Chronic sleep reduction in adolescents
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“It is a common experience that a problem difficult at night is resolved in the morning after the committee of sleep has worked on it.”

- John Steinbeck-
Chapter 8

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

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Under review
Abstract

Study Objective: To investigate the effects of gradual sleep extension on cognitive performance in adolescents with chronic sleep reduction.

Design: Experimental design: 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).

Participants: 55 adolescents with chronic sleep reduction (mean age: 15.44 years; 85.5% female).

Interventions/measurements: Sleep was monitored with actigraphy during three weeks, the first week was the baseline week, the last two weeks were the experimental weeks. 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 the control group. Furthermore, some aspects of cognitive performance, especially visuo-spatial processing, improved significantly in the sleep extension group.

Conclusion: Gradual sleep extension has beneficial effects on sleep and on some aspects of cognitive performance in adolescents with chronic sleep reduction.
8.1. Introduction

It has repeatedly been shown that sleep is associated with adolescents’ school performance [1]. In order to perform well at 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 whether or not adolescents’ cognitive performance is affected by sleep [e.g., 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., good versus poor sleeper, long versus short sleeper) and these groups are subsequently compared on their cognitive performance. A recent meta-analysis of children’s sleep concluded that some cognitive domains, namely executive functions and cognitive performance involving multiple cognitive domains, are positively affected by longer sleep durations. Interestingly, in contrast with findings from adult studies, no significant relationship of sleep duration with sustained attention and memory was found [7].

Studies in children and adolescents that experimentally restrict sleep and examine its effects on cognitive performance are scarce and report mixed results. Randazzo, Muehlbach Schweitzer, and Walsh [8] found that sleep restricted children perform especially worse 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 and colleagues [9] concluded that adolescents are quite resilient on divided attention, working memory, psychomotor speed, and psychomotor flexibility following different extents of sleep restriction. Similarly, Fallone, Acebo, Arnedt, Seifer, and Carskadon [10] found no differences of response inhibition and sustained attention between a sleep restricted (4hrs) and an optimized sleep group (10hrs). Gais, Luca, and Born [11] on the other hand demonstrated that sleep following learning has a beneficial effect on declarative memory consolidation. More than sleep restriction studies, total sleep deprivation studies in children and adolescents involve ethical problems. This may explain why to date only one study has been published that examined the effects of total sleep deprivation in young adolescents. Results from this study show significantly impaired performance on a problem-solving task and a word memory task but not on a listening attention and serial alternation task [12]. Taken together, the studies highly differ in their operationalization of cognitive performance and in study design and it is therefore difficult to draw generalizable conclusions. Generally, it can be stated that sleep seems to play a role in at least some domains of cognitive performance (especially performance that involves higher order cognitive functions), though effects are rather subtle and not very robust.
The above-described experimental studies all focus on the effects of sleep deprivation or sleep restriction on cognitive performance. However, 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, Gruber, and Raviv [13] is the only experiment 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 were found for the sleep extension group. The absence of similar studies in adolescents constitutes an important research gap because many adolescents sleep less than their individual sleep need, and consequently suffer from naturally induced chronic sleep reduction in their daily life [14]. It has been shown that children seem to tolerate a single night of sleep restriction relatively well, whereas relevant differences only emerge after prolonged periods of restricted sleep [5]. It can therefore be expected that adolescents that have experienced sleep loss for a longer time period may benefit from extended sleep in particular. Furthermore, adolescence is a time during which important brain developments, especially in the prefrontal cortex, occur [15], suggesting that the effects of sleep on cognitive performance are especially present in this age group.

However, as the circadian system changes only slowly, adolescents’ sleep should gradually be extended by stepwise advancing bedtimes. In addition, many adolescents compensate insufficient sleep during the week by extending their sleep in the weekends, resulting in irregular sleep timings and jet-lag like symptoms [16]. To overcome these adverse effects, this experimental study combines gradual sleep extension during school nights with the prevention of bedtime shifts during weekends. With this approach the present study aims to gain more insight into the effects of gradual sleep extension on cognitive performance in adolescents with high chronic sleep reduction.

