Associations between objectively measured sleep and cognition in older Icelandic adolescents

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Dissertation submitted in partial fulfilment of a Ph.D.-degree

UNIVERSITY OF ICELAND
SCHOOL OF EDUCATION

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Faculty of Sport and Health Sciences
School of Education, University of Iceland
March 2022

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ISBN (978-9935-9625-4-6)
Printed at: Háskólaprent in Reykjavík, Iceland 2022

Tengsl svefns og hugrænna þátta meðal íslenskra ungmenna

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Ritgerð lögð fram til að uppfylla kröfur um doktorsgráðu

Íþrótta- og heilsufræði
Menntavísindasvið Háskóla Íslands
Mars 2022

Abstract

Background Insufficient sleep is associated with an increased risk of a variety of negative health outcomes and has been shown to adversely affect academic and cognitive function. Despite strong evidence of the deleterious effects of short and disrupted sleep on health, studies that use objective methods to measure adolescent free-living sleep, in general, and its association with academic and cognitive performance, specifically, are scarce, particularly during the critical transition from compulsory to secondary education.

Aim The aim of this research was to use objective measures to quantify the free-living sleep of Icelandic adolescents at ages 15 and 17, as they transition from compulsory to secondary education, and to determine whether their sleep patterns are associated with academic and cognitive outcomes.

Methods The study sample came from six elementary schools in Reykjavík, Iceland. One week of free-living sleep measured with wrist actigraphy was collected at two time points. The first wave of data collection occurred in 2015, where 280 participants had valid sleep data (mean age 15.9±0.3 years). Two years later, 199 participants had valid sleep data (mean age of 17.7±0.3 years). In total, 145 participants had complete data at both data collection points. During the first wave of data collection, academic achievement was objectively quantified using the combined score from standardized national examinations administered to all 10th grade students in mathematics, English, and Icelandic. During the second wave of data collection, an n-back working memory task and Posner cue-target visual attention task were used to objectively assess cognitive function.

Results Over all measured nights at both time points, Icelandic adolescents averaged late bedtimes (00:43 at age 15, 01:12 at age 17), short total sleep time (6.6 ± 0.7 h/night at age 15 and 6.2 ± 0.7 h/night at age 17) and high variability in total sleep time (weekly standard deviations of 1.3 h and 1.4 h at ages 15 and 17, respectively). Thus, during the two year change from age 15 to age 17, students sleep duration decreased, night-to-night variability in sleep duration increased, and students went to bed 29 min/night later. Cross-sectional regression of the data collected at age 15 in those with standardized exam scores (n=253) demonstrated that both bedtime and night-to-night variability in total sleep time were negatively associated with the average score across all topics. Similarly, cross-sectional analysis of students who underwent cognitive function testing at age 17 (n=160) showed that time in bed the night before cognitive testing was negatively associated with response times during the most challenging memory task. However, sleep measures the night before did not correlate with performance on the attention task and weekly sleep parameters were not associated with either cognitive task.

Conclusion In general, Icelandic students go to bed late and have short and inconsistent sleep schedules at both age 15 and age 17. Cross-sectional results at age 15 indicate that those with earlier bedtimes and more consistent sleep schedules score higher on national exams. In addition, the cross-sectional results at age 17 demonstrated that shorter time in bed the night prior to the cognitive testing was associated with poorer performance on the most challenging short-term memory task. Despite the presence of several significant associations, the relationship between free-living sleep and academic and cognitive task performance in healthy adolescents is less clear than that identified in laboratory studies or with self-report, perhaps due to high night-to-night sleep variation. Future studies with longer observation periods and interventional components could further clarify the relationship between free-living sleep and academic and cognitive performance in adolescents.

Ágrip (Abstract in Icelandic)

Bakgrunnur Fyrri rannsóknir hafa sýnt fram á að nægur svefn á unglingsárum er lífsnauðsynlegur, og að stuttur og ófullnægjandi svefn getur haft áhrif á andlega og líkamlega heilsu. Enn fremur hefur verið sýnt fram á að stuttur svefn getur haft neikvæð áhrif á námsárangur og hugræna virkni. Þrátt fyrir sterkar vísbendingar um skaðleg áhrif ófullnægjandi svefns á heilsuna skortir rannsóknir sem mæla svefn hlutlægt (við frjálsar aðstæður). Einnig skortir rannsóknir sem nota hlutlægar mælingar til að kanna tengsl svefns á námsárangur og hugræna frammistöðu, sérstaklega á þessum mikilvæga tíma þegar ungmenni færa sig úr grunnskóla og yfir í framhaldsskóla.

