ADOLESCENT SLEEP AND COGNITION

REVIEW OF ADOLESCENT-SLEEP MANIPULATIONS AND OUTCOMES

MSc writing assignment

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ABSTRACT

The changes in sleep patterns of adolescents and the effects they have on cognitive performance are reviewed in this study. Globally, adolescents go to bed later and wake up early, which results in them losing hours of sleep. To investigate the effects this sleep loss has on cognition a literature review was performed using studies that restricted or extended sleep duration of adolescents. Eleven studies that used objective measures of sleep and measured cognitive performances were qualitatively reviewed. The results suggest a detrimental effect of adolescent sleep loss on (simple) attention, as well as selective effects on working memory, short-term memory, and reasoning. Adolescent sleep gain is suggested to have the opposite effect in most of these domains. Studies that investigated the long-term memory effects of sleep are inconclusive. The experimental studies were furthermore evaluated and recommendations for future research are to include objective sleep measures, use cross-over and repeated measurement experimental designs, perform power analyses, and report pubertal-development stages of the studied sample. Because of the limited number of studies with reliable results it is yet to early to compare the effects of sleep loss during adolescence with those during adulthood.

LAYMAN SUMMARY

Teenagers seem to go to bed late but still wake up the same time as children and adults do. This causes teenagers to lose sleep and they, as a result, are sleepy during daytime. Teenager differ on in the way their brain works, whether this difference and the increased sleepiness undermines their cognitive abilities is unknown. This is why researchers in the past have compared the cognitive abilities of teenagers that are only allowed a short amount of sleep with those that have had plenty of sleep. In this study the findings of these sleep studies are discussed, while taking into account how well the experiments were designed and if the conclusions were correctly drawn. Generally, teenagers that lose sleep seem less alert and are less attentive than those that did have enough sleep. Losing sleep also seems to negatively affect the creativity and problem solving of teenagers. The paper ends with suggestions on how to improve future experiments that look at teenage sleep.

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I. INTRODUCTION

The importance of the nightly slumber is easily overlooked by the general public. This is despite the common knowledge that a good night of sleep seems to help recover from physical and mental fatigue whereas a sleepless night is known to wreck havoc on the physical and mental health. Furthermore, the negative effects of sleep deprivation can easily accumulate and, if completely deprived of sleep, it can even lead to death (Rechtschaffen, Gilliland, Bergmann, & Winter, 1983). Scientific enquiry about the (cognitive) effects of sleep has mainly focused on the young-adult population. This study aims to review studies that have investigated the effects of sleep loss during adolescence on cognition.

Sleep can be defined as an active, repetitive, and reversible state of perceptual disengagement from and unresponsiveness to the environment (Carskadon & Dement, 2005). Voluntarily being disengaged from the environment is very odd from a prey-and-predator point of view. The benefits of sleep must be considerable, given that the organism spends one-third of its life in this hallucinogenic and comatose state, which makes it an easy prey. Hence, illuminating what exact benefit is provided by sleep has been the subject of sleep research for the past decades.

One suggested benefit of sleep is that of restoration. The restorative hypothesis perceives sleep as to facilitate cleaning the metabolic by-products and restocking cellular energy reserves of the brain. Cleaning and restocking is required since this is done poorly during normal metabolic brain activity. That these processes occur during sleep is substantiated by research suggesting that the sleep duration in mammals are better predicted by the metabolic rate of the brain than they are by the metabolic rate of the whole body (Savage & West, 2007).

Another suggested benefit of sleep is that it is important for efficient cognition or information processing. The information processing hypothesis suggest that a temporary pause in sensory processing allows for a scale cognition related processes to occur without interference. A large portion of the literature discusses these proposed functions (McCoy & Strecker, 2011; Poe, Walsh, & Bjornes, 2010). Most studies have investigated the effect of sleep loss on cognition and information processing by studying the effects in young human adults. Limiting the sample to adults ignores the substantial changes that happen during human development. Going from a toddler to an adult changes the way we sleep and it is likely that the effects on cognition differ. This study questions what is currently known about sleep loss affecting cognition during a critical developmental period: adolescence.

Adolescence is the 'growing up' developmental period in the human lifespan in which fundamental biological, psychological, and social factors interact to facilitate the transition from child to adult. Combining inadequate sleep with these bio-psycho-social factors could lead to a myriad of effects—adequately named the "*perfect storm*" by adolescent-sleep researcher Carskadon (2011).

Adolescents tend to spend less time in bed and sleep less hours the older they are. A 2006 cross-sectional survey studied the sleeping habits via a telephone poll in the United States (US) of America (WB&A Market Research, 2006). The American adolescents (*N* = 1 602) reported that between grade 6 (11 – 12 years old [*yo*]) and grade 9 (14 – 15 *yo*) the total sleep time during school nights lowered from 8h 24m to 7h 36m. A larger (*N* = 6 776) US survey assessed the changes in sleep patterns in a longitudinal setting. The survey was performed using three 5-year-apart waves of a study panel that involved a 24-h activity diary from 1997 onward (Williams, Zimmerman, & Bell, 2013). In an elaborate statistical approach the three waves were combined and resulted in a normative sleep pattern during weekdays (and school nights) for children and adolescents from 0 – 18 *yo;* see figure 1. The pattern suggests decreased sleep duration as adolescents become older. Not only the US adolescents seem to sleep less and less; the French and Israeli adolescents show similar patterns, which are, furthermore, dependent on the pubertal-development stage (Leger, Beck, Richard, & Godeau, 2012; Sadeh, Dahl, Shahar, & Rosenblat-Stein, 2009). In fact, the reduction of sleep duration during adolescence is suggested to be a global phenomenon by a review and large meta-analysis of 41 surveys (Gradisar, Gardner, & Dohnt, 2011). Sleep duration of adolescents doest not only go down with age; a recent meta-analysis suggests that children's and adolescent's overall sleep duration has decreased 0.75 minutes per year over the last century (Matricciani, Olds, & Petkov, 2012). This reported decrease would suggest that adolescent today have a larger sleep debt than their parents or grandparents had when they were adolescent.

Several theories are hypothesised as to why sleep duration is lowered during adolescence. Most recently the growth in the domestic electronic entertainment (e.g. television and internet) has been proposed as a possible cause (Cain & Gradisar, 2010). However, the sleep-time reduction has been noted as early as 1913 making this theory unlikely (p. 10 in Colrain & Baker 2011). A more likely cause is a combination of a delayed circadian rhythm, the loss of parental control, and early school starting times. The circadian rhythm is part of the 2-process model of biological sleep regulation (Borbély, 1982). It comprises a daily (circadian) rhythm of sleep propensity that cycles around the hour and a sleep-wake pressure system that builds up during the day and dissipates during sleep. Adolescence seems to induce a slower accumulation of sleep pressure and a changed sensitivity to external time cues resulting in a phase shift of the circadian rhythm (Hagenauer, Perryman, Lee, & Carskadon, 2009). This circadian-rhythm phase shift can be shown by measuring salivary melatonin onset and changes in this phase-shift marker were found to strongly correlate with the age of young adolescents (Carskadon & Acebo, 1997). This delayed circadian rhythm and a lower sleep pressure lead to delayed bedtimes, a process that is made easier by a loss of parental control (Carskadon, 2011). Unlike the delayed adolescent bedtimes, the adolescent rising times are inflexible because of fixed school starting times, which ultimately leads to a reduction in sleep duration during adolescence.

Only a very small number of studies have investigated specifically the effects of sleep loss on information processing or cognitive processes during adolescence. However, there are other, more general, effects known of sleep entailment during adolescence, which might provide insights to the specific effects of sleep loss on cognition.

Risk-taking and limit-testing behaviour are generally associated with adolescence. This behaviour, which includes substance abuse, is reported to increase with the prevalence of sleep problems. For instance, one study suggests that increases in sleep-problems during adolescence are related to increases in cigarette smoking in a dose-response relationship (Patten, Choi, Gillin, & Pierce, 2000). Another study analysed a cross-sectional survey of 13 381 adolescents and found sleep problems to be associated with use of cigarettes, alcohol, and illicit drug use (Johnson & Breslau, 2001). This realtionship between substance abuse and sleep suggests that the ability of sleep deprived adolescents to adequately assess risk is compromised (Carskadon, 1990). This is posibly because the cognitive processes related to good judgement (e.g. impulse inhibition) are affected by sleep deprivation.

Sleep loss during adolescence is also associated with increased risks in traffic. Driving a vehicle is a daily activity for adolescents, and in some parts of the world the minimum driving age can be as low as 14 years (e.g. North America[1]). Vehicle control requires, among others, vigilance and attention and sleep problems are known to affect vehicle control. For instance, an Italian high-school survey showed that 15% of adolescent motor vehicle crashes were reported to have been mainly attributed to sleepiness (Pizza et al., 2010). Another study showed that a 2-year period of delayed Swiss high-school starting times lead to 17% less adolescent vehicle crashes —the delayed starting times allowed for longer sleep (Danner & Phillips, 2008). The effect of longer sleep is emphasised by the actual increase in accident rates of adolescents in the surrounding areas that did not delay high-school starting times. In the Netherlands the minimum age for a driver licence is eighteen years but adolescents still partake in traffic by driving their bicycle or scooter to and from school. The link between crashes and sleep loss suggests that the cognitive processes relied upon during vehicle control (*e.g.* attention or executive control) are affected by sleep loss.