8.2. Method
8.2.1. Participants

60 adolescents agreed to participate, two adolescents dropped out of the study during the experiment. We excluded one individual because of a technical failure during the data collection and two because of unreliable data. Data of 55 adolescents (mean age: 15.44 years (range from 12.76 to 18.52 years), 85.5 % female) 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 the adolescents considered themselves as an evening type (67.3%), 9.1% as a morning type, and 23.6% reported being something in between.

The two 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), and circadian preference (t(53) = 1.87, p = .07). Furthermore, the proportion of boys and girls was not significantly different in the two groups (p = .37, Fisher’s exact test), however, the number of boys was small in both groups (sleep extension group: n = 5; control group: n = 3).

8.2.2. Procedure

Half of the data were collected in spring 2011 and the other half in autumn 2011. Participants from a preceding survey were included in the experimental study if their age was between 12 and 19 years and if they had a score of ≥ 40 on the Chronic Sleep Reduction Questionnaire (CSRQ) [14], which indicates high chronic sleep reduction [17].

We obtained active informed consent from adolescents and parents. Sleep was monitored during the experiment using actigraphy (see description under Measurements). Additionally, adolescents completed online sleep diaries. The baseline week started on a Friday night. Adolescents’ sleep diaries were daily checked 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 at school measuring cognitive performance (pretest). Participants were tested individually in a separate room at school for about 70 minutes. 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 (see Experimental manipulation for a more detailed description) 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, in order to overcome weekend effects, participants in the sleep extension group were also asked not to sleep in on Sunday morning. On the last day of the experiment (Friday), cognitive performance was tested at school (posttest). 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. Figure 1 illustrates the design of the study.
8.2.3. Experimental manipulation

8.2.3.1. Sleep extension group

Participants received a personal sleep schedule in which bedtimes, light-off times, and rise times were provided for each day. Bedtimes, light-off times, and rise times were based on their mean bedtimes, light-off times, and rise times that they reported during the baseline week. The bedtime/light-off time for the first night was 10 minutes earlier than their mean bedtime/light off time. Bedtimes/light-off times were advanced by five minutes (gradual sleep extension) each night. Bedtimes/light-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 one hour. Additionally, we provided an overview of sleep hygiene rules for the sleep extension group, which included limiting the use of social media, consuming only limited drinks with caffeine, napping behavior, and optimizing the sleep environment (e.g., temperature, light/dark, silence).

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2 Figure 1 in Chapter 8 is equivalent to Figure 1 in Chapter 7.
3 The experimental manipulation in Chapter 8 is equivalent to the experimental manipulation in Chapter 7.
8.2.3.2. Control group

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

8.2.4. Measurements

8.2.4.1. Chronic sleep reduction

Chronic sleep reduction was measured with the Chronic Sleep Reduction Questionnaire (CSRQ) [14]. The 20-item CSRQ consists of four scales: ‘Shortage of Sleep’ (6 items; e.g., ‘I am a person who does not get enough sleep’), ‘Irritation’ (5 items; e.g., ‘Others think that I am easily irritated’), ‘Loss of Energy’ (5 items; e.g., ‘I am active during the day’), and ‘Sleepiness’ (4 items; ‘Do you feel sleepy during the day?’) and refers to the previous two weeks. Each question has three ordinal response categories ranging from 1 to 3, with higher scores indicating more chronic sleep reduction. The CSRQ appears to be a reliable and valid measurement for chronic sleep reduction [17].

8.2.4.2. Sleep

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 weeks). Actigraphy is known to be a reliable and valid measure to study sleep in a natural environment [18,19]. Participants were instructed to wear the actiwatch on their nondominant wrist when going to bed and to remove it after getting up. We assessed: (a) sleep onset latency (SOL): time between individuals’ bedtime and sleep onset, (b) time in bed (TIB): time between participants’ bedtime and rise time, (c) total sleep time (TST): number of minutes that individuals actually slept, which is the time between sleep onset and sleep offset corrected for wake times, (d) wake time after sleep onset (WASO): wake time between sleep onset and wake up time in the morning, and (e) sleep efficiency (defined as $100 \times \frac{TST}{TIB}$): percent of uninterrupted night sleep. Information about bedtimes (bedtime and rise time) from online sleep diaries were used to define the sleep scoring interval. Nocturnal activity data were logged at one minute epochs 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 [19].
8.2.4.3. Cognitive performance

