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Original Article

The effects of sleep extension on sleep and cognitive performance in adolescents with chronic sleep reduction: An experimental study

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ABSTRACT

Objective: To investigate the effects of gradual sleep extension in adolescents with chronic sleep reduction. Outcome variables were objectively measured sleep and cognitive performance.
Methods: Participants were randomly assigned to either a sleep extension group (gradual sleep extension by advancing bedtimes in the evening) or to a control group (no instruction). Our sample consisted of 55 adolescents (mean age, 15.44 y; 85.5% girls) with symptoms of chronic sleep reduction (loss of energy, shortness of sleep, sleepiness, and irritation). Sleep was monitored with actigraphy over 3 weeks; the first week was the baseline week and the last two weeks were the experimental weeks. Participants in the experimental group were instructed to extend their sleep during the week by gradually advancing their bedtimes by 5 minutes each night. Additionally participants were asked to prevent bedtime shifts on weekend nights. Cognitive performance was assessed before and after the experimental manipulation.
Results: During the last week of the experiment, adolescents in the sleep extension group had earlier bedtimes, earlier sleep onsets, spent more time in bed, and slept longer than adolescents in the control group. These results indicate that the experimental manipulation was successful and that adolescents in the experimental group fell asleep earlier and slept longer than adolescents in the control group. Furthermore some aspects of cognitive performance, especially visuospatial processing, significantly changed in the sleep extension group.
Conclusion: Gradual sleep extension has beneficial effects on adolescents' sleep and is related to changes in some aspects of cognitive performance.

1. Introduction

Research has repeatedly shown that sleep is associated with adolescents' school performance [1]. To perform well in school, adolescents have to rely on a wide range of intellectual abilities including different cognitive functions (e.g., attention, working memory, executive functioning). However, mixed results have been reported by studies addressing the question of whether or not adolescents' cognitive performance is affected by sleep [2–6]. Most studies within this field are cross-sectional studies in which a sample is, for instance, divided into groups based on their sleep (e.g., long vs short sleeper) and these groups are subsequently compared on their cognitive performance. A recent meta-analysis of children's sleep concluded that longer sleep durations positively influence some cognitive domains, namely executive functions and cognitive performance involving multiple cognitive domains. Interestingly, in contrast with findings from adult studies, no significant relationship of sleep duration with sustained attention and memory was found [7].

Studies that experimentally restrict sleep and examine its effect on cognitive performance in children and adolescents are scarce and report mixed results. Randazzo et al. [8] found that sleep restricted 10 to 14-year-old children perform especially poorly on tasks measuring abstract thinking, concept formation, and verbal creativity. However, the effects of sleep restriction on less complex cognitive functions, including measures of memory, learning, and figural creativity were absent. Voderholzer et al. [9] concluded that 14 to 16-year-old adolescents are resilient on divided attention, working memory, psychomotor speed, and psychomotor flexibility following different degrees of sleep restriction. Similarly, Fallone et al. [10] found no differences in response inhibition and sustained attention between a sleep-restricted group (4 h) and an optimized

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sleep group (10 h) who were between the ages of 8 and 15 years. Only a few sleep deprivation studies with adolescents have been published. Gais et al. [11] demonstrated that sleep following learning has a beneficial effect on declarative memory consolidation in an older sample of adolescents aged 17 to 18 years. Results from a sleep deprivation study, including a younger age group (11.7–14.6 y) showed significantly impaired performance on a problem-solving task and a word memory task but not on a listening attention and serial alternation task [12]. The studies described here greatly differ in their operationalization of cognitive performance and in study design; therefore, it is difficult to draw general conclusions of the effects of sleep on children's and adolescents' cognitive performance.

The experimental studies described above all focus on the effects of sleep deprivation or sleep restriction on cognitive performance. However, such studies have little ecologic validity. On the other hand, the effects of experimentally extended sleep are of particular interest as such results can contribute to important treatment strategies for schools, parents, and clinicians. Despite this need, the study by Sadeh et al. [13] is the only experiment to date that investigated the effects of sleep extension on children's cognitive performance. In this study school-aged children were instructed to either extend or restrict their sleep for three consecutive nights while their cognitive performance was measured before and after the sleep manipulation. Significant improvement of sleep and some aspects of cognitive performance (performance on the digits forward memory test and continuous performance test) were found for the sleep extension group. It has been shown that children seemed to tolerate a single night of sleep restriction relatively well and that relevant differences only emerge after prolonged periods of restricted sleep [5]. As many adolescents sleep less than their individual sleep need, they may suffer from chronic sleep reduction in their daily lives [14]. Consequently, it can be expected that adolescents with chronic sleep reduction in particular may benefit from extended sleep.