Markmið Meginmarkmið þessarar doktorsritgerðar var að nota hlutlæga mælikvarða til að mæla svefn íslenskra ungmenna á aldrinum 15 til 17 ára, við skólaskiptin úr grunnskóla yfir í framhaldsskóla, og að skoða hvort svefnmynstur þeirra tengist námsárangri og hugrænum þáttum.

Aðferðir Rannsóknarúrtakið kom frá sex grunnskólum í Reykjavík. Gögnum var safnað vorið 2015, þar sem 280 þátttakendur höfðu gild gögn um svefn (meðalaldur 15,9 ± 0,3 ár). Tveimur árum síðar höfðu 199 þátttakendur gild svefngögn (meðalaldur 17,7 ± 0,3 ár). Hægt var að tengja gögn hjá 145 nemendum á báðum tímapunktum. Svefn var mældur í eina viku með actigraph hreyfimæli sem var staðsettur á úlnliði. Í fyrri gagnasöfnun árið 2015 var meðaleinkunn í samræmdum prófum í íslensku, stærðfræði og ensku notuð sem mælikvarði á námsárangur. Tveimur árum seinna var hugræn virkni mæld með n-back minnisprófi og Posner cue-target athyglisprófi. Við mat á gögnum var notast við ýmsar tölfræðilegar greiningar, keyrðar í R tölfræðiforritinu.

Niðurstöður Íslensk ungmenni fara að meðaltali seint í rúmið (00:43 við 15 ára aldur, 01:12 við 17 aldur) og heildar svefntími er stuttur (6,6 ± 0,7 klst /nótt 15 ára og 6,2 ± 0,7 klst./nótt 17 ára). Enn fremur er breytileiki í svefni hár á báðum tímapunktum (1,3 klst./nótt og 1,4 klst). Þegar heildarbreyting á svefni frá 15 til 17 ára aldurs er skoðuð, sést að svefnlengd nemanda minnkar, svefnbreytileiki á nóttu eykst og nemendur fara að meðtali að sofa 29 mínútum seinna. Við fyrri gagnasöfnun, árið 2015 (n=253) fundust neikvæð tengsl á milli svefnlengdar, háttatíma og einkunna á samræmdu prófi sem gefur til kynna að nemendur sem fara fyrr að sofa og eru með minni breytileika í svefni fá hærri meðaleinkunn á prófunum. Svipað fannst í seinni gagnasöfnun árið 2017 (n=160), en þar sást að styttri tími í rúminu nóttina fyrir hugræna prófið tengdist slakari árangri, en þó aðeins á mest krefjandi minnisprófinu. Hins vegar voru ekki tengsl á milli svefns kvöldið áður og frammistöðu á athyglisprófinu og engin tengsl fundust á milli heildarsvefns yfir vikuna og niðurstöðum á minnis- og athyglisprófinu.

Samantekt Almennt fara íslensk ungmenni seint að sofa og svefnbreytileiki er hár bæði við 15 og 17 ára aldur. Að sama skapi styttist svefnlengd á tveggja ára tímabili þegar nemendur útskrifast úr 10. bekk og skipta yfir í framhaldsskóla. Þversniðsniðurstöður við 15 ára aldur sýna að svefngæði og háttatími hafa áhrif á einkunnir, en þeir nemendur sem fara fyrr að sofa og eru með lítinn breytileika í svefni fá hærri einkunnir í samræmdum prófum. Að auki sýndu niðurstöður við 17 ára aldur að styttri tími í rúminu nóttina fyrir hugrænu prófin tengdist slakari frammistöðu á mest krefjandi minnisverkefninu. Svefn virðist því hafa áhrif á hugræna þætti hjá 17 ára unglingum. Þrátt fyrir að fyrri rannsóknir hafi sýnt mikilvæg tengsl milli svefns og hugrænnar frammistöðu hjá heilbrigðum unglingum, virðast tengslin sem mælast hlutlægt vera óljósari en þau sem koma fram á rannsóknarstofu eða sem mæld eru með huglægum mælitækjum eins og spurningalistum. Ein skýringin getur verið mikill breytileiki í svefni hjá úrtakinu en framtíðarrannsóknir með lengri athugunartímabilum og íhlutunum gætu skýrt sambandið milli svefns og náms- og hugræns árangurs hjá unglingum enn frekar.