We used three tasks from the Amsterdam Neuropsychological Tasks (ANT) program [20] to assess cognitive performance. 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: (1) speed: Mean reaction time (RT) across all correct responses (in ms) was computed as an index for speed and information processing, (2) speed variability: The mean within-standard deviation of RT across all correct responses was used as a measure of speed variability, (3) accuracy of processing: The mean proportion of errors was used as an index of accuracy of processing, and (4) overall performance efficiency: 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 [21]. Therefore, we additionally used the suggested measure as an indication of overall performance efficiency, which is defined as the mean correct RTs divided by the proportion of correct responses ($RT/p(\text{Correct})$). Consequently, lower scores on this measure indicate better overall performance efficiency.

8.2.4.3.1. Simple reaction time

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). Participants are asked to respond to this signal by pressing the mouse key as fast as possible. After the mouse button was pressed, the cross reappears. Timing between signals is controlled by a random post-response interval of 500 to 2500 ms. The task consists of two parts with 32 trials for each index finger. For the analyses we used the overall scores for both trials together.

8.2.4.3.2. Visuo-spatial processing

This task mainly measures working memory monitoring. Participants have to memorize a visuo-spatial pattern (a 3 x 3 matrix containing of six white ad three red squares). Afterwards, four pattern matrices are presented and participants have to detect the memorized matrix. The test consists of 80 trials of which 50% are target trials. Of the other 40 trials of non-target patterns, half look very similar to the target pattern, the other half look very dissimilar to the target pattern.
8.2.4.3.3. Working memory capacity

We used a divided attention (letter detection) task to assess working memory capacity. This task uses a four-letter display load. The memory load is increased across task parts by increasing the number of letters to be detected in the presented signals from 1 to 3 in part 1, 2, and 3, respectively. The task parts consist of 40, 72, and 96 trials, respectively, each with 50% target trials (‘yes’ key) and 50% non-target trials (‘no’ key).

8.2.5. Analyses

8.2.5.1. Effects on sleep variables (actigraphy)

To examine changes in sleep and the effects of the experimental manipulation, we used linear mixed model analyses. The daily measured observations are considered as nested within subjects. As mixed-model analyses allow inclusion of participants with incomplete data [22], 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 account for individual differences at baseline) and regression coefficients that represent deviations from baseline in the second and third week and in the weekends (representing time effects during the three weeks of the experiment). To test whether the two 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 versus autumn) as control variables. As the number of boys was small in both groups, gender was not included as control variable.

8.2.5.2. Effects on cognitive performance

After removing outliers for each outcome measure (α = .001), we conducted repeated measures ANCOVAs for each outcome variable separately, using ‘group’ (sleep extension versus control group) as between-subject factor and ‘time’ (pre- and posttest) as the repeated within-subject factor. Age and season were used as control variables.

8.3. Results

8.3.1. Effects on sleep variables (actigraphy)

Table 1 gives means and standard deviations 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 sleep extension and the control group did not

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4 The analysis of the sleep variables in Chapter 8 are equivalent to the analyses of the sleep variables in Chapter 7.
5 The results of sleep variables in Chapter 8 are equivalent to the results of the sleep variables in Chapter 7.
differ on any of the sleep variables during the baseline week. We did not find seasonal effects, indicating that the group being tested in autumn did not differ significantly on the sleep variables from the group being tested in spring. In comparison to younger participants, older participants had later bedtimes, later sleep onset times, they woke and got up later, and had shorter SOLs. Bedtimes, sleep onset times, wake up times, and rise times were delayed during the baseline weekend, resulting in longer TIBs and TSTs than during 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 and, although their SOLs increased significantly, also earlier sleep onset times during the second and third week than participants in the control group (see Table 2). Therefore, adolescents in the sleep extension group also spent more time in bed and slept longer (see Figure 2). 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 the timing of their sleep was advanced. The two groups did not differ significantly in sleep efficiencies and WASO times.