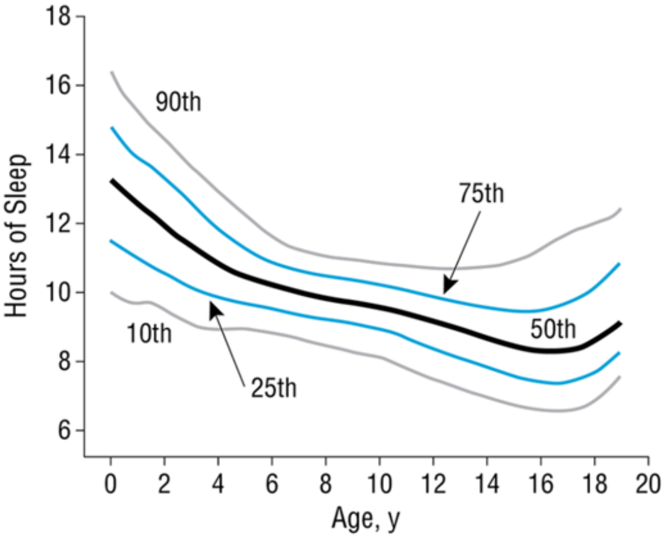

Figure 1: ***Age and Sleep****. Age-conditional 10th, 25th, 50th, 75th, and 90th percentiles of the distribution of children's number of minutes of total sleep for weekdays. Adapted from paper by Williams et al. (2013).*

Another normal day-to-day activity of adolescents is attending school. Improved school performance is associated with increased sleep quality and sleep duration as indicated by a meta-analysis of 50 studies that studied children and adolescents (Dewald, Meijer, Oort, Kerkhof, & Bögels, 2010). The analysis also suggested that school performance was increased when objective sleepiness decreased. Another meta-analysis, using a sample 86 studies of 5 – 12 *yo,* investigated the association between sleep, cognition, and behavioural problems in children (Astill, Van der Heijden, Van Ijzendoorn, & Van Someren,

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[1] Alaska Department of Administration: http://doa.alaska.gov.

2012). The results suggested that executive functioning and school performance were associated with sleep duration but that sleep was not associated with intelligence, sustained attention, or memory. Hence, the analysis suggest that, for children, insufficient sleep is linked with deficits in higher-order and complex cognitive processes.

The shorter sleep times of adolescents are usually ignored because it is incorrectly assumed that sleep need goes down when people grow up. For instance, this assumption is challenged by the results of a study in which adolescents are subjected to a free-sleep regime. The sleep duration was independent of their age and developmental stage; 10 – 17 yo slept for 9h 20m on average (Carskadon & Acebo, 2002). Hence, the results suggest that for adolescents the need for sleep remains stable. However, the need for sleep is known to strongly differ between individuals and the debate on what constitutes 'optimal sleep' is still ongoing. General consensus on what amount is sufficient is mainly based on expert opinion and is not based on bias-free evidence (Matricciani, Blunden, Rigney, Williams, & Olds, 2013). However, earlier described surveys of adolescent sleep durations report increased adolescent sleepiness and increased desire for more sleep. In addition, one study that compared a group of adolescents with low and a group with high scores on an insufficient sleep questionnaire found that the high scorers generally had a short sleep duration and that the low scorers had a short sleep duration (Dewald-kaufmann, Oort, Bögels, & Meijer, 2013). Taking these things into account there are sufficient indications, despite the ongoing debate, that short durations of sleep is prevalent among adolescents and that this generally results in a sleep debt

How this sleep debt interacts with cognition can best be explored by taking into account the different hypotheses that link sleep and cognition. Cognition is theorised to be influenced by two processes during sleep: the consolidating process and resetting process. The information obtained during wakefulness is contained within in the brain circuits and has to be consolidated to ensure future accessibility. One approach to model this is the synaptic-homeostasis hypothesis (Tononi & Cirelli, 2006). It suggests that because of a net increase of synaptic strength during wakefulness and to maintain synaptic homeostasis, synapse downscaling has to occur during slow-wave sleep. This downscaling is biased towards the strong synapses and results in network embossing. It solidifies the already strong memory traces while liquefying the weaker ones and thus acts as a filter for which information needs to be consolidated. The process also resets the synaptic strength to increase the allowance for new information to be encoded after sleep. Another consolidation model is the more active trace-reactivation hypothesis (Born & Wilhelm, 2012). Transient memory traces (hippocampus based for declarative memory) are short-term based and are thought to be copied to the long-term memory (mainly neocortex based) via actively replaying the memory trace during sleep. The reactivation of the trace promotes gradual strengthening of the corticocortical connections and eventually results in a memory trace that is more stable and (mostly) independent of the hippocampus (Walker & Stickgold, 2004; Walker, 2010). Hence, it frees up the hippocampal storage for usage after sleep. After sleep the cognition is hypothesised to be influenced by more than just a failure in resetting of virtual data storages. Normally cognitive processes suffer little from interference from sleep-initiating mechanisms but when the brain is sleep deprived this interference increases (Doran, Van Dongen, & Dinges, 2001). While in the past this increased wakeful-state instability was mostly advocated to be due to top-down control, recent papers suggest local-use dependent neuronal assemblies to be responsible for bottom-up interference (Krueger & Tononi, 2011). In order to maintain the functional integrity of the brain, sleep seems essential.

The consolidation process and resetting process might interact with the brain development that occurs during adolescence. The adolescent brain undergoes rapid maturing involving declining grey-matter volume, declining number of synapses, and shifting inhibitory-excitatory dynamics (Giedd, 2008, 2009). Sleep loss might be especially risky for this population. It can have lasting effects well into adulthood because of the neuronal malleability during adolescence.

This study aims to examine the effect that sleep loss has on the cognition of adolescents via a systematic and critical literature review. Only tests that assessed cognition are to be included and the following definition is used as a criterion. A test is perceived to be a cognitive test if the task requires or relies on a mental process of acquiring knowledge and understanding through perception, related information encoding, or combining the information into new thoughts or to plan an action that involves more than primal reflexes. Moreover, to aid the narrative, the tests are categorised via the general cognitive processes of which they are believed to asses performance. Categories are *attention*, *work memory*, *retention*, and *reasoning (including creativity)* and these categorical subdivisions are inspired by the methodology in a meta-study of J. Lim and D. Dinges (2010). Furthermore, to make it possible to establish causal effects, the present study focuses on studies that have manipulated sleep directly rather than studies that have only correlated sleep patterns. Also, in order to be able to compare the sleep manipulations between the studies, and ensure reliable recordings of the duration of sleep, only studies that measured total sleep duration in combination with objective motion sensors or polysomnographic instruments will be included. Another inclusion criteria is that of brain-development stage. These stages are closely linked to those of pubertal development, but both stages are difficult to determine. Luckily, years of age is an acceptable replacement. Hence, to exclude studies that did not actually study adolescence an age range criterion will be used. Adolescence is a diffuse process but an average-age range of 10 – 18 *yo* is suggested when taking into account the grey-matter volume dynamics described previously (Giedd, 2008). Participants of studies also have to be in good health to ensure a generalisation towards the general adolescent population. Health issues that involve sleep are an exception but study samples with sleep apnoea are excluded because oxygen rather than sleep deprivation might confound any experimental results.

II. METHODS

To explore the effects of sleep loss on the cognitive performance of adolescents a literature search was performed. The methods are described below followed by a narrative description of the studies.

SEARCH STRATEGY AND SELECTION

Two databases were accessed on 14 December 2012; PubMED (maintained by the national library of medicine of the United States of America) and PsycINFO (maintained by the American psychology association). Search queries consisted of a variety of synonyms of '*cognition*', '*sleep*', '*deprivation*', and '*adolescence*'; see supplement I at the end of the report for the search syntax. Cross-referencing interesting papers resulted in additional articles. The inclusion criteria of the articles were:

1. Articles had to be published in peer-reviewed journals.
2. Studied sample had to have an average age in the range of 10 – 19 *yo*, and were in good health; general sleep problems were allowed but sleep apnoea was excluded.
3. Independent variables had to include an experimentally manipulation of the duration of sleep and had to be measured objectively (or involve complete sleep deprivation).
4. Dependent variables or outcome had to include measures of cognition or ability of subjects to process information.