A few aspects have to be considered when adolescents' sleep is experimentally extended. First, their sleep should be extended by gradually advancing bedtimes (e.g., 5 min each day) rather than by rapid changes (e.g., 1 h). Advancing bedtimes gradually has the advantage of not interfering with the nature of the circadian system, which cannot adapt well to such rapid changes. Second, many adolescents compensate for insufficient sleep during the week by extending their sleep at weekends, resulting in irregular sleep patterns and jetlag–like symptoms [15]. To overcome these adverse effects, our experimental study combined gradual sleep extension during school nights with the prevention of bedtime shifts during weekends. With this approach we aimed to investigate if adolescents were willing and able to gradually advance their bedtimes and consequently extend their sleep in their home environment, and to gain more insight into the effects of the experimental manipulation on cognitive performance in adolescents with high chronic sleep reduction.

2. Methods

2.1. Participants

Participants from an earlier survey on sleep and daytime functioning were included in our experimental study if their age was between 12 and 19 years and if they had a score of $\geqslant$40 on the Chronic Sleep Reduction Questionnaire (CSRQ) [14], indicating high chronic sleep reduction [16]. No further exclusion or inclusion criteria were applied.

Sixty adolescents agreed to participate, and 2 adolescents dropped out of the study during the experiment. We excluded one individual because of a technical failure during data collection and 2 because of unreliable data (e.g., actiwatch was worn during the day instead of during the night). Data of 55 adolescents (mean age, 15.44 y [range, 12.76–18.52 y]; 85.5% girls) were analyzed. All fathers (in 7.3% information was missing) and mothers (in 10.9% information was missing) were born in the Netherlands. In 83.6% of the families both parents were employed and in 16.4% only one parent was employed. More than half of adolescents (67.3%) considered themselves as an evening type, 9.1% as a morning type, and 23.6% reported being somewhere in between. Morning and evening types refer to the different chronotypes. Morning types prefer to go to bed early in the evening and spontaneously wake up early in the morning with a good level of awareness. In contrast evening types go to bed late at night and spontaneously wake up late in the day [17].

The 2 groups (sleep extension group, $n = 28$; control group, $n = 27$) did not differ significantly in age ($t[53] = -1.37$; $p = .18$), self-reported sleep need ($t[53] = .95$; $p = .35$), depression ($t[53] = -.23$; $p = .82$), attention problems ($t[53] = .35$; $p = .73$) and chronotype ($t[53] = 1.87$; $p = .07$). Furthermore, the proportion of boys and girls was not significantly different in the 2 groups ($p = .37$, Fisher exact test), but the number of boys was small in both groups (sleep extension group, $n = 5$; control group, $n = 3$).

2.2. Procedure

The study was approved by the Ethical Committee of the Research Institute of Child Development and Education University of Amsterdam. Half of the data were collected in the spring of 2011 and the other half in autumn of 2011. We obtained active informed consent from adolescents and parents. Sleep was monitored during the experiment using actigraphy. Additionally, adolescents completed online sleep diaries. The baseline week started on a Friday night. Adolescents' sleep diaries were checked daily and participants were contacted by telephone when inconsistencies were observed or when they had not filled in their sleep diary. During the baseline week participants completed computerized tests in school that measured cognitive performance (pretest). Participants were individually tested by a trained researcher in a separate room at school for approximately 70 minutes. Data were saved locally on researchers' computers. Verbal task instructions were given before each task, emphasizing performance speed and accuracy. To ensure that adolescents understood the instructions correctly, practice trials were performed before task assessment.

After the baseline week participants were randomly assigned to the sleep extension group or to the control group. A personal sleep schedule was sent to each participant in the sleep extension group and was individually explained over the telephone. The experimental week started on a Sunday night. However, to overcome weekend effects participants in the sleep extension group also were asked not to sleep in on Sunday morning (delay their rise time by maximally 1 h when compared to their rise time during the week). On the last day of the experiment (Friday), cognitive performance was tested in school (posttest). The time of day at which participants were tested was randomly assigned across participants and conditions. All participants received a 30-Euro gift voucher and a summary of their actigraphy data of the baseline week. Schools, parents, and participants received a summary of the study results. Fig. 1 illustrates the design of the study.

2.3. Experimental manipulation

2.3.1. Sleep extension group

Participants received a personal sleep schedule in which bedtimes, lights-off times, and rise times were provided for each day. We used their mean bedtimes, lights-off times, and rise times

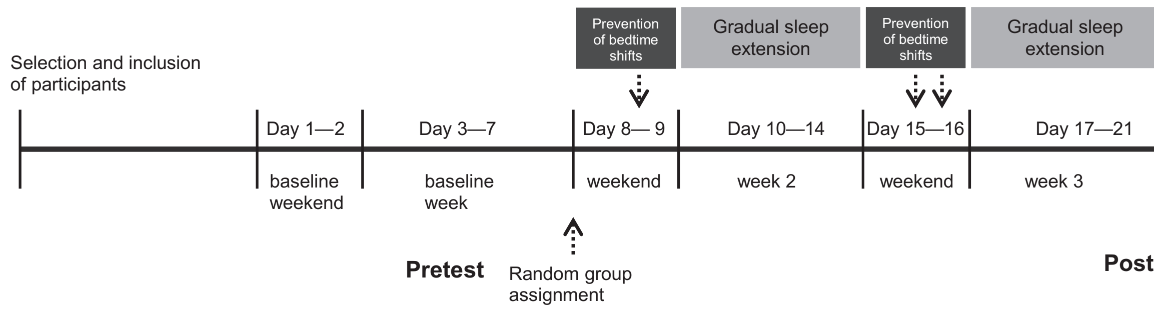

Fig. 1. Graphic illustration of the experiment.

