Effect of chronic sleep restriction on sleepiness and working memory in adolescents and young adults

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Objectives: To test the feasibility of using a home-based sleep restriction protocol in adolescents and young adults; and to examine the different effects of chronic sleep restriction on a subjective sleepiness scale and working memory task in adolescents and young adults. Method: Twenty adolescents (ages 13–16 years) and 20 young adults (ages 18–20 years) underwent a 2-week home-based sleep manipulation protocol consisting of a week of 5 school days with 8 hr spent in bed per night and another week of 5 school days with 6 hr spent in bed per night. The protocol used a counterbalanced crossover experimental design. Subjective sleepiness was scored by the participant each morning, and working memory tests were administered during the weekend corresponding to each experimental week. Results: Adherence to the prescribed protocol was similar in the two groups, and both groups achieved the desired differences in total sleep duration across the two sleep conditions. Subjective sleepiness scores significantly increased in young adults after sleep restriction, but were not accompanied by significant changes in working memory. However, reaction times during simple verbal and arithmetic working memory tasks increased among adolescents after sleep restriction, without affecting accuracy on task, and without eliciting increases in subjective sleepiness scores. Conclusion: Mild sleep restriction for 5 days impairs reaction times during working memory tasks in adolescents in the absence of increased perception of sleepiness.

Keywords: Chronic sleep restriction; Adolescents; Sleepiness; Working memory; Sleep deprivation.

INTRODUCTION

It has now become apparent that the majority of adolescents suffer from insufficient sleep in both developed and developing countries (Gibson et al., 2006; Liu, Zhao, Jia, & Buysse, 2008; Loessl et al., 2008; Wolfson & Carskadon, 1998; Yu et al., 2007). The average duration of sleep per night among adolescents in the United States...
decreased from 9.1 hr/night in 1910 (Terman & Hocking, 1913) to 7.4 hr/night in 1994 (Wolfson & Carskadon, 1998). A recent sleep survey of 1,365 Chinese adolescents who were 12–18 years old revealed that their mean sleep duration is 7.64 hr/night (Yu et al., 2007). However, it is highly unlikely that in the last century the need for physiological sleep has diminished in adolescents, with current estimates proposing a physiological sleep need of 9 hr/night (Carskadon & Acebo, 2002).

Optimal neurobehavioral performance requires activation of the circadian wakefulness circuitry and maintenance of sleep homeostasis (Carrier & Monk, 2000). When subjects experience chronic sleep restriction, the homeostatic drive to sleep rises, and cognitive performance begins to decline. Many epidemiological studies have reported that insufficient sleep is associated with poor academic grades and impaired school performance (Epstein, Chillag, & Lavie, 1998; Giannotti, Cortesi, Sebastiani, & Ottaviano, 2002; Gibbon et al., 2006; Meijer, 2008; Wolfson & Carskadon, 1998). However, the correlative nature of these epidemiological studies precludes any causal inferences. Although substantial evidence has accumulated in adults (Dorrian & Dingess, 2005; Durmer & Dinges, 2005; Harrison & Horne, 2000; Van Dongen, Maislin, Mullington, & Dinges, 2003), only a few studies have assessed the effects of experimental multineight sleep restriction on cognitive or neurobehavioral function in children and adolescents (Beebe et al., 2008; Fallone, Acebo, Seifer, & Carskadon, 2005; Sadeh, Gruber, & Raviv, 2003). The paucity of adolescent sleep restriction studies is probably related to two main reasons: (a) A multineight sleep restriction protocol in the laboratory setting is a substantial imposition for most families of school-aged children or adolescents (Fallone, Seifer, Acebo, & Carskadon, 2002); (b) home-based sleep restriction protocols for children and adolescents relied mostly on parental reporting until recently, when actigraphic recordings became more widely implemented (Beebe et al., 2008; Fallone et al., 2005; Fallone et al., 2002; Sadeh et al., 2003).