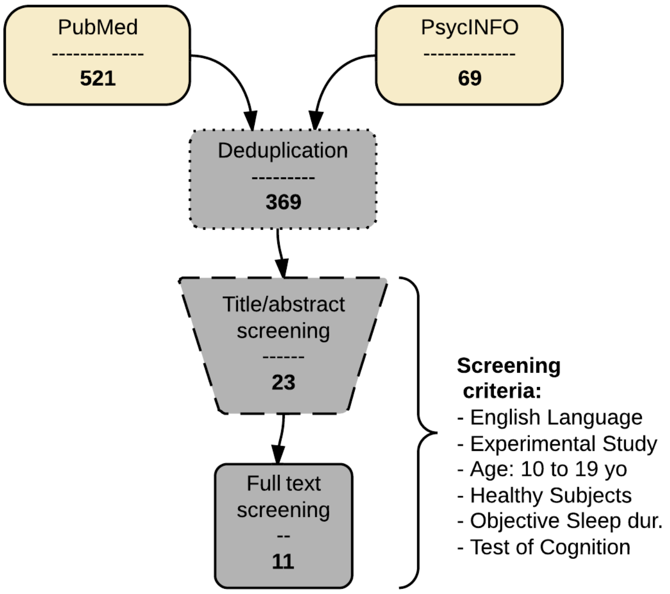

*Figure 2: **Literature Search**. Flow chart depicting the selection process and changes in the pool of articles.*

The selection process is depicted in figure 2 and resulted in the inclusion of 11 studies.

DESCRIPTIVES

The 11 articles are reports of studies performed from as early as 1981 to as recent as 2013. Study details are described in table 1 on page 8. The studies show a variety in age ranges, sleep manipulations, and cognitive tests. The lowest mean-age of subjects was 10.6 *yo* and the highest was 18.1 *yo*. Two studies examined the effects of total sleep deprivation, others have used various amounts of sleep restriction, and only two had specifically extended the duration of sleep. Thirty-three cognitive tests have been performed assessing different aspects of cognition. Eight of these tests mainly relied on attention, seven on working-memory, five involved retention, and two assessed reasoning.

STATISTICAL PARAMETERS

The low number of studies per category made a complete statistical meta-analysis very weak and thus was not performed. Reported statistics are presented by mean ± standard deviation. Reported estimates of effect sizes were of statistical significant results only and were standardised from Cohen's *d* (eq. 1) by calculating Hegens's *g* (eq. 2), which corrected for sample size. In the formula's the N_i is the size of group i. Because the reported correlation statistic (ρ) and variation of change scores were seldom reported the best effect-size estimation was that of an independent-group and not a repeated measurement. Hence, if a study employed a repeated-measurement design and had a strong correlation ($\rho > .5$), the effect size was possibly underestimated (Hedges & Olkin, 1985).

$$\text{EQ(1): } d = \frac{\mu_2 - \mu_1}{\sqrt{\frac{N_1 \cdot \sigma_1^2 + N_2 \cdot \sigma_2^2}{N_1 + N_2}}} \quad \text{EQ(2): } g = d \times \left(1 - \frac{3}{4 \times df - 1}\right)$$

III. STUDIES THAT MANIPULATE SLEEP IN ADOLESCENTS

TESTS OF ATTENTION

Tests of attention evaluate the ability to focus awareness on one stimulus, thought, or action while ignoring others that are irrelevant (Gazzaniga, Ivry, & Mangun, 2009a). Several of the selected sleep studies have examined the effects of sleep on this cognitive sub-domain during adolescence. The tasks assessing attention are labelled measuring simple attention if the task involves reacting to a simple stimulus and are labelled measuring complex attention if a complex stimulus is used or additional processing is required before responding. Study details are presented in table 2 on page 9.

TASKS WITH SIMPLE ATTENTION

The study by Peters *et al.* (2009) had 14 young-adolescents (10 – 11 *yo*) restricting their time-in-bed to 5 h or extending their time-in-bed to 10 h, or *vice versa* one week later, in a cross-over design. The participants were only female which offsets the young-age range because the onset of adolescence in girls is often sooner than it is in boys. The participants spent three nights in a sleep laboratory, twice, undergoing both conditions while making cognitive performance tests. One of the tests was a psycho-motor vigilance test (PVT). In this test, the task was to respond as quickly as possible to a simple stimulus (*i.e.* a bullseye). In the sleep-restriction condition the participants became significantly (*P* = .025; *g* = 0.67) slower in responding to the stimulus. The initial reaction time was 371 ± 125 ms, which increased to 482 ± 186 ms after sleep restriction. The participants in the control condition started with an average response latency of 365 ± 89 ms and ended with 374 ± 99 ms. Additionally, the sleep-restriction condition showed a significantly higher increase in lapses (*i.e.* late or no response) than the control condition (*P* < .001; *g* = 0.79). During baseline the number of lapses were 7 ± 7 on average and after the restriction night this increased to 15 ± 12 lapses. In the control condition the baseline counted 10 ± 9 lapses, which increased to 13 ± 11 lapses. The number of lapses had a large variance but the increase following restriction was robust. Hence, the results of the study by Peters *et al.* argue for a detrimental effect of sleep restriction on the speed in simple attention tasks.

Further indications of the detrimental effect of sleep-restriction on simple attention come from a study that manipulated sleep at home. Sadeh *et al.* (2003) instructed 9 – 12 *yo* to change their sleep durations and divided them into three groups based on their compliance to the instructions. The first group successfully slept one hour less than their normal sleep duration (sleep-restriction group; *N* = 28). The second group successfully slept one hour more than their normal sleep duration (sleep-extension group; *N* = 21). The third group did not successfully decrease or increase their sleep duration by at least 30 minutes (no-change group; *N* = 23). One test the participants had to make was a simple reaction-time test, similar to the PVT of Peters *et al.* but with a slightly different stimulus; a large square. When comparing the response latency within the participants Sadeh *et al.* found that the sleep-restricted group and no-change group became significantly slower after three nights of adjusted sleep (*P* = .025; *g* = 0.33). The sleep-restricted group had an average reaction time of 431 ± 83 ms on the pretest but slowed to 458 ± 77 ms on the post test. The no-change showed a similar change but this was not commented on by the authors. It is likely that the no-change group still contained participants that actually reduced their sleep duration, but insufficient to the standards set forth by the experimenters, which would explain why this group became slower.

Table 1: ***General Description Of Studies****. Table shows details of the 11 selected studies.*

Reference	*Sample*						*Experiment*								
			Age (y)									*Cognitive test categories*			
Reference	N	Gender (% male)	Mean	Min.		Max.	Design	Sleep manipulation	Sleep measure	Sleep location	Adapt. period[c]	Attention	Working memory	Retention	Reason.
Carskadon et al. (1981)	12	66.7	13.5	11.9	-	13.3	W	Deprivation	Poly.	Lab.	2 n (10 h)	●	●	●	
Randazzo et al. (1998)	16	43.8	11.9	10	-	14	B	Restriction	Poly.	Home	3 n (10 h)	●	●	●	●
Fallone et al. (2001)	82	52.9	11.9	8.6	-	15.8	B	Restriction	Poly.	Lab.	5 n (10 h)	●			
Sadeh et al. (2003)	77	50.6	10.6	9.1	-	12.2	W	Rest. + Ext.	Acti.	Home	0	●	●		
Gias et al. (2006)	14	100	18.1	na	-	na	CO	Deprivation	Obs.	Lab.	0			●	
Kopasz et al. (2008)	22	45.5	15.5	14	-	16	CO	Restriction	Poly.	Lab.	1 n (9 h)	●		●	●
Peters et al. (2009)	14	0	10.6	10	-	11	CO	Restriction	Acti.	Lab.	2 n (free)	●			
Beebe et al. (2009)	6	66.7	15.3	na	-	na	CO	Restriction	Acti.	Home	5 n (free)		●		
Voderholzer et al. (2010)	76	44.7	15	14	-	16	W/B	Restriction	Acti.	Home/Lab.	1 n (9 h)	●	●	●	
Jiang et al. (2011)	17[a]	50	15	13	-	16	CO	Restriction	Acti.	Home	0		●		
DeWald-K. et al. (2013)[b]	55	14.5	15.4	12.8	-	18.52	WB	Extension	Acti.	Home	0	●	●		

Note: [a] sample statistics non-exclusion group ($N = 20$). [b] DeWald-Kaufmann; participants had a chronic sleep reduction. [c] Adaptation period, number of nights followed by set hours in bed or self elected. Design: **W** = Within groups, **B** = between groups, **CO** = cross-over (participants did both control and manipulation). Sleep measure: **Poly.** = polysomnography, **Acti.** = actigraphy, **Obs.** = observation. Sleep location: **Lab.** = sleep laboratory and **Home** = home environment. '**na**' = not available.

*Table 2: **Tests Of Attention**. Table shows sleep manipulation and cognitive outcomes of attention tests. Tests with significant results are bold.*

			Manipulation		*Outcome*				
First author (*year*)	*N*	Exp. Type	Sleep (h)	Nights	Cognitive test	Att. Type	Speed	Acc.	Score
Carskadon (1981)	12	W	0	1	Serial Alternation	S		=	
					Listening Attention	C		=	
Randazzo (1998)	16	B	5 or 11	1	The Steer Clear	C		=	
Fallone (2001)	82	B	4	1	GS Delay	S		=	=
					GS Vigilance	C	=	=	
Sadeh (2003)	77	W	BSLN – 1	3	**Simple RT Test**	S	↓		
					CPT	C	=	=	
			BSLN + 1	3	Simple RT Test	S	=		
					CPT	C	↑↑	=	
Kopasz (2008)^{a}	22	CO	4 or 9	1	TMT – part B	C	=		
					TAP-flexibility	C			=
					TAP-divided attention	C			=
					d2 test	C			=
Peters (2009)	14	CO	5 or 10	1	**PVT**	S	↓		↓↓^{c}
Voderholzer (2010)	76	W/B	9, 8, 7, 6, or 5	4	TAP-divided attention	C			=
					TMT – part A	C	=		
					TMT – part B	C	=		
DeWald-K. (2013)^{b}	55	W/B	BSLN + 5 min.	10	Simple RT Test	S	=		

Note: ^{a}tests were done after recovery night. ^{b}chronic sleep reduction. ^{c} number of lapses went up.