as reported in the sleep diaries to calculate their starting bedtimes and lights-off times. During the following school nights their bedtimes and lights-off times were advanced by 5 minutes (gradual sleep extension) each day. The bedtime and lights-off time for the first night was 10 minutes earlier than their mean bedtime and lights-off time. Moreover at the end of the experiment, adolescents' bedtimes and lights-off times were 55 minutes earlier than their bedtimes and lights-off times during the baseline week. Advancing sleep by approximately 1 hour was inspired by previous research [13]. Bedtimes and lights-off times during the weekends were equal to the Friday night before the weekend, and participants were allowed to delay their rise time by a maximum of 1 hour compared to their weekend rise times. Additionally, together with their individual sleep schedule, they received an overview of sleep hygiene rules such as limiting the use of social media (e.g., 'do not play video games or watch television 1 h prior to your bedtime'), limiting consumption of drinks with caffeine (e.g., 'make sure that you don't drink coffee, tea, cola, or cocoa after 8 PM'), napping behavior (e.g., 'don't nap during the day. If you need to take a nap make sure that it does not take longer than 30 min, and don't nap during the 4 h before your bedtime'), and optimizing the sleep environment (e.g., temperature, light/dark, silence ['make sure that you dim the light at least 1 h prior to your bedtime. In the morning open the curtains immediately']) [18]. Providing these rules aimed at optimizing their sleep environment and consequently helping participants to fall asleep.

2.3.2. Control group

The control group did not receive any instructions regarding their sleep.

2.4. Measurements

2.4.1. Chronic sleep reduction

Chronic sleep reduction was measured with the CSRQ [14]. The 20-item CSRQ measures symptoms of insufficient or poor sleep and consists of 4 scales: (1) shortage of sleep (6 items [e.g., 'I am a person who does not get enough sleep']); (2) irritation (5 items ['Others think that I am easily irritated']); (3) loss of energy (5 items [e.g., 'I am active during the day']); and (4) sleepiness (4 items [e.g., 'Do you feel sleepy during the day?']) with reference to the previous 2 weeks. Each question has 3 ordinal response categories ranging from 1 to 3 with higher scores indicating more chronic sleep reduction. The CSRQ is based on the assumption that symptoms of insufficient or poor sleep only occur when sleep concerns have occurred over a long time period. Measuring symptoms of insufficient or poor sleep rather than sleep duration directly has the advantage that individual sleep need is considered. Using the CSRQ enables all adolescents that regularly experience poor sleep or obtain less sleep than they would need to function optimally throughout the day to be identified. The CSRQ is a reliable and valid measurement tool for chronic sleep reduction [16].

2.5. Sleep

2.5.1. Actigraphy

Participants' sleep activity was monitored using AW4 actiwatches (Cambridge Neurotechnology Ltd, Cambridge, UK). Actigraphy involves use of a wristwatch–like portable device that can record movements over an extended period of time (e.g., a few wks). Actigraphy is known to be a reliable and valid measure to study sleep in a natural environment [19,20]. Participants were instructed to wear the actiwatch on their nondominant wrist when going to bed and to remove it after getting up. We assessed sleep onset latency (SOL) (time between individuals bedtime and sleep onset); time in bed (TIB) (time between participants' bedtime and rise time); total sleep time (TST) (number of minutes that participants actually slept, which is the time between sleep onset and sleep offset corrected for wake times); wake time after sleep onset (WASO) (wake time between sleep onset and wakeup time in the morning); and sleep efficiency (defined as $100 \times TST/TIB$), which is the percentage of uninterrupted night sleep. Information regarding bedtimes (bedtime and rise time) from online sleep diaries was used to define the sleep scoring interval. Nocturnal activity data were logged at 1-minute intervals and scored with the Actiwatch Sleep Analysis 7 software. As recommended by the manufacturer, we used the medium sensitivity sleep algorithm. It has been shown that this algorithm corresponds well with polysomnographic estimates [20]. To minimize the influence of artifacts, it was advised that we visually inspect actigraphy data and compare them with the information provided in the daily sleep diaries [21]. Therefore, we visually examined all actigraphy data and corrected them where deemed necessary (e.g., removed days of which participants were ill). The actigraphy data were analyzed with linear mixed-model analyses, which could handle incompleted data. Using this statistical method has an advantage, as removal of these data do not negatively affect the result.