In the present study, we chose to examine both adolescents and young adults, since life and study schedules may vary significantly in this narrow age range. Adolescents are normally involved in prescriptive school schedules with early start times, often before 8:00 A.M., while young adults who attend colleges have much more flexible class schedules and more “free time.” Furthermore, most studies on chronic sleep restriction have included either young adults or children, such that comparative research is lacking between the adolescents and young adult populations.

Working memory task performances involving verbal learning and serial subtraction can be impaired even after a single night of total sleep deprivation as well as following chronic partial sleep restriction in adult subjects (Chee & Choo, 2004; Drummond et al., 1999; Van Dongen et al., 2003). Of note, extensive evidence has accumulated indicating that working memory performance is linked to key learning outcomes in literacy and numeracy (Cowan & Alloway, 2008). Moreover, chronic sleep restriction involving 6 hr or less of sleep per night for two weeks was accompanied by cognitive performance decrements that were equivalent to those identified after two consecutive nights of total sleep deprivation (Van Dongen et al., 2003). However, cognitive performance seems to be better preserved in aging people than in younger adults after either total sleep deprivation or chronic partial sleep restriction (Bliese, Wesensten, & Balkin, 2006; Philip et al., 2004; Stennit & Kerkhofs, 2005). To our knowledge, there has been no experimental evidence assessing the potential modulating effect of age (adolescent vs. young adult) on cognitive performance during partial sleep restriction. Considering the critical importance of working memory for executive function, we hypothesized that working memory would be markedly altered in adolescents and young adults after experimental sleep restriction. The study was therefore designed to examine the effect of a home-based sleep restriction protocol in adolescents and young adults on working memory task performances.

METHOD

Subjects

A total of 20 young adults and 20 adolescents were recruited from a local medical school and two high schools in Shanghai, respectively. The average age of the young adult group was 18.9 ± 0.6 years (range = 18–20 years), and 13 of the 20 participants were female; the average age for the adolescent group was 15.0 ± 0.8 years (range = 13–16 years), and half of them were female. There were 2 minority ethnic participants in both groups, and the other 36 were ethnic Han Chinese. Background information was obtained through questionnaires and the Epworth Sleepiness Scale completed by the subjects. Our recruiting methods included distributing brochures to large numbers of first-year medical school students and first-year high-school (10th grade) students and displaying posters at the corresponding campuses. Participant exclusion criteria included the following: currently suspected or diagnosed obstructive sleep apnea, excessive sleepiness, narcolepsy, periodic leg movement, insomnia or any other sleep disorders; currently suspected or diagnosed seizure, learning disorder, attention deficit and hyperactivity disorder, or any other neurological or psychiatric disorder; currently taking any medication known to affect sleep or daytime functioning; alcohol and recreational drug use; reported pregnancy and obesity; and erratic sleep schedules (variation of more than 3 hours across a week). Eligible volunteers and the parents or guardians of adolescents received a description of the study procedures and provided informed consent at an information meeting in accordance with procedures approved by the Institutional Review Board of Shanghai Children’s Medical Center. Participants received monetary compensation for participating in the study.

Procedure

During the spring of 2008, each participant was asked to follow their normal school-night sleep schedule in the
preexperimental week and then to adhere to the assigned sleep schedule at home that included 8 hours of sleep (RegS) or 6 hours of sleep (ResS) for 2 weeks. On the Monday–Friday nights of the ResS week, we requested that participants set a late bedtime that limited them to 6 hours in bed, while on the Monday–Friday nights of the RegS week, the bedtime was set earlier to allow for 8 hours in bed. There was a one-week period between the two sleep conditions; the order of the sleep condition was counterbalanced across subjects to reduce the potential influence of practice and learning. The subjects were not restricted in terms of their normal daily life activities for the purposes of the study. They were instructed to act normally, except that they were prohibited from consuming caffeinated beverages, alcohol, or medication and from taking daytime naps during the experiment period. Participants were asked to document any of these protocol violations in their sleep diary. Each Saturday of the RegS and ResS weeks, participants came to the hospital and completed a series of neurobehavioral tests. Research staff telephoned participants every day during the experimental weeks to obtain sleep schedules and verified that actigraphy watches were worn. In our original protocol, a third sleep condition corresponding to an extension of normal sleep duration was planned, and it required participants to spend 10 hr of time in bed. However, none of the adolescents in the pilot study adhered to this sleep regimen, primarily due to the large homework load, which did not allow for early bedtime on weekdays. Therefore, in the reported protocol, this arm of the study was not included.