Acknowledgements

This project is based upon studies performed by the Centre of Sport and Health Sciences at the University of Iceland in collaboration with National Institutes of Health (NIH), Bethesda, USA. The measures for the first wave of the study was conducted in 2015 at the University of Iceland. During the second wave measurements in 2017, the department of Sport and Physical Activity, Western Norway University of Applied Sciences, Norway joined the collaboration. I would like to thank all the participants and funders, without their contributions, this study would not exist. The Icelandic Centre for Research (RANNIS) primarily funded the study. The Ministry of Education, Science and Culture, the Iceland Primary Health Care Research Fund, and doctoral grants of the University of Iceland Research Fund provided additional support.

First and foremost I would like to thank my main supervisor Professor Erlingur Jóhannsson for not only his guidance and help but his understanding of the process, willingness to listen to my complaining and endless support, especially during the final stretch. I am beyond grateful for the trust he gives me. I am sincerely thankful to have my co-supervisor, Dr. Robert Brychta at the NIH along on this journey as his endless patience and guidance was critical and much appreciated. Without his supervision and help I would not have been able to graduate. His understanding and technical/data help was vital and much cherished. Thank you Rob! Lastly, I would like to thank Dr. Hilde Gundersen for assistance with collecting and analyzing the cognitive data and all her help and assistance as part of the doctoral committee. Having these fantastic researchers behind you when you are starting your research and academic career is not something I take for granted and I am extremely grateful for all their effort and hard work.

I would also like to thank my co-workers at the University and doctor students (now doctors) that were in their journeys when I started mine. Vaka Rögnvaldsdóttir, my friend, colleague and my role model that started her PhD during the first wave of data collection and I was so lucky to be by her side while she mastered teaching, being a doctor student and having a large family. Seeing her succeed gave me courage that I could also finish this degree. Her support, guidance, comparing notes, sharing ideas and tables/graphs is probably the reason I can soon call myself a doctor as well. There are no words to thank you so Takk! Further I need to thank Dr. Sunna who was finishing her

PhD when I was starting mine and helping organizing the large data collection and Soffía who was part of our valuable team. Although I was the younger and less experienced, these amazing ladies took me in and helped me tremendously. I have to give a huge thank you to Sigga Lára who was my supervisor in my master thesis and dragged my into the data collection in 2015, that was probably one of the better decision I have taken in my life so far. Þórdís, Örn, Gréta and all the other amazing teachers at School of Education for helping me at the starting of my teaching career. There are so many obstacles to climb and endless things to learn that I would never had made it without their assistance. I would also like to thank Dr. Kong Chen for guidance and help in reviewing the papers, his valuable input and always willing to ask the right questions. Lastly, the team of students and researchers that collected the data. It was remarkable to have such great group of people that worked so efficiency together.

I want to thank Hans Haraldsson at the Educational Research Institute for the help with data analyses, the many great discussions and always being available and ready to discuss different way to look at the concept and the overall data. Further, I have to give a special thanks to the other staff members at the Educational Research Institute who sat with me for large portions during my studies and really made it amazing and exciting every day to go to the office. I also want to thank Randi and her team at the Writing Center for their guidance, and Bjarnheiður who was in her PhD journey with me, it was great to have fellow students to talk to when you felt very much alone.

This journey would not have been possible without the help of my parents and my friends and family. My mother, Erla Gunnarsdóttir, who is my role model and my best friends. For all the talks, shoulder to cry on and endless help; whether it was by going out to run with me or just taking Elísabet Erla for few hours while I finished yet another draft or another round reviews. I am amazed by her incredible courage and strength every day! And for my father, Stefán, for his support and guidance. Further, this PhD journey would not have been possible if it wasn´t for the amazing support that my husband, Pablo, gives me every day. Reading over my text, listening to complains and letting me sleep in for 30 more minutes in the morning. I am so thankful to have this amazing family and many friends that give me endless support and always have my back, thank you!

This thesis is for my biggest supporters in life, my husband Pablo Punyed and my daughter Elísabet Erla. They gave me the strength to do this thing called life every day <3

Table of Contents

List of figures

List of tables

List of papers

This thesis is based upon the following three original research papers.

Paper 1

Stefansdottir, R., Rognvaldsdottir, V., Gestsdottir, S., Gudmundsdottir, S. L., Chen, K. Y., Brychta, R. J., & Johannsson, E. (2020). Changes in sleep and activity from age 15 to 17 in students with traditional and college-style school schedules. *Sleep Health*, *6*(6), 749-757.

Paper 2

Stefansdottir, R., Rognvaldsdottir, V., Chen, K. Y., Johannsson, E., & Brychta, R. J. (2022). Sleep timing and consistency are associated with the standardised test performance of Icelandic adolescents. *Journal of sleep research*, 31(1), e13422.