2.5.2. Cognitive performance

We used 3 tasks from the Amsterdam Neuropsychological Tasks program [22] to assess cognitive performance (i.e., simple reaction time, visuospatial processing, and divided attention). In these tasks test stimuli are presented on a computer screen. Participants have to respond to the stimuli by pressing the right (yes for right-handed, no for left-handed participants) or the left (no for right-handed, yes for left-handed participants) mouse button. The following parameters were calculated for each task including, speed (mean reaction time [RT] across all correct responses were computed in milliseconds as an index for speed and information processing), accuracy of processing (the mean proportion of errors was used as an index of accuracy of processing), and overall

Fig. 2. Fixation cross and stimulus of the simple reaction time task.

performance efficiency. Due to the fact that the proportion of errors is related to the response speed, several strategies have been proposed to deal with this concern. It has been shown that a score that combines speed and accuracy would be a better representation of the overall performance efficiency than interpreting RTs and error rates alone [23]. For this reason we used the suggested measure as an indication of overall performance efficiency as follows, mean correct RT divided by the proportion of correct responses (RT/*p* [correct]). Consequently, lower scores on this measure indicated better overall performance efficiency. Therefore, this measure should particularly be used when interpreting changes in cognitive performance.

2.5.3. Simple RT

Simple RT was measured with the baseline speed task. In this task a fixation cross is displayed on the computer screen, which changes into a white square (signal) (Fig. 2). Participants were asked to respond to this signal by pressing the mouse key as fast as possible. After the mouse button was pressed the cross reappeared. Timing between signals was controlled by a random postresponse interval of 500 to 2500 milliseconds. The task consisted of 2 parts with 32 trials for each index finger. For the analyses we used the overall scores for both trials together.

2.5.4. Visuospatial processing

The visuospatial processing task measures the manipulation and monitoring of content that is stored in the working memory. Participants had to memorize a visuospatial pattern (a 3×3 matrix consisting of 6 white and 3 red squares) (Fig. 3). Afterwards 4 pattern matrices were presented and participants had to detect the memorized matrix. The test consisted of 80 trials of which 50% were target trials. Of the other 40 trials of nontarget patterns, half looked similar to the target pattern, and the other half looked dissimilar to the target pattern.

2.5.5. Divided attention

We used a divided attention (letter detection) task to assess divided attention. As a consequence of imposed working memory demand, the task required controlled information processing. In this task participants were asked to memorize one or more letters (memory load) and afterwards detect the letters in 4 presented letters. The memory load was increased across task parts by increasing the number of letters to be detected in the presented signals from 1 to 3 in parts 1, 2, and 3, respectively. The task parts consisted of 40, 72, and 96 trials, respectively, each with 50% target trials (yes key) and 50% nontarget trials (no key).

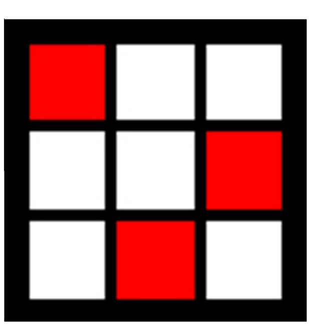

Fig. 3. Visuospatial pattern of the visuospatial processing task that had to be memorized.

3. Analyses

3.1. Experimental manipulation check: changes in sleep (actigraphy)

To examine changes in sleep and consequently check if the experimental manipulation was successful, we used linear mixed-model analyses. The daily measured observations were considered as nested within participants. As mixed-model analyses allow inclusion of participants with incomplete data [24], all participants that provided baseline data (regardless of missing data at one or more assessment points) were included in the analyses. We fitted a model with a random intercept (to consider individual differences at baseline) and regression coefficients that represented deviations from baseline in the second and third week and in the weekends (representing time effects during the 3 wks of the experiment). To test if the 2 groups varied in changes in sleep, we added interaction effects (representing additional experimental effects in the sleep extension group). All analyses included age and season (spring vs autumn) as control variables. As the number of boys was small in both groups, gender was not included as a control variable.

3.2. Changes in cognitive performance

We used repeated analysis of covariance measures to test the effects of sleep extension on changes in cognitive performance. After outliers were removed for each outcome measure ($\alpha = .001$), we conducted the analyses for each outcome variable separately, using group (sleep extension vs control group) as between-participant factor and time (pretest and posttest) as the repeated within-participant factor. Age and season were used as control variables.

4. Results

4.1. Experimental manipulation check: changes in sleep (actigraphy)

Table 1 gives mean and standard deviation for the sleep variables for the baseline week, the last week, the baseline weekend, and the last weekend. Results from the linear mixed-model analyses are presented in Table 2. The time effects in the control group are given in the top half of the table, whereas the time effects in the sleep extension group are obtained by adding the additional experimental effects to the time effects. The sleep extension and the control group did not differ on any of the sleep variables during the baseline week. We did not find seasonal effects showing that the group tested in autumn did not significantly differ in sleep variables from the group tested in spring. In comparison to younger participants, older participants had later bedtimes and later sleep onset times; they woke and got up later and had shorter SOLs.

Bedtimes, sleep onset times, wakeup times, and rise times were delayed during the baseline weekend, resulting in longer TIBs and TSTs compared to the baseline week. Furthermore SOLs were significantly shorter during the baseline weekend than during the baseline week.