Sleep measures and sleepiness evaluation

Sleep was monitored by self-report and by objective measures in the preexperimental week and during the two experimental weeks. Each participant was required to complete a sleep diary that included bedtime and rise-time schedules and daytime napping behavior. In addition, participants continuously wore a wrist actigraphy watch (ActivWatch; Mini Mitter, Inc.) on the nondominant wrist, except in those situations when the actigraphic device might get wet or when engaging in contact sports. Participants were required to document such “off” periods in the sleep diary.

Analysis of the actigraphy data was conducted using the manufacturer's supplied software (Actiware 3.4; Mini Mitter, Inc.). The analysis method was adopted from that previously reported by Knutson and colleagues (Knutson, Rathouz, Yan, Liu, & Lauderdale, 2007), and the following variables were assessed: sleep onset time and sleep offset time (both automatically calculated by the software); total sleep duration (sum of epochs between sleep onset and sleep end that are scored as “sleep” according to the algorithm); sleep latency (the length of time between bedtime and sleep onset); and sleep efficiency (percentage of time between onset and offset actually spent asleep). During the preexperimental week, 3 participants failed to wear the actigraph for one day, with all the other participants wearing the actigraphic device every day. In the two experimental weeks, research staff called the participants every evening to increase adherence of the participants. In addition, every morning throughout the two experimental weeks, participants rated their sleepiness using the Stanford Sleepiness Scale (SSS) after waking.

To examine individual compliance with our experimental manipulation of sleep, we defined the targeted sleep restriction as acceptable if the subject had an average reduction in their sleep period that was at least 90 min less than their corresponding average regular sleep period. Participants classified as noncompliant were examined with regard to whether the deviation occurred at bedtime (i.e., bedtime schedule deviation), rise time (i.e., rise-time schedule deviation), or both.

Neurobehavioral tests

Neurobehavioral tests, including verbal and arithmetic working memory, were evaluated for each participant on each Saturday morning following the RegS and ResS weeks. Two verbal working memory tasks were used, in which the simple verbal working memory (SVWM) task evaluated maintenance, and the complex verbal working memory (CVWM) task tested manipulation as well as maintenance. The tasks were adapted from Chee and colleagues (Chee & Choo, 2004). In the SVWM task, four different uppercase letters were presented for 0.5 s, followed by a delay period of 3.0 s, during which a fixation cross was displayed. A lowercase probe letter was then presented for 1.5 s, and this was followed by a fixation cross for an additional 0.5 s. Participants signaled whether the letter was a match or a nonmatch by pressing one of two response buttons on the PST Serial Response Box (Psychology Software Tools, Inc., Pittsburgh, PA), which was directly connected to the computer. In the CVWM task, two different uppercase letters were presented, and participants were instructed to shift each letter forward alphabetically and to mentally retain the results. For example, if “D” and “K” were presented, participants had to remember “E” and “L” to be matched with the probe. Stimulus presentation sequence and timing were identical to those used in the SVWM task. There were a total of 84 possible responses in the SVWM and CVWM tasks.