![Figure 2. Changes in time in bed and total sleep time for the sleep extension group and the control group separately](image)
Table 1. Means and standard deviations of sleep variables for the sleep extension and for the control group (actigraphy)\(^6\)

<table>
<thead>
<tr>
<th></th>
<th>Sleep extension group</th>
<th>Control group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline week</td>
<td>Week 3</td>
</tr>
<tr>
<td>Bedtime (hrs:min)</td>
<td>23:12 (00:46)</td>
<td>22:28 (00:52)</td>
</tr>
<tr>
<td>Sleep onset (hrs:min)</td>
<td>23:28 (00:44)</td>
<td>22:59 (00:51)</td>
</tr>
<tr>
<td>Wake up time (hrs:min)</td>
<td>7:41 (00:41)</td>
<td>7:27 (00:40)</td>
</tr>
<tr>
<td>Rise time (hrs:min)</td>
<td>7:46 (00:42)</td>
<td>7:28 (00:39)</td>
</tr>
<tr>
<td>Sleep onset latency (hrs:min)</td>
<td>00:16 (00:14)</td>
<td>00:31 (00:21)</td>
</tr>
<tr>
<td>Time in bed (hrs:min)</td>
<td>8:33 (00:38)</td>
<td>9:03 (00:43)</td>
</tr>
<tr>
<td>Total sleep time (hrs:min)</td>
<td>6:56 (00:32)</td>
<td>7:09 (00:36)</td>
</tr>
<tr>
<td>Wake time after sleep onset (hrs:min)</td>
<td>1:18 (00:21)</td>
<td>1:19 (00:20)</td>
</tr>
<tr>
<td>Sleep efficiency (%)</td>
<td>81.24 (5.12)</td>
<td>79.15 (4.65)</td>
</tr>
</tbody>
</table>

\(^6\) Table 1 in Chapter 6 is equivalent to Table 1 in Chapter 7.
Table 2. Effects of gradual sleep extension on sleep variables (actigraphy)^7

<table>
<thead>
<tr>
<th>Time effects^7</th>
<th>Bedtime ( \beta ) (SE)</th>
<th>Sleep onset ( \beta ) (SE)</th>
<th>Wake up time ( \beta ) (SE)</th>
<th>Rise time ( \beta ) (SE)</th>
<th>Sleep onset latency ( \beta ) (SE)</th>
<th>Time in bed ( \beta ) (SE)</th>
<th>Total sleep time ( \beta ) (SE)</th>
<th>Wake time after sleep onset ( \beta ) (SE)</th>
<th>Sleep efficiency ( \beta ) (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline week (intercept)</td>
<td>18.69 (1.13) p &lt; .01</td>
<td>19.80 (1.11) p &lt; .01</td>
<td>4.67 (.79) p &lt; .01</td>
<td>4.74 (.81) p &lt; .01</td>
<td>.97 (.31) p &lt; .01</td>
<td>10.30 (.94) p &lt; .01</td>
<td>8.22 (.89) p &lt; .01</td>
<td>.90 (.59) p &lt; .01</td>
<td>81.37 (8.45) p &lt; .01</td>
</tr>
<tr>
<td>Week 2 (vs. baseline week)</td>
<td>.18 (.07) p = .02</td>
<td>.08 (.08) p = .33</td>
<td>-.08 (.12) p = .52</td>
<td>-.08 (.12) p = .51</td>
<td>-.11 (.04) p = .01</td>
<td>-.34 (.13) p = .01</td>
<td>-.16 (.11) p = .16</td>
<td>-.05 (.04) p = .24</td>
<td>.61 (.56) p = .27</td>
</tr>
<tr>
<td>Week 3 (vs. baseline week)</td>
<td>-.15 (.08) p = .07</td>
<td>.22 (.09) p = .02</td>
<td>.05 (.12) p = .69</td>
<td>.04 (.12) p = .73</td>
<td>.06 (.05) p = .23</td>
<td>-.11 (.14) p = .42</td>
<td>-.15 (.11) p = .20</td>
<td>-.05 (.05) p = .31</td>
<td>-.90 (.62) p = .15</td>
</tr>
<tr>
<td>Baseline weekend (vs. baseline week)</td>
<td>1.10 (.22) p &lt; .01</td>
<td>1.01 (.22) p &lt; .01</td>
<td>1.93 (.23) p &lt; .01</td>
<td>1.98 (.24) p &lt; .01</td>
<td>-.09 (.05) p = .05</td>
<td>.76 (.23) p &lt; .01</td>
<td>.66 (.20) p &lt; .01</td>
<td>.12 (.06) p = .07</td>
<td>.78 (.71) p = .27</td>
</tr>
<tr>
<td>Weekend 2 (vs. baseline weekend)</td>
<td>.25 (.30) p = .40</td>
<td>.25 (.30) p = .42</td>
<td>.27 (.31) p = .38</td>
<td>.28 (.31) p = .37</td>
<td>-.00 (.05) p = .97</td>
<td>-.11 (.37) p = .77</td>
<td>-.02 (.31) p = .95</td>
<td>-.04 (.09) p = .64</td>
<td>-.34 (.83) p = .68</td>
</tr>
<tr>
<td>Weekend 3 (vs. baseline weekend)</td>
<td>.22 (.26) p = .39</td>
<td>.27 (.26) p = .30</td>
<td>.47 (.28) p = .10</td>
<td>.45 (.28) p = .10</td>
<td>-.01 (.06) p = .89</td>
<td>.39 (.27) p = .15</td>
<td>.20 (.24) p = .40</td>
<td>.10 (.08) p = .20</td>
<td>-.68 (.86) p = .43</td>
</tr>
</tbody>
</table>