Participants in the sleep extension group had earlier bedtimes. Although their SOLs had significantly increased, they also

Table 1
Mean and standard deviation of sleep variables for the sleep extension and for the control group (actigraphy).

	Sleep extension group				Control group			
	Baseline week	Week 3	Baseline weekend	Weekend 3	Baseline week	Week 3	Baseline weekend	Weekend 3
Bedtime (h:min)	23:12 (00:46)	22:28 (00:52)	01:14 (02:10)	23:01 (01:01)	23:02 (00:50)	23:06 (00:45)	00:09 (00:52)	00:21 (01:32)
Sleep onset (h:min)	23:28 (00:44)	22:59 (00:51)	01:26 (02:08)	23:20 (00:58)	23:27 (00:40)	23:35 (00:42)	00:29 (00:53)	00:42 (01:29)
Wakeup time (h:min)	7:41 (00:41)	7:27 (00:40)	9:53 (01:49)	8:20 (00:53)	7:35 (00:46)	7:37 (00:45)	09:19 (01:09)	09:48 (01:22)
Rise time (h:min)	7:46 (00:42)	7:28 (00:39)	9:56 (01:50)	8:25 (00:52)	7:39 (00:48)	7:38 (00:45)	09:25 (01:12)	09:54 (01:22)
Sleep onset latency (h:min)	00:16 (00:14)	00:31 (00:21)	00:12 (00:09)	00:19 (00:18)	00:24 (00:23)	00:29 (00:20)	00:21 (00:21)	00:22 (00:22)
Time in bed (h:min)	8:33 (00:38)	9:03 (00:43)	8:42 (01:14)	9:24 (01:00)	8:36 (00:49)	8:34 (00:43)	09:16 (01:18)	09:33 (01:39)
Total sleep time (h:min)	6:56 (00:32)	7:09 (00:36)	7:18 (01:08)	7:35 (00:55)	6:54 (00:45)	6:49 (00:42)	07:30 (01:07)	07:40 (01:20)
Wake time after sleep onset (h:min)	1:18 (00:21)	1:19 (00:20)	1:09 (00:18)	1:25 (00:24)	1:15 (00:24)	1:14 (00:21)	01:20 (00:32)	01:26 (00:28)
Sleep efficiency (%)	81.24 (5.12)	79.15 (4.65)	83.75 (4.04)	80.64 (5.80)	80.61 (6.82)	79.70 (5.55)	81.01 (7.87)	80.35 (5.24)

had earlier sleep onset times during the second and third week than participants in the control group (Table 2). Hence adolescents in the sleep extension group spent more TIB and slept longer. Furthermore, participants in the sleep extension group went to bed earlier, fell asleep earlier, and woke and got up earlier during the second and third weekend. These changes indicate that their sleep schedule was advanced. The 2 groups did not significantly differ in sleep efficiencies and WASO times.

4.2. Changes in cognitive performance

Table 3 provides mean, standard deviation, and test statistics for all outcome variables.

4.2.1. Simple RTs

Speed did not significantly change from the pretest to the posttest. Furthermore, the sleep extension group did not significantly differ from the control group in changes in speed (Table 3). No measure of performance accuracy exists for this task, so no accuracy score and no score for the overall performance efficiency could be calculated.

4.2.2. Visuospatial processing

RTs on correct responses decreased from the pretest to the posttest in both groups. However, the significant time and group interaction effects indicate that RTs on correct responses significantly decreased more in the sleep extension group than in the control group (Table 3 and Fig. 4). Although not significant at the .05 level, accuracy decreased from the pretest to the posttest in the sleep extension group, which was not the case in the control group ($p = .06$). At the end of the experiment, both groups were better on the overall efficiency performance variable; however, the sleep extension group improved even more than the control group (Table 3 and Fig. 4).

4.2.3. Divided attention

We found a time effect for all variables in which adolescents in both groups became faster on correct responses and became less accurate but developed a better overall performance efficiency. However, the sleep extension group became significantly faster on correct responses than the control group (Table 3 and Fig. 4). In comparison to participants in the control group, participants in the sleep extension group had increased error rates from the pretest to the posttest (Table 3 and Fig. 4). Despite this negative effect, the 2 groups did not experience significantly different changes on their overall performance efficiency.

5. Discussion

Our study demonstrates that adolescents are willing and able to advance their bedtimes and sleep onset times on school nights and consequently extend their sleep. Furthermore, we showed that different changes in cognitive performance occurred in the experimental group and in the control group. Although changes in performance in the experimental group were no different from the control group in regard to speed in a simple RT task, speed of correct responses increased in tasks assessing cognitive performance that involves visuospatial processing and divided attention. In contrast with the control group, the sleep extension group had increased error rates from the pretest to the posttest; however, the overall process efficiency was not negatively affected. Therefore, our study is the first experimental study to demonstrate that gradual sleep extension is possible in adolescents' home environment and that it causes changes in cognitive performance when applied to adolescents with chronic sleep reduction.