In the arithmetic working memory (AWM) task, which has been modified based on Drummond’s study (Drummond, et al., 1999), a random three-digit number (first “seed” number) appeared on the screen, and the participant was required to serially subtract 6, 7, 8, or 9 (randomly chosen for each subject) from the number. The first “seed” number was presented for 1 s. This was followed by a second three-digit number presented for 1.5 s, and this was followed by a fixation cross for an additional 0.5 s. Participants signaled whether the letter was a match or a nonmatch by pressing one of two response buttons on the PST Serial Response Box (Psychology Software Tools, Inc., Pittsburgh, PA), which was directly connected to the computer. In the CVWM task, two different uppercase letters were presented, and participants were instructed to shift each letter forward alphabetically and to mentally retain the results. For example, if “D” and “K” were presented, participants had to remember “E” and “L” to be matched with the probe. Stimulus presentation sequence and timing were identical to those used in the SVWM task. There were a total of 84 possible responses in the SVWM and CVWM tasks.
was 8.35 ± 0.72 hr for adolescents and 8.06 ± 0.52 hr for young adults (p = .152). As illustrated in Figure 1, there were 3 participants (all adolescents) who met the criterion for noncompliance as they did not achieve a difference in duration of sleep duration between sleep restriction and regular sleep periods of at least 90 minutes. The compliance rate between adolescents (85%) and young adults (100%) was not significantly different (p = .231). All three noncompliant participants were boys between 14–15 years of age; the small sleep time differential observed across the two sleep conditions was entirely due to the bedtime schedules during the last 2 or 3 nights of the restricted sleep condition.

Results from HLM suggest that sleep restriction affects adolescents and young adults differently for some of the response variables. Results indicate that as prescribed, both groups indeed shortened their sleep time significantly during the restricted sleep condition (Table 1). The changes in sleep time across sleep conditions were mostly due to changes in bedtime rather than changes in waking time. The recorded values for the time spent in bed and total sleep time were not different between the two groups across sleep conditions.

Night-by-night main sleep variables across sleep conditions are illustrated in Figure 2. The main effect of sleep conditions (p < .0001) and time (p = .0016) on total sleep time was significant, and no group differences and interaction effects emerged. As predicted, sleep efficiency was increased after sleep restriction in both cohorts, and the observed increase was slightly more prominent in adolescents than in young adults and approached our threshold for statistical significance (p = .0243). The main effect of sleep condition on sleep latency was significant in both groups (p < .001), and there was no significant main effect of time or a time-by-condition interaction.

Subjective sleepiness

As seen in Figure 3, scores on the SSS significantly increased after sleep restriction in young adults (p = .0008) but not in adolescents. In a regular sleep week, a higher average score on the SSS was seen in adolescents than in young adults, and the difference almost reached the statistically significant level (p = .054).

Working memory tests

During analyses of the working memory tests analyses, the three noncompliant participants were excluded, resulting in 20 young adult participants and 17 adolescent participants. In the adolescent group, working memory responses showed a trend towards impairment after 5 days of sleep restriction. Only the reaction time for the arithmetic WM test (p = .0138) and simple verbal WM test (p = .0170) reached statistical significance (Figure 4). In the young adult group, there were no significant changes across the two sleep conditions.

Spearman correlation analysis revealed that there were no significant associations between scores on the SSS and working memory test variables across the two sleep conditions in either the adolescent or the young adult groups.
TABLE 1
Comparison of sleep across conditions in adolescents and young adults