BSLN = baseline sleep. Type: **W** = within groups, **B** = between groups, and **CO** = cross-over (participants did both). Attention Type: **S** = simple attention and **C** = complex attention. Tests: **CPT** = continuous performance test, **TMT** = trail-making test, **GS** = Gordon System, **TAP** = Test of Attentional performance. Outcome: **'='** = no significant effect, ↓ = *P* < .05, ↓↓ = *P* < .01, ↓↓↓ = *P* < .001. Arrows point up for an positive effect and down for a negative effect.

The participants of Sadeh *et al.* also performed the continuous performance test (CPT), which involved responding to when a certain animal type was shown but withholding a response when others were shown. Only the sleep-extension group became significantly quicker in responding, going from 616 ± 74 ms on the pre-test to 589 ± 68 ms on the post-test (*P* = .003; *g* = -0.38). The no-change and restricted-sleep group showed no significant changes on the speed on the CPT. None of the groups showed any significant changes in the accuracy on the CPT. Sadeh *et al.* argue that sleep restriction seems to lower attention performance on a simple task but no indications arise that performance on the complex tasks is affected. Sleep extension is then argued to result in the same but opposite effect; decreased performance on the complex tasks but no indications of effects on simple tasks. A study that has specifically extended the sleep duration of adolescents and also conducted tests of attention might provide further insights into this relation.

DeWald-Kaufmann *et al.* (2013) extended the sleep duration of 12 – 18 *yo* that showed signs of severe chronic sleep reduction (*N* = 28). Task performance was assessed before and after two weeks of gradually increasing sleep duration in 5 min. intervals. The changes were compared to a control group (*N* = 27) that had similar chronic sleep reduction, which underwent comparable procedures but received no instructions to adjust their sleep pattern. A simple reaction-time task was performed by the participants before and after the sleep manipulation. The sleep manipulation caused no significant differences of in the groups in speed before, after, or between the pre- and post-tests. Since no power-analysis was performed the results are inconclusive on the effects on attention and do not suggest an effect of sleep extension on performance in tasks of simple attention.

Two studies argue against the findings described above. The first contradicting study is by Fallone *et al.* (2001). They had two groups and each slept one night in a laboratory. One group (*N* = 44) of 8 – 15 yo spent 4 h in bed, whereas the other group (*N* = 37) spent 10 h in bed. The following day the participants performed several tests among which a Gordon System (GS) delay test, which assesses simple attention and allowed for a comparison between the two groups. The task in this test was to respond to a simple stimulus but the participants were only given points and positive feedback if they minimally delayed their response by 6 seconds. The latter was unknown to the participants. The groups showed no significant differences in points on the GS delay test. This contradicts the results of Peters *et al.* and Sadeh *et al.* in that it does not suggest an effect of sleep restriction on simple attention. Another test the participants performed was the GS-vigilance test in which participants had to respond when a certain sequence (1 – 9) occurred in a continuous stream of single digits, which requires complex attention. No significant group differences in speed or accuracy on this task were found.

The experimental design of Fallone *et al.* was considerable weaker than the studies of Peters *et al.* and Sadeh *et al.* For instance, Peters *et al.* restricted the sleep by one hour less but their statistical power for detecting effects was far stronger because of a cross-over design. The study by Sadeh *et al.* Also used a within-group design that allowed for repeated measurements. Fallone *et al.* restricted sleep by one hour more but used a limiting between-group design. Not employing a repeated measurement design is especially weak in sleep research because of high inter-individual sleep parameters (Van Dongen, Baynard, Maislin, & Dinges, 2004) and the research question enquires about the effect sleep loss has on an individual. Another important difference between the studies is that Fallone *et al.* incorporated a five night adaptation period of 10 h in-bed-time before the restriction night, whereas Sadeh *et al.* and Peters *et al.* had no specific time-in-bed regulations. This could have had the effect that the participants in the studies of Sadeh and Peters were not free of sleep debt and as a result these authors studied a sample that was sleep deprived rather than well rested. This could have increased the effect of further sleep loss. Above mentioned differences have likely prevented Fallone *et al.* from duplicating findings by Sadeh *et al.* and Peters *et al.*

The second study that did not find an effect of sleep restriction on simple attention is also the oldest. Carskadon *et al.* (1981) compared the cognitive performance of 12 young-adolescents (11 – 13 *yo*) before and after a night of complete sleep deprivation. The attention tests were of both simple and complex attention. The first test, the serial alteration test, required the participants to press two buttons alternately and repeatedly in a steady rhythm. The second test, the listening attention test, tasked the participants with pressings one of two buttons while listening to a text being read in which two keywords, linked to the buttons, were marked with a tone. One night of complete sleep deprivation had no statistically significant effect on the accuracy of serial alteration (simple) nor the listening attention (complex). However, Carskadon *et al.* are critical upon the results of the statistical tests since sleep deprivation was "*clearly related to decrements in performance*" and the effects not reaching statistical significance "*reflects the wide variability of the performance test scores*" (p. 309). This is exemplified by the cumulative seconds without tapping during the serial-alteration task averaging 5.6 s during the baseline but averaging 74.6 s(!) after sleep deprivation[2]. Further strains on the statistical detection-power were the small sample size and the lack of a control group employed by the study of Carskadon *et al*. Hence, despite non-significant results there was an effect of sleep loss in the study of Carskadon *et al,* but this did not show up as a statistical significant difference in performance on the tasks of simple and complex attention.

To <u>summarise</u>, the effects of sleep restriction in the studies of Sadeh et al. and Peters et al. suggested an effect of sleep loss on tasks of simple attention. The studies by Fallone et al. and Carskadon et al. found no effect but had weak experimental designs. This lead to low statistical power, which is the likely cause of null findings in these studies. The results of the study by DeWald-Kaufmann et al. were inconclusive on the effects of sleep extension on performance in tasks of simple attention. None of the test or results described above suggest an effect of sleep loss on tasks of more complex attention, but there are other studies that had tasks of complex attention.

TASKS WITH COMPLEX ATTENTION

In a between-group design Randazzo *et al.* (1998) allowed one group of 10 – 14 yo only 5 h time-in-bed (*N* = 8) and another group 11 h (*N* = 8). A range of cognitive-performance tests were performed on the day following the manipulation night, which included a steer clear test. In this test the participants had to use the arrow keys to control a computer game in which a vehicle was to steer clear of obstacles; a task of complex attention. No significant changes were detected between the groups on

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[2] No variance was reported.

Table 3: ***Tests Of Working Memory.*** *Table shows sleep manipulation and cognitive outcomes of working memory tests. Tests with significant results are bold.*

			Manipulation		*Outcome*			
First author (*year*)	*N*	Exp. Type	Sleep (h)	Nights	Cognitive test	Speed	Acc.	Efficiency
Carskadon (1981)	12	W	0	1	**Wilkinson Addition Test**	↓↓^{d}	=	
Randazzo (1998)	16	B	5 or 11	1	**DSST**	=	↓^{e}	
Sadeh (2003)	77	W	BSLN – 1	3	DSST	=		
					Digit Span (backwards)		=	
					Digit Span (forwards)		=	
			BSLN + 1	3	DSST	=		
					Digit Span (backwards)		=	
					Digit Span (forwards)		↑	
Beebe (2009)	6	CO	6.5 and 10	5	0-back	=	=	
					2-back	=	=	
Voderholzer (2010)	76	W/B	9, 8, 7, 6, or 5	4	Digit Span^{c}		=	
Jiang (2011)	17^{a}	CO	6 and 8	5	**Simple verbal WM**	↓	=	
					Complex verbal WM	=	=	
					Arithmetic WM	↓	=	
DeWald-Kaufmann (2013)^{b}	55	W/B	BSLN + 5 min.	10	**Visuospatial processing**	↑↑	(↓)	↑↑↑
					Divided Attention	↑	↓	=

Note: ^{a} sample statistics non-exclusion group. ^{b} chronic sleep reduction. ^{c} backwards & forwards. $^{e/d}$ likely due to lapses.

BSLN = baseline sleep. Type: **W** = within groups, **B** = between groups, and **CO** = cross-over (participants did both). Tests: **DSST** = digit substitution serial task. **WM** = work memory. Outcome: '=' = no significant effect, ↓ = $P < .05$, ↓↓ = $P < .01$, ↓↓↓ = $P < .001$, **(↓) = P = .057**. Arrows point up for an positive effect and down for a negative effect.

the number of obstacles hit. The between-group design and small sample size combined with the low accuracy of the test likely resulted in insufficient statistical power. Hence the results of Randazzo *et al.* concerning complex attention are inconclusive. Other studies faired better on aspects of study quality.