Our data show that adolescents in the sleep extension group followed their bedtime instructions well. Adolescents in the experimental group had earlier bedtimes, earlier sleep onset times, longer TIBs, and longer TSTs during the third week. Although their SOLs increased during the experimental weeks, they fell asleep earlier than those in the control group. Based on these results, we conclude that it is indeed possible to shift adolescents' bedtimes and extend their sleep durations by gradual sleep extension on school nights and to prevent bedtime shifts during the weekend. Additionally, participants in the experimental group advanced their sleep schedule on the weekend, as they went to bed earlier, fell asleep earlier, and woke and got up earlier during the weekends. We did not find significant changes in sleep efficiency and WASO times; however, although the results were not significant, sleep efficiencies decreased in the sleep extension group. This result is in line with previous research, which shows that longer TIBs are associated with lower sleep efficiencies [25]. These changes in sleep justify the conclusion that the experimental manipulation of our study was successful.

Speed in general (RT), as measured by a simple RT task did not significantly change from the pretest to the posttest and the 2 groups did not significantly differ in changes over time. Sadeh et al. [13] also found that children who extended their sleep by at least 30 minutes did not significantly improve on the simple RT task. At present our study is the only study that has investigated the effects of sleep extension by advancing bedtimes on adolescents' cognitive performance and that has consequently addressed the causal relationship between sleep and cognitive performance. However, experimental sleep restriction or sleep deprivation studies focus on the same relationship from a different angle, as they aim to gain more insight into the same relationships. Previous

Table 2
Effects of gradual sleep extension on sleep variables (actigraphy).

	Bedtime	Sleep onset	Wakeup time	Rise time	Sleep onset latency	Time in bed	Total sleep time	Wake time after sleep onset	Sleep efficiency
	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)	β (SE)
*Time effects**									
Baseline week (intercept)	18.69 (1.13)***	19.80 (1.11)***	4.67 (.79)***	4.74 (.81)***	.97 (.31)**	10.30 (.94)***	8.22 (.89)***	.90 (.59)	81.37 (8.45)***
Week 2 (vs baseline week)	.18 (.07)*	.08 (.08)	−.08 (.12)	−.08 (.12)	−.11 (.04)**	−.34 (.13)**	−.16 (.11)	−.05 (.04)	.61 (.56)
Week 3 (vs baseline week)	.15 (.08)	.22 (.09) *	.05 (.12)	.04 (.12)	.06 (.05)	−.11 (.14)	−.15 (.11)	−.05 (.05)	−.90 (.62)
Baseline weekend (vs baseline week)	1.10 (.22)***	1.01 (.22)***	1.93 (.23)***	1.98 (.24)***	−.09 (.05)*	.76 (.23)***	.66 (.20)***	.12 (.06)	.78 (.71)
Weekend 2 (vs baseline weekend)	.25 (.30)	.25 (.30)	.27 (.31)	.28 (.31)	−.00 (.05)	−.11 (.37)	−.02 (.31)	−.04 (.09)	−.34 (.83)
Weekend 3 (vs baseline weekend)	.22 (.26)	.27 (.26)	.47 (.28)	.45 (.28)	−.01 (.06)	.39 (.27)	.20 (.24)	.10 (.08)	−.68 (.86)
Additional experimental effects in the sleep extension group									
Sleep extension group baseline week (vs control group baseline week)	.02 (.19)	−.11 (.19)	.07 (.17)	.08 (.18)	−.11 (.06)	.04 (.20)	.09 (.18)	.04 (.10)	.68 (1.40)
Sleep extension group week 2 (vs control group week 2)	−.47 (.10)***	−.29 (.12)**	−.16 (.16)	−.18 (.16)	.18 (.06)***	.39 (.18)*	.22 (.16)	.01 (.06)	−.71 (.76)
Sleep extension group week 3 (vs control group week 3)	−.83 (.11)***	−.62 (.12)***	−.26 (.17)	−.25 (.17)	.17 (.07)*	.60 (.20)**	.38 (.16)*	.04 (.07)	−1.32 (.85)
Sleep extension group baseline weekend (vs control group baseline weekend)	.78 (.32)*	.80 (.32)*	.09 (.33)	.03 (.34)	.03 (.06)	−.69 (.33)*	−.40 (.29)	−.23 (.09)**	1.16 (1.01)
Sleep extension group weekend 2 (vs control group weekend 2)	−1.07 (.42)**	−.96 (.42)*	−.86 (.42)*	−.81 (.43)	.04 (.07)	.40 (.50)	.06 (.43)	.16 (.12)	−1.31 (1.16)
Sleep extension group weekend 3 (vs control group weekend 3)	−2.17 (.36)***	−2.09 (.37)***	−1.65 (.39)***	−1.61 (.39)***	.08 (.09)	.52 (.38)	.24 (.34)	.17 (.11)	−1.84 (1.21)
Control variables									
Age	.28 (.07)***	.23 (.07)**	.18 (.05)***	.18 (.05)***	−.04 (.02)*	−.11 (.06)	−.08 (.06)	.02 (.04)	−.03 (.53)
Season	.08 (.19)	.10 (.19)	−.02 (.13)	−.02 (.14)	−.02 (.05)	−.10 (.16)	−.08 (.15)	−.01 (.10)	−.56 (1.42)

