)	7.11	0.80	7.37	0.87	1.17	0.25
TST on average (h)	6.40	0.79	6.32	0.74	0.20	0.84
Global score	5.28	2.05	5.63	2.46	0.61	0.55
Actigraphy						
TIB on weekdays (h)	6.86	0.86	6.63	1.00	0.95	0.35
TIB on weekends (h)	8.19	0.86	8.31	0.90	0.52	0.60
TIB on average (h)	7.34	0.73	7.14	0.80	1.01	0.32
TST on weekdays (h)	5.99	0.97	5.85	0.94	0.54	0.59
TST on weekends (h)	7.11	0.80	7.37	0.87	1.17	0.25
TST on average (h)	6.36	0.79	6.32	0.74	0.20	0.84
Sleep efficiency (%)	87.00	6.00	89.00	5.00	1.44	0.16

SD, standard deviation; TIB, time in bed; TST, total sleep time.

indicated by the percentage of trials correctly responded to. Median reaction time for these correct trials was also derived.

In the encoding session, after completion of the semantic categorization task, participants were told that researchers had a secondary interest in their ability to remember to perform actions in the future. They were instructed to remember to press a special key ('Q') when they came across the words 'table' and 'horse' the next time they performed the semantic categorization task. Hence, participants expected that they would perform the category decision task at a future time, but they were unaware of when this would be (ie five days later). The instructions for the prospective memory task were as follows: "In addition to all the different tasks you have been doing and will be performing, we have a secondary interest in your ability to remember to perform an action in the future. If you ever see the words "table" or "horse" during the semantic categorization task in the next experimental session, we would like you to press the 'Q' key. If you see either of these two keywords, press 'Q' right away or as soon thereafter that you remember seeing one of those words (even if it's no longer on the screen). Please note that you will not be reminded of the keywords or this task. Also note that your primary goal during this experiment will be performing whatever ongoing task you are given."

At the end of the encoding session, to ensure that participants successfully encoded the prospective memory target words and action, they were required to type the two target words ('table, horse') as well as the key they had to respond with ('Q'). Failing to do so would re-direct them to the screen displaying the prospective memory task instructions. A research assistant verbally explained the instructions to all participants.

In the intention retrieval session, instructions for the semantic categorization task were presented again, but no mention of the prospective memory task or target words was made. Each target word occurred only once. Prospective memory performance was quantified by the percentage of target words detected. Only targets responded to within five trials of the semantic categorization task were scored as "detected". Furthermore, the number of participants who were able to detect at least one target word was noted.

2.4. Sleepiness rating and sustained attention task

Subjective sleepiness was measured with the Karolinska Sleepiness Scale (KSS; [27]), in which participants rated their level of sleepiness on a nine-point Likert scale (one-very alert, nine-very sleepy, great effort to keep awake).

Sustained attention was measured with a 10-min Psychomotor Vigilance Task (PVT; [28]). Participants were instructed to respond by pressing the spacebar on the keyboard as quickly as possible whenever the counter on screen started counting. The number of lapses, defined as responses exceeding 500 msec, was used as a measure of sustained attention.

2.5. Actigraphy

Sleep patterns were assessed with wrist-worn actigraphy (Actiwatch 2, Philips Respironics Inc., Pittsburgh, PA) for screening purposes during term time, for verification of compliance with the specified sleep schedule during the pre-study period, as well as for determining the efficacy of sleep opportunity manipulation during the 11-day study protocol. Temporal resolution was set at 30 s, and data was scored with the Actiware software (version 6.0.2). Total sleep time (TST) was calculated using a medium sensitivity algorithm, with which an activity count greater than or equal to 40 was defined as waking. Participants also kept a sleep diary during the actigraphically-monitored periods at home. Bedtimes and wake times were determined by self-reported sleep-wake timing on the sleep diary and the event markers on the actogram.

2.6. Statistical analyses

Analysis of variance (ANOVA) was employed to determine the statistical significance of the group x session interaction on the semantic categorization task performance, KSS score, and PVT performance. Pairwise contrasts were tested with independent- and paired-samples *t* tests. Independent-sample *t* tests were also performed to test whether the two groups differed in sleep duration, as well as the percentage of target words correctly responded to in the prospective memory task. Additionally, a chi-squared test was used to determine whether there was any group difference in the proportion of participants who were able to detect at least one target word.