In a cross-over study design Kopasz *et al.* (2008) compared a control condition of three nights, in which 9 h were spent in bed each night, with a restriction condition of three nights in which the sleep duration in the second night was lowered to 4 h. The age range of the sample was 14 – 16 yo (*N* = 22). The participants performed a neurological test battery after the third night, which included three tests that involved tasks of complex attention. None of the tests revealed any significant difference between the conditions. The first test was part B of the trail-making test (TMT), which consisted of connecting a series of dots marked sequentially by alternating letters and numbers. The dots had to be connected as quickly and as accurately as possible. The second test was a test of attentional performance (TAP), which is a computerized standardized test battery including the sub-tests '*divided attention*' and '*flexibility*'. The first is a dual-task test and the latter involves shifting the attention. The third test was the d2 test, which required the participants to mark a '*d*' on a matrix of randomly mixed letters ('*p*' or '*d*'). Sleep conditions did not significantly differ on the speed on the TMT and did also not differ in TAP or d2 test performance. However, the time at which the attention tests were performed might have been ill chosen to detect effects of sleep restriction. Participants performed the tests after the recovery night and had 9 h of sleep between the sleep restriction and testing. Hence, the effects (if any) of sleep loss were possibly countered. Luckily, another study performed nearly the same battery of tests without such a recovery night.

Voderholzer *et al.* (2011) had five groups of 14 – 16 yo following five sleep protocols with 9, 8, 7, 6, or 5 h of time-in-bed for four consecutive nights (*N* = 12, 16, 16, 15, and 17; respectively). On the first and last experimental day a TMT and TAP-'*divided attention*' were performed by the participants. The TMT, trail-making task, was extended compared to Kopasz *et al.* and consisted of part A and part B; part A is slightly easier because the dots are only marked with numbers. The between-group comparison in the repeated measures revealed no significant effect of the time-in-bed on the speed of the TMT and also not on the score of the TAP.

To summarise, the results of Voderholzer et al. and by Kopasz et al. do not suggest sleep loss affecting tasks involving complex attention. Because of the experimental design the results of the study by Randazzo et al. are unreliable and lack of statistical-power analysis makes the results inconclusive. Hence, no additional evidence is provided towards an effect of sleep loss on performance in tasks of complex attention.

TESTS OF WORKING MEMORY

Tests of working memory (WM) evaluate the ability to maintain and manipulate relevant information over a brief period of time (Gazzaniga et al., 2009a). The tests should involve a decision followed by a response and are notably different from long-term memory. For instance, a test that require the participant to learn a set of items and repeat them after a very short period can be considered WM. Recall after a few minutes or recall of a large set of items (>10) involve non-working memory. Studies that incorporated tests that are WM-related are detailed in table 3.

TASKS WITH WORKING MEMORY

Chinese high school students were recruited by Jiang *et al.* (2011) to study the feasibility of chronic sleep restriction in a home environment. Seventeen 13 – 16 yo participated in a cross-over experiment in which they either slept 6.5 h or 8 h for 5 consecutive nights. After these nights they were subjected to a simple and also a complex verbal WM test. The complex test required the participants to mentally shift two letters alphabetically forward, after that they had to match or non-match the resulting letters with a target. No significant difference were found on the speed or accuracy of performance on the complex verbal WM test.

The simple version of the test had the participants of Jiang *et al.* indicate when a lower-case letter matched or non-matched with an earlier shown upper-case letter. The results revealed significant but small decreases in speed but not accuracy of the WM (P = .014; g = 0.58). Response latency[3] went from 646 ± 45 to 677 ± 57 ms following nights of short sleep.

Participants of Jiang *et al.* also performed an arithmetic WM test in which they had to subtract a number (6, 7, 8, or 9) from a three-digit seed number and respond when the result was the same as a shown probe. Here the data showed significant effects on speed, which was once more significantly lowered following nights of mild sleep restriction (P = .017; g = 0.65). Response latency was 647 ± 51 ms in the control condition and 686 ± 63 ms in the restriction night. Curiously, no exact statistics for the accuracy were reported, only a general lack of effect on accuracy is remarked upon. The results of the study by Jiang *et al.* suggest a negative impact of sleep restriction on WM performance.

Beebe *et al.* (2009) had 6 adolescents (mean age = 15.3 years) complete a working memory task during magnetic-resonance imaging in a cross-over experiment after 5 consecutive nights of either 6.5 h or 10 h time-in-bed. The 0- and 2-back task required the participants to remember the location of a number that appeared in one of four visual quadrants (1 – 4) after which they had to press a button indicating the stimulus location 0 or 2 stimuli back. The 2-back task is generally considered to be substantially more difficult than the 0-back task, since the latter consists of just following the instructions on screen. However, no significant effects of sleep restriction on accuracy and speed were found. The authors remark that this is *"consistent with prior studies [using the same test]"* (p. 3). As to why Jiang *et al.* with a similar sleep-restriction did find a significant effect is likely because the sample size was twice as big as the one used by Beebe *et al.* (*i.e.* 17 *v.* 6). The very low sample size is likely related to the expenses involved in brain-scanning techniques but has limited the interpretation of the results on the behavioural level. As such, the outcome is unreliable and other studies must be further examined.

The earlier discussed study by Carskadon *et al.* (1981) had 12 adolescents also perform a Wilkinson addition test before and after a night of complete sleep deprivation. The task was to add up as many columns of five two-digit numbers as possible within a time limit. Before the deprivation the participants managed to attempt 105 ± 22 problems on average, whereas they became significantly slower after the no-sleep night and only attempted 87 ± 27 problems. However, the authors note that the drop in average number was found to be because of the occurrence of lapses, which were easily detectable via the polysomnography. Only incorporating trails where the participants had no polysomnographic lapses resulted in an average of 106 problems attempted,

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[3] Statistics had to be deduced from the graphs included in the article since no report was made in the text.

*Table 4: **Tasks With Retention**. Table shows sleep manipulation and cognitive outcomes of short-term and long-term memory retention tests. Tests with significant results are bold.*

			Manipulation			*Outcome*			
First author (*year*)	*N*	Exp. Type	Sleep (h)	Awake period (h)	Nights	Cognitive test	Test type	Retention interval (h)	Perform.
Carskadon (1981)	12	W	0	--	1	**Williams Word Memory**	Rc	<½	↓
Randazzo (1998)	16	B	5 or 11	--	1	CVLT	Rc + Rg	<½	=
						WRAML: Learning	Rc + Rg	<½	=
						WRAML: Verbal	Rc + Rg	<½	↑↑↑[d]
						WRAML: Visual	Rc + Rg	<½	=
						WRAML: General	Rc + Rg	<½	=
Gias (2006)	14	CO	0[a] and 7.6 *or* 7.4 and 7.5	10 3	1	**English-German Pairing**	Rc (cued)	48	↓
Kopasz (2008)	22	CO	4 and 9 *or* 9 and 9	9 4	1	Paired-Word List Task	Rc (cued)	41	=
						VVM: verbal (Construction)	Rc (cued)	41	=
						VVM: spatial (City Map)	Rc (cued)	41	=
						VLMT	Rc	41	=
Voderholzer (2010)	76	W/B	9, 8, 7, 6, or 5	14 -17^{5h} 10-12^{9h}	4	Paired-Word List Task	Rc (cued)	96	=
						Mirror Tracing task[b]	--	96	=

Note: [a] but 5.6 ± 0.6 h of daytime sleeping. [b] only test assessing procedural memory. [d] differences was due to control group performing badly.

Awake period refers to time that was spend being awake after learning the items/task. **BSLN** = baseline sleep. Type: **W** = within groups, **B** = between groups, and **CO** = cross-over (participants did both). Type: **Rc** = recall and **Rg** = recognition.Tests: **CVLT** = California verbal-learning test, **WRAML** = wide range assessment of memory and learning V1, and **VVM** = visual and verbal memory. Outcome: '**=**' = no significant effect, ↓ = $P < .05$, ↓↓ = $P < .01$, ↓↓↓ = $P < .001$. Arrows point up for an positive effect and down for a negative effect. '**na**' = not applicable.

which is nearly identical to the baseline average. This observation highlights the danger that is associated with the focus on statistical results and advocates careful examination of behavioural data involving cognitive effects of sleep deprivation. When taking this into account the results of Carskadon *et al.* might suggest an effect of sleep deprivation on tasks that measure WM performance, but this effects is likely not because of the basal WM function being impacted.

The digit-span test was done by multiple studies and involved participants remembering presented digit sequences of various lengths and recalling the sequence forward or backward. Recalling a sequence backwards is considered to be a heavier load on the working memory since it requires mentally reversing the digit order. The digital-span test was, among others, performed in the earlier discussed study by Sadeh *et al.* (2003) in which both a group with sleep extension and a group with sleep restriction were compared. The group that successfully extended their sleep with an hour, on average, recalled a maximum of 5.4 ± 1.0 digits forward on the baseline measurement and 5.7 ± 0.9 following the extra hours of sleep; a significant improvement ($P < .05$; $g = 0.31$). However, the same group showed no significant changes on the outcomes of the backward version of the digit recall and the other group—that successfully reduced their sleep by an hour—showed no significant changes in either of the versions, backwards or forwards. The results of Sadeh *et al.* suggest a positive effect of sleep extension on the accuracy of the working memory of adolescents but are inconclusive about the effects of sleep restriction.