The time effects (representing time effects during the 3 wks of the experiment) refer to both groups. For the sleep extension group the additional experimental effects have to be added. As a result the top half of the table should be used to interpret the effects of the control group and the bottom half to interpret the effects of the experimental group.
*$p \leqslant .05$; **$p \leqslant .01$; ***$p \leqslant .001$.

experimental research in children and adolescents has demonstrated that sleep restriction and sleep deprivation especially affects higher-order cognitive functions rather than performance on simple RT tasks [7,8]. These findings differ from results that have been reported from sleep deprivation studies in adults, which demonstrated that sustained attention was highly affected by chronic and total sleep deprivation [26,27]. Differences in designs of adult studies and studies that include children or adolescents may explain these inconsistencies. Furthermore differences may result from the fact that independent from the amount of sleep obtained, sustained attention over a prolonged time period, which is needed for all cognitive performance tasks, may be difficult for adolescents. This idea would suggest a ceiling effect of sustained attention in adolescents, which is not influenced by other factors such as sleep.

Adolescents in the sleep extension group had faster RTs on correct responses for visuospatial processing; however, the proportion of errors also increased. As participants also became faster on correct responses, we did not find an adverse effect on their overall performance efficiency due to the result that overall performance efficiency improved even more in the sleep extension group than in the control group. Moreover, the relationship between speed and error rate changed in the sleep extension group. One explanation for this result may be that adolescents developed more efficient cognitive performance strategies when extending their sleep. An alternative explanation could be that the effects on this task were moderated by alertness at the time of testing, such that the sleep extension group was more rested and alert and thus performed faster.

Table 3
Mean, standard deviation, and test statistics of cognitive performance for the sleep extension group and the control group.

	Sleep extension group		Control group		Time effect	Time*group effect
	Pretest	Posttest	Pretest	Posttest		
Simple reaction time						
Speed	267.00 ± 29.51	264.04 ± 26.47	272.60 ± 24.58	272.36 ± 27.63	F (1,49) = .24	F (1,49) = .05
Visuospatial processing						
Speed	1056.69 ± 176.38	846.08 ± 138.40	1038.38 ± 156.00	918.27 ± 128.85	F (1,48) = 122.42***	F (1,48) = 10.05**
Accuracy (proportion errors)	.09±.05	.12±.07	.10±.04	.09±.04	F (1,48) = 2.05	F (1,48) = 3.80
Overall efficiency of performance	1184.62 ± 167.34	948.30 ± 127.32	1158.92 ± 146.34	1026.68 ± 136.00	F (1,48) = 129.34***	F (1,49) = 11.52***
Divided attention						
Speed	712.81 ± 82.30	600.71 ± 75.77	695.59 ± 76.13	616.73 ± 81.42	F (1,49) = 139.87***	F (1,49) = 4.12*
Accuracy (proportion errors)	.05±.02	.07±.04	.05±.02	.05±.03	F (1,49) = 7.49,**	F (1,49) = 6.18*
Overall efficiency of performance	799.54 ± 86.29	684.08 ± 72.26	781.24 ± 86.59	684.19 ± 81.88	F (1,49) = 133.69***	F (1,50) = 1.26

The main effects for group were all not significant ($p > .05$).
*$p \leqslant .05$; **$p \leqslant .01$; ***$p \leqslant .001$.