Additional experimental effects in the sleep extension group

| Sleep extension group baseline week (vs. control group baseline week) | .02 (.19) p = .93 | -.11 (.19) p = .56 | .07 (.17) p = .69 | .08 (.18) p = .63 | -.11 (.06) p = .08 | .04 (.20) p = .86 | .09 (.18) p = .60 | .04 (.10) p = .72 | .68 (1.40) p = .63 |
| Sleep extension group week 2 (vs. control group week 2) | -.47 (1.10) p < .01 | -.29 (.12) p = .01 | -.16 (.16) p = .32 | -.18 (.16) p = .27 | .18 (.06) p < .01 | .39 (.18) p = .03 | .22 (.16) p = .17 | .01 (.06) p = .83 | -.71 (.76) p = .35 |
| Sleep extension group week 3 (vs. control group week 3) | -.83 (.11) p < .01 | -.62 (.12) p < .01 | -.26 (.17) p = .12 | -.25 (.17) p = .14 | -.17 (.07) p < .01 | .60 (.20) p = .01 | .38 (.16) p = .02 | .04 (.07) p = .54 | -.13 (.85) p = .12 |
| Sleep extension group baseline weekend (vs. control group baseline weekend) | .78 (.32) p = .02 | .80 (.32) p = .02 | .09 (.33) p = .78 | .03 (.34) p = .92 | .03 (.06) p = .64 | -.69 (.33) p = .04 | -.40 (.29) p = .16 | -.23 (.09) p = .01 | 1.16 (.101) p = .26 |
| Sleep extension group weekend 2 (vs. control group weekend 2) | -.107 (.42) p < .01 | -.96 (.42) p < .01 | -.86 (.42) p < .01 | -.81 (.43) p < .01 | -.04 (.07) p = .59 | .40 (.50) p = .43 | .06 (.43) p = .89 | .16 (.12) p = .16 | -.13 (1.16) p = .26 |
| Sleep extension group weekend 3 (vs. control group weekend 3) | -.217 (.36) p < .01 | -.209 (.37) p < .01 | -.165 (.39) p < .01 | -.161 (.39) p < .01 | -.08 (.09) p = .34 | .52 (.38) p = .17 | .24 (.34) p = .47 | .17 (.11) p = .13 | -.84 (1.21) p = .13 |

Control variables

| Age | .28 (.07) p < .01 | .23 (.07) p < .01 | .18 (.05) p < .01 | .18 (.05) p < .01 | -.04 (.02) p = .05 | -.11 (.06) p = .07 | -.08 (.06) p = .13 | .02 (.04) p = .55 | -.03 (.53) p = .95 |
| Season | .08 (.19) p = .69 | .10 (.19) p = .62 | -.02 (.13) p = .88 | .02 (.14) p = .89 | -.02 (.05) p = .67 | -.10 (.16) p = .54 | -.08 (.15) p = .81 | -.01 (.10) p = .91 | -.56 (1.42) p = .69 |

Note: ^ The time effects (changes in sleep during the three weeks of the experiment) refer to both groups. For the sleep extension group the additional experimental effects have to be added.