The study by Voderholzer *et al.* (2011) that involved having five groups sleep 4 nights for 9, 8, 7, 6, or 5 h sleep, also had the participants perform the digit-span test. The report does not separate the forward or backward version of the test but reports the combined accuracy. They found no significant effect of the hours slept on the longest sequence that was recalled and thus do not suggest an effect of sleep restriction on WM.

Another test that multiple studies performed was the digit-symbol substitution test (DSST). It asks the participants to transcribe numbers to symbols using a key of nine numbers paired with symbols. Both the above mentioned study by Sadeh *et al.* and the earlier discussed study by Randazzo *et al.* (1998) assessed WM performance via the DSST. Sadeh *et al.* found no differences in speed between the extension or restriction group. In the study of Randazzo *et al.* no significant differences in overall speed between the groups on the DSST was found the following day. However, across the day both groups became more accurate as they performed the task more often. At one o'clock in the afternoon the sleep-restricted group showed a significant lower accuracy at the third test. The authors note that this indicates either reduced learning or optimisation, or possibly a shift in circadian rise resulting in lapses of attention. The increase in lapses is more likely since both groups improved similar on the other three test tries spread over the day. As such, the results of Sadeh *et al.* and Randazzo *et al.* do not suggest an effect of sleep restriction on performance in tasks that involve the WM.

Finally, there is the earlier discussed study of DeWald-Kaufmann *et al.* (2013) in which adolescents gradually had their sleep extended by 5 minute increments for 10 nights. They found significant improvements in the speed ($P < .01$; $g = -1.33$) and performance efficiency[4] ($P < .001$; $g = -1.59$) but not accuracy ($P = .057$) of visuospatial processing following the sleep extension. They assessed visuospatial processing via a task that involved memorising a pattern of three-by-three matrix consisting of 6 white and 3 red squares. Directly following the matrix the participants had to detect the matrix among 4 matrices. In the control group the response latency lowered from 1 038 ± 156 to 918 ± 128 ms, while the sleep extension group showed a larger improvement; from 1 057 ± 176 to 846 ± 138 ms. Overall performance efficiency changed in the control group from 1 159 ± 146 to 1 027 ± 136 units; the sleep extension group improved from 1 185 ± 167 to 948 ± 127 units.

The participants of DeWald-Kaufmann *et al.* also performed a divided attention task. It is categorised as WM since the task description suggests that it requires WM and not purely attention. The task was to remember 1, 2, or 3 letters after which the participant was asked to detect the letters in 4 presented letters. Significant improvements were found in the speed ($P < .05$; $g = -1.40$) but not performance efficiency, while the accuracy went significantly down after sleep extension ($P < .05$) . Speed-wise the control group improved from an average response latency of 696 ± 76 to 617 ± 81 ms, whereas the sleep-extension group started slower but improved significantly more; 713 ± 82 to 601 ± 76 ms. Accuracy-wise the control group remained nearly identical in their errors: 5 ± 2 % before and 5 ± 3 % after the manipulation. The sleep restriction group started at the same error proportion (5 ± 2 %) but made significantly more errors on the post test (7 ± 4 %). The significant negative change in accuracy found in the divided-attention test would suggest that the accuracy of visuospatial processing was also affected (despite the P-value being below statistical threshold). Increased speed but decreased accuracy suggest a strategy change in the tasks following sleep extension. This lead to increased performance efficiency in the visuospatial but not the divided-attention task. The results of DeWald-Kaufmann suggest a positive effect of sleep extension on the mechanisms of WM.

To summarise, only the results of the study by Jiang et al. suggest a (negative) effect of adolescent-sleep loss on tasks involving WM. The study by Beebe et al. was likely statistically underpowered and failed to detect effects on the behavioural level. Carskadon et al. found that the decreases in WM performance was due to increases in the number of lapses. Results of the effects of sleep loss on the DSST by Sadeh et al. are inconclusive. However, results of the digit-span test performed by participants in the studies of Voderholzer et al. and Randazzo et al. suggest a positive effect of adolescent-sleep gain on WM performance, but only when the WM load is low. The results of DeWald-Kaufmann et al. also suggest that sleep gain leads to better performance on WM-related tasks for adolescents. Hence, sleep loss is suggested to be detrimental to some aspects of WM performance whereas sleep gain is beneficial.

TESTS OF RETENTION

Tests of memory assess the performance of encoding, consolidation, or retrieval of both the short-term and long-term memory (Gazzaniga, Ivry, & Mangun, 2009b). Working memory, as it was discussed in the previous section, is a special case of short-term memory that not only retains pieces of information but also involves manipulating and changing the information retained. The short-term memory tasks, that this section focuses on, do not require the information to be manipulated in any task-related manner but the interval between encoding and retrieval of the information is similar to that of working-memory tasks but involve generally more items. Longer-term memory tasks are characterised by retention intervals of hours to days. All studies discussed involve retention of declarative information, only one study (Voderholzer et al., 2010) tested the retention of non-declarative memory; procedural memory. Details of all the studies and tests are presented in table 4on page 13.

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[4] Calculated as reaction time divided by the proportion of correct responses (RT / [p | correct]); lower is better.

TASKS WITH SHORT-TERM RETENTION

The study by Carksadon *et al.* (1981) in which young-adolescents did not sleep for an entire night had the participants perform the Williams word memory test. The participants had to memorise 25 4-letter words that were pronounced and written down in 10 second intervals. Every test used a new list of words. The written words were checked and corrected after which the free recall was initiated. Before the sleep deprivation the average number of correct words remembered was 11.7 ± 2.3, which dropped significantly ($P = .02$; $g = -1.28$) to 8.4 ± 2.5 words during the post test. These differences suggest that the short-term memory system is negatively affected by sleep deprivation. This is furthermore indicated by observation that the number of correct words recalled restored to baseline on the following days after the recovery nights.

Short-term memory was also investigated by the study of Randazzo *et al.* (1998) in which two groups of adolescents slept either 5 or 11 h after which two short-term memory tests were performed. The California verbal learning test (CVLT) consisted of memorising 14 words during five identical trails and a sixth trail following an interference list. This list was followed up by two recognition trails. A general score, combining recall and recognition performance, was then calculated. The groups showed no significant differences in scores. The second set of tests was the wide range assessment of memory and learning (WRAML v1) that is an elaborate array of sub-tests that generates three indexes of performance: learning, visual, verbal, and a general one. Curiously, the verbal index was significantly ($P < .01$; $g = 1.43$) higher in the sleep-restricted group (115.0 ± 11.7 units) than it was in the control group (96.8 ± 12.5 units). The authors note that the reverse direction of the effect was accounted for by the poor performance of the control group rather than an improvement of the sleep-restricted group, making it unrelated to the experimental manipulation. Hence, the study results of Randazzo *et al.* do not suggest an effect of sleep restriction on short-term memory.

To summarise, the effects found in the study by Carskadon et al. would suggest that only a full night of sleep loss could have a detrimental effect on short-term memory. The sleep loss in the study of Randazzo et al. was likely not severe enough to elicit the same effect.

TASKS WITH LONG-TERM RETENTION

For a memory trace to transfer from the limited short-term to the abundant long-term memory it requires additionally processing. Additionally, it requires a consolidation process that stabilises the memory trace required after the initial encoding. Hence, studies investigating the effects of sleep on long-term memory the amount of time between encoding and retrieval is important. Another important factor is how much of this time is spent awake and how much is spent asleep. Three studies have investigated the effects of sleep restriction on long-term memory performance.

The first, not yet discussed, is the study of Gias *et al.* (2006) that employed a cross-over design. They used a sample of 14 males that were on average 18.1 *yo*, the sample might seem old but it is offset by that adolescence tends to start late in boys. The participants were to memorise 24-pairs of English words and their German translation in under 10 minutes after which their retention was tested to establish a retention baseline. The sleep-deprivation condition then consisted of keeping the participants awake for 10 hours or a whole night before allowing a few hours in bed during day time after which they had a normal night. On average, the sleep-deprivation condition slept 5.6 h during the daytime and 7.6 h on the normal night. Only after the second night was the retention of the word pairs tested via a cued recall. In the control condition the participants were only awake for 3 h after the initial encoding and slept two normal nights before the cued recall. Participants slept 7.4 and 7.5 h on average during the control-condition nights. Both conditions had a retention interval of 48 h. Hence, the study was designed to delay any consolidation effects that sleep might have. They confirmed that in the sleep-deprivation group the participants forgot significantly ($P = .02$; $g = -1.31$) more words than they did in the control condition. A sleepless night followed by a normal night led to a change of -1.8 ± 0.6 words on average and two normal nights changed the retention by -0.2 ± 0.6 words. A problem is that only when the change between short-term and long-term memory retention is compared an effect is found. The authors remark on this but argue that the short-term memory retention is still a valid "*measure of encoding during the preceding learning phase*" (p. 261). But since comparing the actual retention after the second night of both conditions does not suggest an effect of sleep deprivation it, to an extent, undermines the reported detrimental effect of sleep loss on long-term memory.