<table>
<thead>
<tr>
<th>Sleep</th>
<th>Adolescents</th>
<th>Young adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reported bedtime</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular(^b)</td>
<td>21:52</td>
<td>(21:30, 22:13)(^a)</td>
</tr>
<tr>
<td>Restricted(^b)</td>
<td>23:26</td>
<td>(23:05, 23:48)</td>
</tr>
<tr>
<td>Reported uptime</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular(^b)</td>
<td>6:29</td>
<td>(6:06, 6:53)(^a)</td>
</tr>
<tr>
<td>Restricted(^b)</td>
<td>6:04</td>
<td>(5:40, 6:27)</td>
</tr>
<tr>
<td>Reported time in bed (hr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular(^b)</td>
<td>8:63</td>
<td>(8:33, 8:92)(^a)</td>
</tr>
<tr>
<td>Restricted(^b)</td>
<td>6:63</td>
<td>(6:33, 6:92)</td>
</tr>
<tr>
<td>Sleep onset time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular(^b)</td>
<td>22:11</td>
<td>(21:49, 22:33)(^a)</td>
</tr>
<tr>
<td>Restricted(^b)</td>
<td>23:35</td>
<td>(23:14, 23:57)</td>
</tr>
<tr>
<td>Sleep offset time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular(^b)</td>
<td>6:19</td>
<td>(5:54, 7:13)(^a)</td>
</tr>
<tr>
<td>Restricted(^b)</td>
<td>6:04</td>
<td>(5:39, 6:28)</td>
</tr>
<tr>
<td>Total sleep time (hr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular(^b)</td>
<td>8:12</td>
<td>(7:84, 8:41)(^a)</td>
</tr>
<tr>
<td>Restricted(^b)</td>
<td>6:47</td>
<td>(6:18, 6:75)</td>
</tr>
<tr>
<td>Sleep efficiency (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular(^b)</td>
<td>76.80</td>
<td>(72.74, 80.41)(^a)</td>
</tr>
<tr>
<td>Restricted(^b)</td>
<td>81.12</td>
<td>(77.60, 84.20)</td>
</tr>
<tr>
<td>Sleep latency (min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular(^b)</td>
<td>16.68</td>
<td>(12.96, 21.20)(^a)</td>
</tr>
<tr>
<td>Restricted(^b)</td>
<td>7.08</td>
<td>(5.36, 9.29)</td>
</tr>
</tbody>
</table>

Note. Estimates are least squares means (LSM) with 99% confidence intervals based on a hierarchical linear modeling (HLM) analyses. Note that the resulting estimates for sleep efficiency and sleep latency have been back-transformed to an original measurement scale. Statistically significant differences \((p < .01)\) are marked as follows:

\(^a\)difference in sleep conditions for a given cohort;

\(^b\)difference in cohorts for a particular sleep condition.

DISCUSSION

The present study determined the effect of 5 days of sleep restriction at home on sleepiness and working memory in adolescents and young adults. The main findings were that it is feasible to use a home-based sleep restriction protocol in adolescents during regular weekdays, and that shortened sleep duration significantly increased sleep efficiency and shortened sleep latency. Furthermore, subjective sleepiness scores significantly increased in young adults, but surprisingly, no significant differences occurred in adolescents until the fourth sleep restricted night. Finally, significant increases in reaction times only occurred during simple verbal and arithmetic working memory tasks for the adolescent group and were void of any effect on accuracy.