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^ Table 2 in Chapter 6 in equivalent to Table 2 in Chapter 7.
8.3.2. Effects on cognitive performance

Table 3 provides means, standard deviations, and test statistics for all outcome variables.

8.3.2.1. Baseline speed

Speed and speed variability did not change significantly from the pre- to the posttest. Furthermore, the sleep extension group did not differ significantly from the control group in changes on speed and variability in speed (see Table 4). For this task no measure of performance accuracy exists. Therefore, no accuracy score and no score for the overall performance efficiency could be calculated.

8.3.2.2. Visuo-spatial processing

In both groups RTs on correct responses and speed variability decreased from the pre- to the posttest. Still, the significant time*group interaction effect indicates that RTs on correct responses decreased significantly more in the sleep extension than in the control group (see Figure 3). Although not significant at the .05 level, the proportion of errors increased from the pre- to the posttest in the sleep extension group which was not the case in the control group ($p = .06$). Both groups were better on the overall efficiency performance variable, however, the sleep extension group improved even more than in the control group (see Figure 4).

8.3.2.3. Working memory capacity

We found a time effect for all variables, meaning that adolescents in both groups had faster RTs on correct responses, became less accurate, but had a better overall performance efficiency. Furthermore, the sleep extension group became significantly faster on correct responses than the control group (see Figure 5). In comparison to the control group, the proportion of errors increased significantly more in the sleep extension group from the pre- to the posttest (see Figure 6). Despite this increase in errors rates, the two groups did not experience significantly different changes on their overall performance efficiency.
Table 3. Means, standard deviations, and test statistic of cognitive performance for the sleep extension group and the control group

<table>
<thead>
<tr>
<th></th>
<th>Sleep extension group</th>
<th>Control group</th>
<th>Time effect</th>
<th>Time *group effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretest</td>
<td>Posttest</td>
<td>Pretest</td>
<td>Posttest</td>
</tr>
<tr>
<td><em>Baseline speed</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>267.00 ± 29.51</td>
<td>264.04 ± 26.47</td>
<td>272.60 ± 24.58</td>
<td>272.36 ± 27.63</td>
</tr>
<tr>
<td>Variability in speed</td>
<td>55.27 ± 17.47</td>
<td>54.31 ± 18.34</td>
<td>59.36 ± 20.53</td>
<td>67.04 ± 35.82</td>
</tr>
<tr>
<td><em>F (1,49) = .24, p = .63</em></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><em>Visuo-spatial processing</em></td>
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</tr>
<tr>
<td>Speed</td>
<td>1056.69 ± 176.38</td>
<td>846.08 ± 138.40</td>
<td>1038.38 ± 156.00</td>
<td>918.27 ± 128.85</td>
</tr>
<tr>
<td>Variability in speed</td>
<td>262.95 ± 61.95</td>
<td>206.50 ± 49.83</td>
<td>253.94 ± 56.16</td>
<td>212.87 ± 45.86</td>
</tr>
<tr>
<td>Accuracy (proportion errors)</td>
<td>.09 ± .05</td>
<td>.12 ± .07</td>
<td>.10 ± .04</td>
<td>.09 ± .04</td>
</tr>
<tr>
<td>Overall efficiency of performance</td>
<td>1184.62 ± 167.34</td>
<td>948.30 ± 127.32</td>
<td>1158.92 ± 146.34</td>
<td>1026.68 ± 136.00</td>
</tr>
<tr>
<td><em>F (1,48) = 122.42, p &lt;.001</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Working memory capacity</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>712.81 ± 82.30</td>
<td>600.71 ± 75.77</td>
<td>695.59 ± 76.13</td>
<td>616.73 ± 81.42</td>
</tr>
<tr>
<td>Variability in speed</td>
<td>271.68 ± 49.74</td>
<td>212.16 ± 33.93</td>
<td>266.26 ± 59.86</td>
<td>216.97 ± 43.13</td>
</tr>
<tr>
<td>Accuracy (proportion errors)</td>
<td>.05 ± .02</td>
<td>.07 ± .04</td>
<td>.05 ± .02</td>
<td>.05 ± .03</td>
</tr>
<tr>
<td>Overall efficiency of performance</td>
<td>799.54 ± 86.29</td>
<td>684.08 ± 72.26</td>
<td>781.24 ± 86.59</td>
<td>684.19 ± 81.88</td>
</tr>
<tr>
<td><em>F (1,49) = 139.87, p &lt;.001</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. The main effects for 'group' were all not significant (p > .05)
Figure 3. Changes in speed of visuo-spatial processing in the sleep extension group and in the control group.