The second study assessing long-term memory was done by Kopasz *et al.* (2008). In a similar design as that of Gias *et al.* they had participants sleep two nights, twice. The sleep-restriction condition had the participants sleep 4 and 9 h during the two nights and during the control condition they slept two 9 h nights. The design focuses on consolidation of information. Before the two manipulation nights they learned four types of information of which the retention was tested 41 h later. During the sleep-restriction no significant differences in performance on any of the tests was detected between the two conditions.

The first test involved repeating 32 related-word pairs until the participant recalled at least 60%. Word retention was tested by cued recall.

The second and third test were part of the visual and verbal memory test (VVM). The first part involved learning a course of a route and then mark it on the same map during recall to measure visuospatial retention. The second part involved memorising a verbal description of a building via names, numbers and propositional contents. At recall they were given questions to test verbal retention.

The fourth test was the auditory verbal learning and memory test (VLMT) and required the participants to memorise 15 concrete items that were repeatedly and verbally presented. Four cued-recalls followed and on the fifth recall a similar intrusion list was presented followed by a sixth recall of the original 15 items. The seventh recall occurred after the two-night interval with an additional recognition test of the combined word list (30 words) from which the original-list items had to be identified.

Why Kopasz *et al.* found no effect in the above described tests is shown when one looks at the data . It reveals that the results of the VVM and VLMT are unreliable because of ceiling and flooring effects. A very high number of items were correctly recalled on the VLMT (~15) and a very low rate of forgetting was measured in the VVM (~0.3). These effects could mask any actual differences between the conditions. This is not the case for the paired words.

Not finding any differences in retention of the paired words by Kopasz *et al.* is in conflict with the findings of Gias *et al.* who did find an effect of sleep restriction. The difference in task might be accountable since learning one word in two languages is different from learning related words in the same language. Another possible culprit is the difference in the amount of sleep-restriction, though the full night sleep deprivation by Gias *et al.* is offset by the occurrence of daytime sleeping. These factors and the lack of power analysis makes the findings by Kopasz *et al.* inconclusive.

The following study also tested the retention of word pairs but incorporated a more severe (chronic) sleep-restriction than Gias *et al.* did. The third study that measured long-term memory performance was performed by Voderholzer *et al.* (2010). Similar to the two studies discussed above they had five groups of adolescents learn 46 related-word pairs until they could recall at least 60% correctly. After this they slept either 9, 8, 7, 6, or 5 hours for 4 consecutive nights. Ninety-six hours after learning the words the retention was tested via cued recall. No significant differences were found between the groups with increasing sleep restriction on the word pairs that were correctly recalled. As such, the study does not suggest an effect of sleep restriction on the retention of word pairs.

Before the sleep-restriction the participants of Voderholzer *et al.* also performed a mirror tracing task in which they had to trace several line-drawn stimuli. After the sleep restriction the retention of this procedural memory was tested by repeating the task. No significant differences were found between the groups on the speed and accuracy before or after the restriction. Overall, there was a significant decrease in the retention from the difference between the pre- and post-test. One important difference between the study of Gias *et al.* and Voderholzer *et al.* is the time the control-group participants spent awake after learning. In Gias *et al.* they were awake for only 3 hours, whereas this was 10-12 hours for the 9 h sleep group of Voderholzer *et al.* This might have increased the benefit of sleep for the control group of Gias *et al.* and thus have resulted in a larger effect. However, this would reflect on early and late bed times rather than sleep restriction *per se*. The results of Volderholzer *et al.* do not suggest a detrimental effect of sleep restriction on long-term memory performance.

To summarise, the study of Gias et al. found an effect of total sleep loss on the change in retention of word pairs. However, only when comparing short-term memory retention with long-term memory retention, which is a debatable comparison. In addition, the short time-awake-after-encoding might have been extra beneficial for the control condition, which would explain the increased scores. Results from the other two studies by Kopaz et al. and Volderholzer et al. do not suggest an effect of sleep loss on long-term memory. The first might have suffered from flooring or ceiling effects masking the results. The latter did not find an effect despite more severe sleep loss. As such, there are no clear indications for a detrimental

*Table 5: **Tests Of Reasoning And Creativity**. Table shows sleep manipulation and cognitive outcomes of reasoning tests. Tests with significant results are bold.*

			Manipulation		*Outcome*						
First author (*year*)	*N*	Exp. Type	Sleep (h)	Nights	Cognitive test	Function measured	Performance parameters				
Randazzo (1998)	16	B	5 or 11	1	**TTCT**	**verbal creativity**	Flexibility =	Fluency ↓	Originality ↓		Average ↓
					TTCT	figural creativity	Fluency =	Original. =	Titles =	Rich =	Closure =
					CCT	connecting ideas		Accuracy =			
					WCST	**abstraction ability**	Flexibility =	Accuracy ↓↓↓	Learning =		
Kopasz (2008)[a]	22	CO	4 and 9 *or* 9 and 9	1	ToL	mental problem solving	Accuracy =				

Note: [a] cognitive tests were done after the recovery night.
Type: **W**= within groups, **B** = between groups, and **CO** = cross-over (participants did both). Tests: **TTCT** = Torrance tests of creative thinking, **CCT** = children's category test, **WCST** = Wisconsin card sorting test, **ToL** = tower of London. Outcome: '=' = no significant effect, ↓ = P < .05, ↓↓ = P < .01, ↓↓↓ = P < .001. Arrows point up for an positive effect and down for a negative effect. 'na' = not applicable.

effect of sleep loss on long-term memory.

TESTS OF REASONING AND CREATIVITY

Reasoning involves mental processes that signify cognitive-control functions such as problem solving, abstract thinking, creativity, and goal-orientated thinking (Gazzaniga et al., 2009b). Only two studies assessed the effects of sleep restriction on the higher cognitive processes. Study and test details are listed in table 5.

TASKS WITH REASONING AND CREATIVITY

The first study, earlier discussed, was by Kopaz *et al.* (2008). The cross-over design had a sleep-restriction condition with a 5 h night followed by a normal night (9 h), whereas the control condition consisting of two normal nights (9 h). After the normal night the participants did the tower of London test (ToL), which required mental problem solving. Participants were presented with arrangements of balls and had to indicate how many 'moves' were required to reach a given end configuration by following a given set of rules. The two conditions did not differ significantly on accuracy of the task. This might have been because of the measurement being taken after a recovery night, limiting the amount of sleep debt the participants might have had because of the sleep restriction.

The second study, also earlier discussed, was by Randazzo *et al.* (1998). In the study two groups had either 5 h or 11 h sleep after which a battery of cognitive tests was performed. It should be noted that all reported test data were standard scores based on normative data by age and thus partially corrected for the confound of age. The Torrance tests of creative thinking (TTCT) consists of two versions. The verbal version tests the creative development by scoring their flexibility (variety of strategies), fluency (generate a large number of ideas), and originality (unique or unusual ideas). The group that had 11 h of sleep scored significantly higher on fluency $P < .05$; $g = 1.31$), and originality ($P < .05$; $g = 1.34$). The control group, on average, scored 83 ± 17 on fluency while the sleep-restriction group scored 63 ± 12. On originality the control group average score was 93 ± 24 but the sleep-restriction group scored only 69 ± 10. This suggests a negative effect of sleep restriction on verbal creativity. The second version of the TTCT assess figural creativity via scoring the drawings made by the adolescents on fluency, originality, creative titles, richness, and resistance to closure of a drawing. None of these scores were significantly different between the short-sleep and long-sleep group.

A third test the two groups performed in the Randazzo *et al.* study was the Children's category test (CCT). This test evaluates learning and problem solving by asking the participant to identify as many connecting ideas or principles for one or more shapes, lines or figures shown on a card. The groups showed no significant differences on the total number of errors made while identifying the ideas.

The fourth and last test the groups performed was the Wisconsin card-sorting test that measures abstraction ability among others. In the test the participant is presented with four stacks with three predetermined but not shared principles that separate them. The participants are required to learn the criteria by adding new cards and receiving feedback. The perseverance and learning scores did not significantly differ between the groups. However, the accuracy in the long-sleep group was significantly higher than in the short-sleep group ($P < .01$; $g = -0.87$). Overall, the long-sleep group chose 114 ± 20 stacks correctly while the short-sleep group only chose 97 ± 17 stacks correctly. However, the experimental night was reported to be preceded by 3 nights consisting of 10 h sleep each night. However, the manipulation night was 11h for the control group and constituted a small sleep-extension. It might be that the sleep extension caused the difference and because of the between-group study a separation of effects of sleep loss or gain can be made.

To summarise, the results of the study by Randazzo et al. would suggest a negative effect of sleep loss or a possible effect of sleep gain on verbal creativity and abstraction ability. The study by Kopasz et al. found no effect of sleep loss on reasoning but this was likely because of a recovery night, limiting the actual sleep debt during the reasoning measure. As such, sleep is related to creativity and to abstract thinking.