When considering the potential advantages of home-based sleep restriction protocols relative to in-laboratory studies, there is a clear reduction in the burden on staff and diminished costs, which are also paired with greater acceptability by subjects and families. However, the most important advantage is that home-based restriction protocols are more applicable to real-life conditions and allow for data collection on larger subject samples (Beebe et al., 2008; Fallone et al., 2005; Fallone et al., 2002; Sadeh et al., 2003). Nevertheless, the utility of home-based protocols could be undermined by difficulties in maintaining compliance with the prescribed sleep schedules, especially in children and adolescents. In a 6-night sleep restriction study (6.5–8.0 hr spent in bed each night) done in American children (6.5–12.9 years old) at home, Fallone found that 4 of 72 (6%) children met a priori criteria for noncompliance, and most of the children, including the children as young as 6 years of age, achieved a substantial difference in sleep behavior across different sleep conditions (Fallone et al., 2002). A 3-night home-based sleep restriction study (1 hr less spent in bed each night) conducted in a similar age group (9.1–12.2 years old) in Israel showed that out of 77 total children, 35% did not meet the compliance criteria for restricted sleep; moreover, the younger students in second grade could not comply with the sleep restriction protocol and therefore were not included in the study (Sadeh et al., 2003). However, in a larger scale study in Louisville, KY, only 23 of 162 (14%) 4–8-year-old children who were assigned to a home sleep restriction protocol failed to adhere (Dayyat, Spruyt, Roman, Molfese, & Gozal, 2008), suggesting that home-based sleep manipulations are feasible and applicable to larger cohorts. We should also point out that discrepancies between these results in these studies and the present study may be related to differences in the cultures or socioeconomic backgrounds of the participants or the study procedures. Regarding adolescents, an age group that suffers from insufficient sleep because of social and physical reasons, there is only one American study investigating the feasibility of home-based, multineight sleep restriction protocols (Beebe et al., 2008). They found that 19 of 20 (95%) adolescents (13.9–16.9 years old) successfully complied with a short sleep schedule. In our comparative study, we found that 17 of the 20 (85%) adolescents were compliant, while all 20 young adults were compliant; this difference between young adults and adolescents did not reach statistical significance, which may reflect the low statistical power due to a modest sample size. From these results, we suggest that when conducting a home-based...
Figure 2. Night-by-night sleep variables (mean ± SEM) measured by Actiwatch across regular (solid line) and restricted (dash line) sleep conditions. As shown in Figures 2a and 2b, differences in total sleep time were fairly consistent across nights between the two conditions for the two groups; there was a significant increase in hours of sleep on the fourth night of the young adults’ restricted sleep regime compared to the previous night. A significant time-by-condition interaction effect was found for sleep efficiency in young adults (Figure 2d) but not in adolescents (Figure 2c). In both groups, as shown in Figures 2e and 2f, sleep latency was similar between conditions on the first night, but there was a divergent trend for the subsequent nights as sleep became cumulatively more deprived in the restricted sleep condition.
Figure 3. Night-by-night Stanford sleepiness scores (mean ± SEM) across regular (solid line) and restricted (dash line) sleep conditions (excluding the 3 noncompliant subjects). As shown in Figure 3b, young adults have a significantly higher mean score on the Stanford Sleepiness Scale (SSS) in the restricted sleep condition than in the regular sleep condition (differences in least squares: 0.30, 1.06). No significant differences were observed in the adolescent cohort (Figure 3a). During the fourth night of sleep for the adolescents, there was a lower score on the SSS in the regular sleep condition than in the restricted sleep condition, which trended towards statistical significance ($p = .0491$).

Figure 4. Comparison of reaction time in working memory (WM) tests across regular sleep (white bars) and restricted sleep (grey bars) conditions in young adults and adolescents. Asterisks denote statistical significance $p < .05$. 
sleep restriction study in adolescents, there may be a need for more detailed and well-designed procedures aimed at incentivizing adherence to achieve high compliance rates.