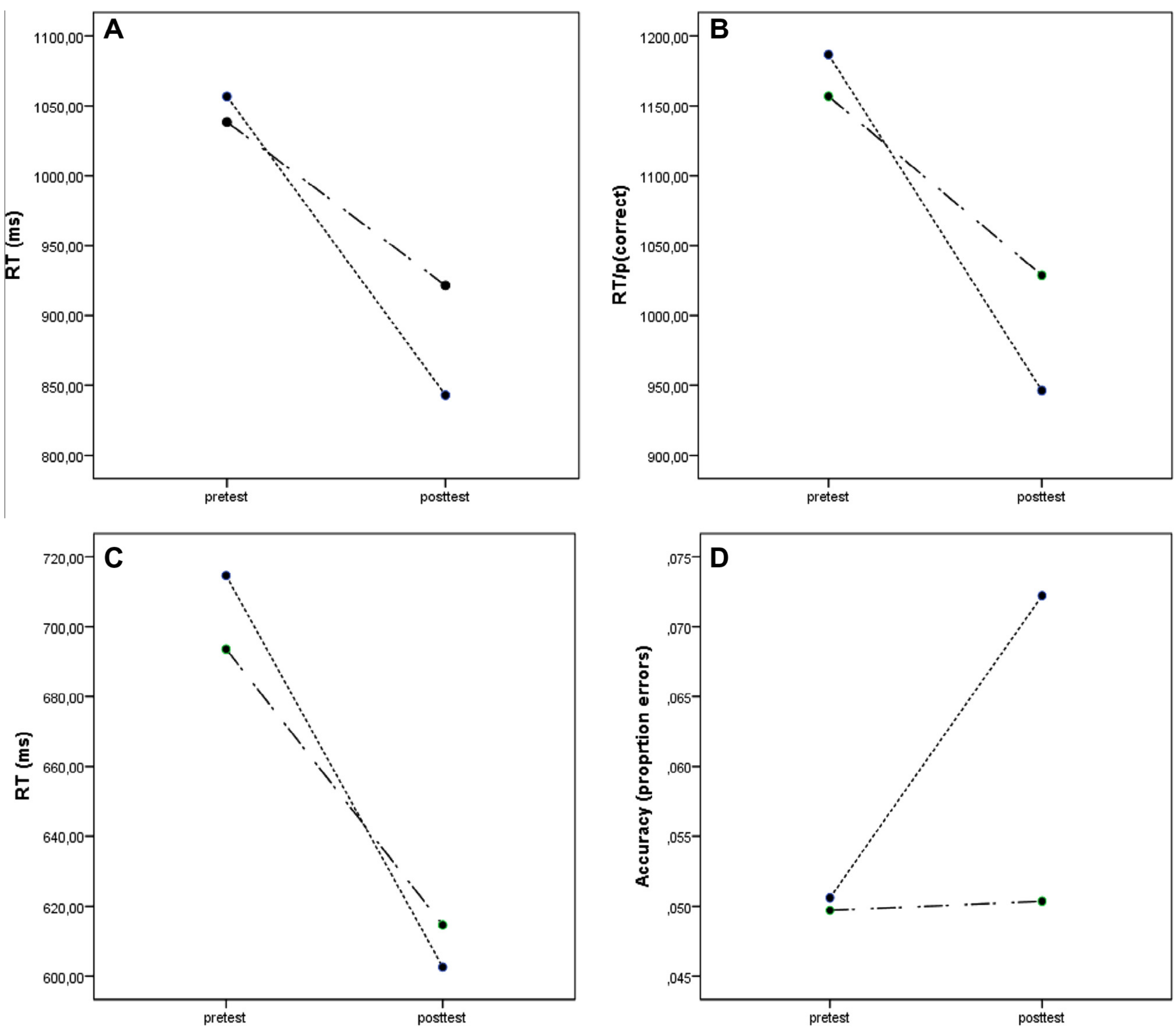

Fig. 4. Graphic representation of changes in cognitive performance in the experimental group and in the control group. (A) Changes in speed of visuospatial processing; (B) changes in overall efficiency of visuospatial processing; (C) changes in speed of divided attention; (D) changes in accuracy (proportion errors) of divided attention. Sleep extension group (••••); Control group (• – •).

The question remains if specific changes in sleep actually caused changes in cognitive performance. Therefore we repeated the analyses with changes in sleep parameters and their interactions with time as covariates. Results from these analyses revealed that it was especially changes in bedtimes on school that influenced changes in cognitive performance. More specifically, the more adolescents advanced their bedtimes during the third week the more they improved on the cognitive performance tasks. However, as their bedtimes were advanced until the last day of the experiment and aggregated covariates had to be used in the additional analyses, results must be carefully interpreted. Therefore, replicating our study and including a stabilization period (e.g., 1 wk) during which participants in the experimental group are asked to follow the last bedtimes is highly recommended.

5.1. Limitations

We feel it is important to mention a few limitations. First the majority of participants were girls; therefore, the results should not be generalized to adolescents and research including more boys is greatly needed. Second although the experimental design allows causal conclusions for the time period of the experiment, nothing can be said about long-term effects of our approach and longitudinal studies addressing this question are recommended. Third the results from our study only hold for the assessment tools used. Whether or not similar results can be found if constructs such as chronic sleep reduction are differently defined and operationalized remains to be investigated. Lastly we did not control for other influential factors such as the amount of caffeine that was consumed in the sample. Such information should be included in upcoming studies, as caffeine use can affect performance on cognitive tasks.

6. Conclusions

The results of our study have several implications. First the changes in sleep in the experimental group show that it is indeed possible to extend adolescents' sleep by advancing their bedtimes, which provides the opportunity to investigate the effects of extended sleep on outcome variables without delaying school start times. Second we demonstrated that this approach also affects cognitive performance, which is needed for school performance. Because it has been shown that longer sleep durations are related to better school performance [1], our findings may be a first step in improving not only cognitive performance but also performance at school.

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All authors declare the absence of financial support and off-label or investigational use. There are no conflicts of interest for any author.

Conflict of interest

The ICMJE Uniform Disclosure Form for Potential Conflicts of Interest associated with this article can be viewed by clicking on the following link: http://dx.doi.org/10.1016/j.sleep.2013.01.012.

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