IV. DISCUSSION

This analytic meta-review was set out to elucidate what is currently known of the effects of sleep (loss) on the cognitive ability of adolescents. Eleven studies that measured task performance and manipulated the sleep of adolescents were investigated. Two studies suggest an effect of sleep loss on the performance in tasks that mainly require processes of *simple attention*. Tasks that mainly require more *complex* processes of attention were not reliably indicated affected by sleep by any of the studies. The results of three studies suggest that increasing sleep duration leads to improved performance on task that are reliant on *working memory.* Only one study suggests that sleep loss has the opposite effect. Performance in tasks that require to keep items in *memory* for a *short period* is only impacted by severe sleep loss, as suggested by two studies. None of the studies made reliable indications of sleep loss affecting performance in tasks that require *long-term* retention. Finally, a single study suggests that sleep loss affects performance in tasks that rely heavily on creativity and abstract thinking (or *reasoning*). Taken together, the reviewed studies suggest that the cognitive ability of adolescents are affected by sleep loss. However, untangling the underlying mechanisms of this effect in terms of cognitive processes is difficult because task performance cannot be easily accounted for by single cognitive functions or processes.

Unravelling which processes are, or a single process is, responsible for decreased performance is complicated by what some sceptics call "*task impurity*" (Whitney & Hinson, 2010). Generally, simple cognitive tasks reflect multiple cognitive processes at once. Verbal terms like 'WM test' or 'PVT' cause researchers to confuse terminology with actual cognitive processes. Beside cognitive processes there are also non-cognitive processes involved in any given task, confounding the tangle further. For instance, a simple-reaction time test relies on the attentional processes to perceive the target, on the memory processes to remember what to do at target presentation, and finally requires the non-cognitive motor systems to produce a response. Moreover, analysing performance changes on more complex tasks in terms of cognition, is further confounded by different individual tactics that participants employ. The task-impurity problem can be overcome by dissociating between important processes via selecting specific, designing new, or combining the results of tasks. For instance, one adult sleep study has challenged the prevailing view that executive functions are impacted by sleep deprivation by dissociating the related processes and finding no effect on the executive functions (Tucker, Whitney, Belenky, Hinson, & Van Dongen, 2010).

The task-impurity problem has led some sleep researchers to theorise that insufficient sleep affects performance on nearly all cognitive tests in a global manner through degraded alertness and attention (Killgore, 2010; Whitney & Hinson, 2010). This is a bigger concern for the cognitive tests that rely on working or short-term memory than it is for those tests that are designed specifically to measure attention or vigilance. The results of current reviewed studies are in line with this view. For instance, Carskadon et al. (1981) interpreted their findings differently by taking into account the lapses of the participants during cognitive tests. The authors concluded that without the lapses the performance on the tests was nearly identical to the baseline prior to the sleep deprivation. Unfortunately, none of the other studies remarked on or investigated the possibility that simple loss of vigilance is responsible for changes in the score on cognitive performance tests. Hence, it is difficult to asses if this global degradation via attention also occurs in adolescents.

Adult sleep studies have shown similar effects of sleep loss on cognitive abilities of adults as the current review does for adolescents. In a large meta-analysis study the cognitive effects of adult short-term sleep deprivation (<47h) were quantified (Lim & Dinges, 2010). More than 70 adult studies were investigated. The authors found the largest combined effect size of the impact of sleep loss on the reaction time in the cognitive sub-domain of simple attention. Additionally, the adult study meta-analysis showed progressively lower effect sizes when going from the simpler to the more complex cognitive categories (e.g. attention to reasoning). The opposite pattern seems to be suggested in the sleep-loss effect sizes of the currently reviewed adolescent studies. The largest effect sizes are in task performance involving abstract thinking, followed by short- and long-term memory, working memory, and finally attention. It is possible that the effect of adolescent sleep-loss shows this reversed pattern because the frontal lobe of adolescents is known to undergo especially large developmental changes and is known to play a role in most control-function processes (Stuss & Alexander, 2000).

In contrast to the findings in adult studies are those of a meta-analysis that investigated the effect of sleep loss in children (5 – 12 *yo; Astill et al., 2012)*. In children the combined effect size of sleep loss on sustained attention is not present or very slim. In adults attention was the cognitive domain most affected by sleep loss, whereas in the present study the effect of sleep loss during adolescence on attention was small but present. Hence, a trend from childhood to adulthood is suggested in that the loss of vigilance due to sleep loss might be dependent on age. This is possibly due to earlier discussed maturation processes. Sleep loss also appears to have a moderate effect across all ages on complex attention and working memory. Retention, however, seems not to be associated with sleep curtailment in children, whereas in adults and in adolescence the short-term retention is suggested to be affected by sleep deprivation. Further direct comparison between the current review and the meta-analysis is made difficult due to the lack of experimental studies of effects in children and differences in how the cognitive tests are categorised between the studies (*e.g.* short *v.* long and explicit *v.* implicit for retention).

The current review has one minor and one major limitation. The minor limitation is that of brain development phase, or the close approximation: years of age. The minimum age of a number of the studied samples might have been too low to ensure a certain stage of development. In some study samples this was, luckily, compensated by the differences in adolescence-onset age of girls and boys. The study sample used by Gias *et al.* were all older males and the sample used by Peters *et al* contained all young females. However, the studies by Sadeh *et al.* and Fallone *et al.* might have sampled some pre-adolescent children. This might have influenced the relevance of their sample to the current review but hopefully only in a small way because of majority of adolescents. A major limitation of the current review is the small number of studies that were found to have investigated adolescent sleep effects. Just eleven studies in three decades might be explained by the fact that studies with expected adverse effects in young participants are rarely approved by ethical committees or parents. A morally superior alternative is to approach the adolescent sleep enquiry from the opposite direction; alleviate sleep debt by extending sleep and evaluate the changes that occur. For example, this was done in the study of De Wald-Kaufmann, Oort, and Meijer (2013). Additionally, most of the studies that were screened were rejected because of the age of the sample. Hence, dropping the criterion of objective-sleep measurements would not have resulted in an increased inclusion. The low number of studies and the general soundness of the studies allows for a rough idea of what is known but makes any solid conclusion on the topic of adult versus adolescent sleep premature.

RECOMMENDATIONS FOR FUTURE RESEARCH

Only one of the studies (Carskadon et al., 1981) included measures of pubertal-development stages. Age is only indirectly related and not equal to pubertal or brain development. Therefore, when an effect of adolescent development is expected, it is more accurate to look at pubertal stages than it is to look at age.

Seven of the eleven sleep-restriction studies that were reviewed made the effort to include an adaptation period with sleep guidelines in which participants had to sleep a set number of hours to ensure them being well-rested during baseline measures. In two of these studies the adaptation period was only meant to let the participants get accustomed to the sleep laboratory and let the adolescents self elect their sleep. However, three of the overall reviewed studies did not include an adaptation period and as a result might have investigated the effects of relative weak sleep-restriction on a sample with already a sizeable sleep debt (Sadeh *et al.*, Gias *et al.,* and Jiang *et al.*). Special care should be taken of the sleep history because the opposite might also hold. For instance, one study compared the effects of sleep loss on task acquisition after a week of habitual sleeping and after a week of extended sleep (Rupp, Wesensten, & Balkin, 2010). The results suggested that the extended sleep mediated the effect of subsequent sleep loss. Hence, a sample with a sleep buffer would confound experimental studies. To control for sleep debt a questionnaire could be used that assess symptoms of insufficient sleep (*e.g.* the CSRQ [Meijer, 2008]).

A large portion of the measures resulted in non-statistically significant differences between groups or conditions. Performing a *post-hoc* statistical power-analysis would allow for these null findings to be interpreted as an absence of an effect of a maximum size with a given likelihood (power). Most of the reviewed studies have ignored this optional power analysis and as a result the non-significant findings are very difficult to interpret. As a free software tool for power analysis the program G*Power is recommended (Faul, Erdfelder, Lang, & Buchner, 2007). *A priori* power analysis is additionally useful in reviewing the number of participants needed to achieve sufficient sensitivity or statistical power. For instance, if a medium effect is expected (d = 0.5) and a normal power (β-1 = .8) needs to be achieved, a repeated-measurement study requires approximately 35 participants. This number is nearly doubled if an independent-group design is used showing the clear benefit of using a repeated-measure design. Taking into account the suggested limit of 35 participants means that 7 out of 11 studies are possibly underpowered to detect medium effect sizes.

Future studies should strive to measure sleep-duration objectively. All things considered the best method is via activity-based monitoring since it is easy and cost-effective to employ (Sadeh, Hauri, Kripke, & Lavie, 1995). The benefit of using polysomnography instead of actigraphy is separating attentional lapses from actual task performance and can be done relatively simple during data analysis. This prevents the lapses from confounding the scores on cognitive-performance tests. Furthermore, as discussed above, efforts should be made towards acknowledging the task impurity problem and designing possibly (dual) tasks that isolate cognitive processes. Above described recommendations underline how experiments can be improved to investigate the actual mechanisms of the impact of sleep loss in an efficient manner.

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