3. Results

3.1. Sleep duration

In the week prior to the protocol, both groups complied with the 9-h TIB schedule at home and the two groups did not differ in TIB (mean ± SEM for SR: 8.79 ± 0.08 h versus control: 8.79 ± 0.05 h, $t(57) = 0.07$, $p = 0.95$). There was also no statistically significant difference in TST between groups (SR: 7.41 ± 0.12 h versus control: 7.49 ± 0.10 h, $p = 0.61$).

During the baseline nights, the SR and control groups did not differ in TIB (SR: 8.99 ± 0.01 h versus control: 8.99 ± 0.01 h, $p = 0.75$) or TST (SR: 7.59 ± 0.09 h versus control: 7.56 ± 0.10 h, $p = 0.83$). As expected, during the five nights of sleep manipulation, the SR group had a significantly reduced TIB (SR: 5.01 ± 0.001 h versus control: 9.00 ± 0.004 h, $p < 0.001$) and TST (SR: 4.38 ± 0.05 h versus control: 7.46 ± 0.09 h, $p < 0.001$) compared to the control group.

3.2. Prospective memory and ongoing tasks

We found no significant group difference in the percentage of target words correctly responded to in the prospective memory task ($t(57) = 0.78$, $p = 0.44$; Table 2). Both groups performed poorly regardless of the amount of sleep obtained over the five-day retention interval (SR: 15.52 ± 6.61% versus control: 23.33 ± 7.48%). Furthermore, a similar and small proportion of participants in the SR group (n = 5 out of 29) and the control group (n = 8 out of 30) detected at least one target word ($\chi^2(1) = 0.76$, $p = 0.38$).

Table 2
Performance for the ongoing, the prospective memory, and the sustained attention tasks, and subjective sleepiness rating.

	Sleep Restriction		Control		*t*	*p*
	Mean	SE	Mean	SE		
Intention encoding						
Ongoing task accuracy (%)	91.05	0.70	91.49	0.67	0.40	0.69
Ongoing task RT (ms)	1057	33	1051	24	0.13	0.90
KSS score	4.64	0.23	4.40	0.23	0.59	0.56
PVT lapses	4.07	0.99	3.63	1.20	0.21	0.83
Intention retrieval						
Ongoing task accuracy (%)	89.86	2.81	93.38	0.64	1.24	0.22
Ongoing task RT (ms)	1058	35	1038	27	0.45	0.66
KSS score	6.54	0.27	4.77	0.19	5.43	<0.001
PVT lapses	13.36	2.50	3.80	0.99	3.57	<0.001
Prospective memory accuracy (%)	15.52	6.61	23.33	7.48	0.78	0.44

RT, reaction time; KSS, Karolinska Sleepiness Scale; PVT, Psychomotor Vigilance Task.

For the semantic categorization task, there was no significant group x session interaction for both performance accuracy ($F(1,57) = 0.06$, $p = 0.81$) and median RT ($F(1,57) = 0.303$, $p = 0.58$). Baseline performance accuracy ($t(57) = 0.40$, $p = 0.69$) and median RT ($t(57) = 0.13$, $p = 0.90$) did not differ between groups (Table 2). Despite sleep restriction, performance accuracy ($t(28) = 0.46$, $p = 0.65$) and median RT ($t(28) = 0.05$, $p = 0.96$) of the SR group did not significantly worsen when tested at the retrieval session. Furthermore, there were no significant differences between the SR and control groups in performance accuracy ($t(57) = 1.24$, $p = 0.22$) or median RT ($t(57) = 0.45$, $p = 0.66$) in the retrieval session.

3.3. *Subjective sleepiness and sustained attention*

We found a significant group x session interaction on both KSS score ($F(1,56) = 15.79$, $p < 0.001$) and PVT performance ($F(1,56) = 12.93$, $p < 0.001$). Groups did not differ in KSS score ($t(57) = 0.59$, $p = 0.56$) and the number of PVT lapses ($t(57) = 0.21$, $p = 0.83$; Table 2) assessed at the encoding session. However, as expected, after five nights of restricted sleep, the KSS score of the SR group increased ($t(27) = 5.40$, $p < 0.001$) and was significantly higher than that of the control group ($t(56) = 5.43$, $p < 0.001$). Similarly, at the intention retrieval session, the number of PVT lapses among the sleep-restricted participants increased from baseline ($t(27) = 3.73$, $p < 0.001$) and was significantly greater than that of the control group ($t(56) = 3.57$, $p < 0.001$).

4. Discussion

In this study, we investigated whether five nights of sleep restriction that simulated a typical school/work week would influence the retrieval of an intention previously encoded. We found that despite clear deficits in subjective alertness and sustained attention the ability of the sleep-restricted participants to retrieve the encoded intention in the prospective memory task as well as their performance in the semantic categorization task was similar to that of the well-rested participants.