During the sleep restriction week, the scores on the SSS gradually increased up to the 5th day for young adults, suggesting that sleep restriction imposes a cumulative effect on daytime sleepiness during the 5 study days, a finding that has been previously reported in other similar studies (Dinges et al., 1997; Kobayashi et al., 2007; Van Dongen et al., 2003). However, in adolescents there were no differences in SSS scores across the two sleep conditions until the 4th day. Although the average total sleep time (TST) during control conditions was similar (TST: 8.12 hours in adolescents vs. 8.04 hours in young adults), SSS scores were higher in adolescents than in young adults. These findings suggest that adolescents were already sleep restricted during the baseline assessment week, particularly when considering the previously reported need for 9.2 hours of sleep to achieve optimal alertness (Carskadon & Acebo, 2002). Thus, adolescents appear to carry a sleep debt in their daily life and yet appear to have adapted to the ongoing chronic sleep restriction. This sustained adaptation hampered their ability to predict actual sleepiness levels, even during the first few days of experimental sleep restriction. Notwithstanding, in contrast to the smaller changes in SSS scores among adolescents, sleep restriction significantly increased reaction times during simple verbal and arithmetic working memory tasks without affecting overall task accuracy in this group. In young adults, significant changes in SSS scores occurred with sleep restriction but were not accompanied by concomitant changes in the working memory tasks. Our findings therefore resemble the findings in prior reports that demonstrated a discrepancy between subjective sleepiness and cognitive performance after chronic sleep restriction (Van Dongen et al., 2003). It remains unclear whether there are different neurobiological mechanisms responsible for the ability to gauge subjective sleepiness and performing cognitive tasks after chronic sleep restriction. It has been suggested that subjective sleepiness may develop adaptive processes in response to chronic partial sleep deprivation, while objective sleepiness (i.e., measured by the Multiple Sleep Latency Test) monotonically increases during sustained sleep restriction, in contrast with subjective sleepiness, which remains stable (Carskadon & Dement, 1981; Dinges et al., 1997; Drake et al., 2001). Our results reveal that adolescents, one of the most chronically sleep-deprived populations, lack self-awareness of their level of sleepiness in their daily lives, even when their cognitive performance is impaired by such sleep restriction.

Several methodological limitations should be considered in the interpretation of our results. First, Actiwatch is not the gold standard measurement of sleep characteristics, as Actiwatch has low predictive power and overestimated total sleep time and sleep efficiency especially in conditions involving more wakefulness (Paquet, Kawinska, & Carrier, 2007). But by expert consensus (Standards of Practice Committee of the American Academy of Sleep Medicine, 2003), Actiwatch is still accepted as a method to determining sleep–wake patterns in healthy persons and those suspected of circadian rhythm sleep disorders (Beebe et al., 2008; Erickson, 2009). Secondly, pubertal status was not evaluated in our adolescent population. Even though pubertal status, usually rated as Tanner stages, is not directly related to sleep duration in adolescents (Carskadon et al., 1980; Yu et al., 2007), an association between puberty and daytime sleepiness as well as delayed phase preference were found in several research studies (Carskadon, Vieira, & Acebo, 1993; Waldhauser & Steger, 1986). However, our adolescent subjects (13–16 years old) were in the middle to late adolescent stage, and in this age range overall sleep measures parallel those seen in young adult subjects (Carskadon et al., 1980; Richardson et al., 1978). In addition, late adolescent subjects show similar slow wave electroencephalography (EEG) activity responses after total sleep deprivation to those seen in young adults (Jenni, Achermann, & Carskadon, 2005). Therefore, we believe that the effect of puberty on our findings was minimal. Secondly, we were unable to implement the extended sleep schedule, and such intervention could provide insights into the ongoing chronic sleep restriction and its impact on working memory system. This would be particularly relevant considering the effect of prior sleep history on performance after sleep restriction (Rupp, Wesensten, Bliese, & Balkin, 2009). Therefore, it is not clear whether the discrepancy in working memory test results was due to a true difference in the response to sleep restriction between these two groups or to the different prestudy sleep conditions; this issue will definitely need to be clarified in a future study, which will require in-sleep laboratory rather than in-home implementation. In summary, we confirm the efficacy of multnight home-based sleep restriction protocols in adolescents as a valid approach aiming to mimic real-life situations while enabling objective sleep assessments. A 6-hour sleep restriction protocol for 5 days significantly decreased the speed of execution during the working memory tasks in adolescents, but not in young adults. The cognitive changes after chronic sleep restriction were independent of the subjective sleepiness scores. The unique vulnerability of adolescents to subacute sleep restriction in a setting of ongoing chronic sleep restriction is therefore manifest as an inability to perceive sleepiness changes in a timely manner, while cognitive performance is definitely adversely impacted by such a priori “nonsleepy” conditions.

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