Figure 4. Changes in overall efficiency of visuo-spatial processing in the sleep extension group and in the control group.
**Figure 5.** Changes in speed of working memory capacity in the sleep extension group and in the control group

**Figure 6.** Changes in accuracy (proportion errors) of working memory capacity in the sleep extension group and in the control group
8.4. Discussion
Inconclusive results have been reported from studies addressing the question whether sleep affects cognitive performance [e.g., 2,3,5]. Furthermore, only few experimental studies have been published investigating the effects of sleep, and especially sleep extension, on cognitive performance. To gain more insight into this causal relationship, we conducted an experimental study that compared a sleep extension group (bedtimes were gradually advanced on school nights and bedtime shifts were prevented on weekend nights) with a control group that did not receive any instructions about sleep. Cognitive performance was assessed at baseline (pretest) and at the last day of the experiment (posttest).

Although this experiment was conducted in participants’ natural environment, which theoretically provides them with the opportunity to neglect the instructions, our data show that adolescents in the sleep extension group followed the instruction of their betimes quite well. As a result, they had earlier bedtimes, earlier sleep onsets times, longer TIBs, and longer TSTs during the third week. Although their SOLs increased during the experimental weeks, they fell asleep earlier than the control group. Furthermore, they advanced their sleep schedule in the weekend as they went to bed earlier, fell asleep earlier, and woke and got up earlier during the weekends. Based on these results, it can be concluded that the experimental manipulation was effective.

Speed in general (RT) and speed variability, as measured by a simple RT task, did not change significantly from the pre- to the posttest and the two groups did not differ significantly in changes over time. This result is at least partly supported by Sadeh and colleagues [13], who found that performance on the simple RT task decreased significantly for children who restricted their sleep or who did not experience changes in sleep, but not for children that extended their sleep by at least 30 minutes. Furthermore, previous research demonstrated that sleep deprivation in children 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 demonstrate that sustained attention is highly affected by chronic and total sleep deprivation [e.g., 23,24]. 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 obtained sleep, sustained attention over a prolonged time period may be difficult for adolescents. This idea would suggest a ceiling effect of sustained attention in adolescents which is not influenced by sleep.

In the sleep extension group adolescents had faster RTs on correct responses for visuo-spatial processing, however, the proportion of errors also increased. Still, as participants also became faster on correct responses, we did not find an adverse effect on
their overall performance efficiency as is apparent by the result that overall performance efficiency enhanced even more in the sleep extension group than in the control group. This result raises the idea that adolescents develop more efficient cognitive performance strategies when extending their sleep. So, gradual sleep extension can be beneficial for higher order cognitive functions which are highly important for adolescents’ school performance. Our results are in line with a recent meta-analysis of the relationship between children’s sleep and cognition which did not find significant effects of sleep on sustained attention and memory (implicit and explicit), whereas higher order cognitive functions, such as executive functions and cognitive domains that involve multiple cognitive functions, were affected by sleep durations [7]. Although this meta-analysis focused on younger children, the present study supports the idea that the effects of sleep on cognitive performance are different in children and adolescents than those being reported in adults.

In conclusion, gradual sleep extension did not affect speed of simple RT tasks, however, speed of correct responses increased in tasks assessing cognitive performance that involve higher order cognitive functions. In contrast with the control group, the sleep extension group had increased error rates from the pre- to the posttest, however, the overall process efficiency was not negatively affected. The present study is the first experimental study that demonstrates that gradually advanced bedtimes and consequently gradual sleep extension can improve cognitive performance when being applied to adolescents with chronic sleep reduction.
8.5. References