There are two explanations as to why the sleep-restricted and the well-rested participants attained similar prospective memory performance. While subjective alertness and sustained attention are more affected by sleep deprivation relative to other neurobehavioural measures [16,29], the prospective memory task as well as the semantic categorization task used in the present study may not be sufficiently sensitive to detect any impairing effect of partial sleep deprivation on cognitive performance.

Alternatively, the delay between intention formation and retrieval might have been too long, resulting in poor prospective memory performance for both the sleep-restricted and the well-rested participants. The apparent floor effect might have masked any significant impairing effect of post-learning sleep restriction on prospective remembering. Compared to a study which tested prospective remembering after a 12-h retention interval containing sleep and showed that an average of 50% of targets were remembered [6], our study found that even the well-rested participants who had five nights of 9-h sleep opportunity could respond to an average of only 23% of target words. Furthermore, the proportion of participants who remembered the intention at all was low and did not statistically differ between the SR and control groups. These findings may suggest that a requisite level of activation is necessary in order for intentions to be retrieved, and an extended delay period between intention formation and intention retrieval may have resulted in a decay of target-action representations; thereby increasing the difficulty in memory retrieval even for the group that obtained optimal sleep.

Notably, these findings point to a temporal boundary in the maintenance and retrieval of intentions. Although it has been argued that intentions are represented at a heightened level of sub-threshold activation in the brain compared to other items that are only verbally recalled at a future time [30], these representations inevitably fade over time especially if they are not retrieved in the interim. Despite this obstacle, a small number of participants were able to successfully execute the intention. Future studies should examine why some individuals are able to retrieve ‘aged’ intentions while others fail to do so, and identify factors critical for successful retrieval of intentions despite an extended delay.

Our finding does not preclude the possibility that sleep curtailment during the retention interval can impair the retrieval of prospective memory, since a previous study has shown that total sleep deprivation significantly impaired the execution of a previously formed intention [7,8]. Moreover, sleep deprivation has deleterious effects on the underlying mechanisms of the two routes to successful prospective remembering: strategic monitoring and spontaneous retrieval [31]. Specifically, strategic monitoring for the appearance of the prospective memory target requires working memory [32,33], which is impaired by multiple nights of sleep restriction [16–18]. Alternatively, spontaneous retrieval is contingent on the noticing of the significance of the prospective memory target when it appears [34]. Lower levels of alertness and poorer attention induced by sleep loss may impair the process that signals significance as well as the ability to reorient to the prospective memory task.

The mechanisms by which sleep benefits prospective memory remain relatively unexplored. Relative to the second half of the night, sleep in the first half which contains more slow wave sleep seems to offer greater benefits on prospective memory by strengthening the representations of intentions, supporting retrieval even under conditions of divided attention [5,35]. However, the dose–response relationships of slow wave sleep duration and perhaps other sleep features, such as slow wave and sleep spindle activity, with prospective memory need to be addressed in future studies.

4.1. *Limitations*

Although the effects of sleep curtailment across multiple nights on prospective memory remain inconclusive, our findings shed light on a temporal boundary for the maintenance and retrieval of a prospective memory intention. Future studies may consider employing a shorter delay interval to examine whether one to two nights of restricted sleep opportunities affects prospective remembering. Additionally, alternative designs may be employed whereby both encoding and retrieval of intentions occur after a period of partial or total sleep deprivation. Such designs may be more sensitive to the effects of sleep loss.

In this study, a retrospective memory check for the target words and response key was not conducted after the intention retrieval session, limiting the conclusion that it is the component of prospective memory, rather than the retrospective component, that decayed over time. Future studies that include such a test may explore whether the retrospective and the prospective components of prospective memory are differentially impaired by sleep restriction.

Future studies may also extend the present work to other age groups. Given that various aspects of sleep are altered with increasing age, it remains to be studied whether restricted sleep has a similar impact on prospective memory in other age groups.

5. Conclusions

Post-learning sleep restriction across five nights does not influence prospective remembering. It is likely that the extended retention interval led to a significant decay of the intention, thereby masking any potential impairing effects of sleep curtailment. However, this finding sheds light on a temporal boundary for the maintenance and retrieval of intentions.

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Conflicts of interest

The authors declare no competing financial interests.

The ICMJE Uniform Disclosure Form for Potential Conflicts of Interest associated with this article can be viewed by clicking on the following link: https://doi.org/10.1016/j.sleep.2017.09.037.

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