Paper 3

Stefansdottir, R., Gundersen, H., Rognvaldsdottir, V., Lundervold, A. S., Gestsdottir, S., Gudmundsdottir, S. L., ... & Johannsson, E. (2020). Association between free-living sleep and memory and attention in healthy adolescents. *Scientific reports*, *10*(1), 1-13.

Declaration of contribution

The PhD student collected the data in 2015 and 2017. For the first data collection in 2015 the student was part of the research team that measured participants at the schools while assisting with the actigraph data collection. In 2017 the student was project manager over contacting the participants, measuring, collecting, and analyzing the actigraph and questionnaire data.

The student participated in organizing the research and collecting both objective and subjective data and lined up the 2017 data constructed after the 2015 data base.

The contribution of the PhD student in writing the papers was accordingly:

Paper 1 - Collected and analyzed the data, drafted the manuscript and helped manage reviews from co-authors.

Paper 2 - Collected and analyzed the data, drafted the manuscript and managed reviews from co-authors. Help submit and go over revision from journal.

Paper 3 – Collected and analyzed the data, wrote the manuscript, managed reviews from co-authors and was the corresponding author.

List of abbreviations

ADHD	Attention-deficit hyperactivity disorder
BMI	Body mass index
DXA	Dual energy X-ray absorptiometry
DSP	Delayed sleep phase
DLMO	Dim light melatonin onset
LSOC	Lifestyle of 7-9-year-old children
GABA	gamma-Aminobutyric acid
GMT	Greenwich Mean Time
HHUI	Health behavior of Icelandic youth
NREM	Non-REM
NSchD	Non-school days
NSF	National Sleep Foundation
PA	Physical activity
PSG	Polysomnography
REM	Rapid eye movement
SchD	School days
SD	Standard deviation
SCN	Suprachiasmatic nucleus
WASO	Wakening after sleep onset
WC	Waist circumference
WHO	World Health Organization

1 Introduction

Sleep is one of the basic biological states that occurs in almost all living creatures approximately every 24 hours. Humans spend about one third of their life sleeping, a state of total unconsciousness. Yet we do not fully understand the function or importance of sleep. In recent years, the science behind sleep has advanced and remarkable discoveries have been made highlighting the importance for the mind and body to gain adequate sleep.

Teenagers are recommended to sleep at least 8-10 hours per night (Hirshkowitz et al., 2015) and follow a consistent schedule in order to maintain overall health and well-being (Gruber et al., 2014). Insufficient sleep has been associated with numerous negative physical (Garaulet et al., 2011), mental (Sivertsen, Harvey, et al., 2014), and cognitive outcomes (Dewald et al., 2010; Lo et al., 2016), while sleep extension has been shown to improve metabolic factors and eating habits (Chaput & Tremblay, 2012), academic performance (Curcio et al., 2006), and cognitive function (Dewald et al., 2013). Furthermore, adequate sleep may be important for continued brain development during adolescence (Kopasz et al., 2010). Most of what is known about the deleterious effects of short and disrupted sleep on health has come from laboratory studies or self-reported data; studies that measure sleep objectively in free-living conditions are lacking. Likewise, studies using objective measures to explore the association between sleep and academic and cognitive performance during the critical stage when adolescents transition from compulsory education to secondary education are scarce.

1.1 Sleep anatomy

The study of human sleep has a relatively short history, which is reflected in the limited scientific sleep experiments conducted prior to the second half of the 20th century. During this time, there was a lack of scientific interest in sleep since, according to the widely accepted “passive process theory”, brain activity was simply turned off while asleep (Dement, 1998). It was not until 1952, when Aserinsky and Kleitman made the breakthrough discovery that, during certain periods of sleep, continuous eye movement could be detected using electrooculography (Aserinsky & Kleitman, 1953). The pair concluded that the periods of sleep with rapid eye movement (later termed REM sleep), which also included irregular respiration and increased heart rate, were associated with dreaming. A few years later Kleitman´s pupil, Dement, first published a description of the basic sleep cycle and sleep stage architecture (Dement & Kleitman, 1957).

To understand how sleep occurs, a brief description of the brain structures and biological mechanisms that underlie it is required. Deep inside the brain is a peanut-size structure called the hypothalamus where groups of nerve cells act as control centers affecting sleep and arousal. The suprachiasmatic nucleus (SCN) is located inside the hypothalamus and plays an important role in controlling our circadian rhythm through light exposure (Fuller et al., 2006). At the base of the brain, the brain stem communicates with the hypothalamus to control the transition between wake and sleep. There, the sleep-promoting cells produce gamma aminobutyric acid (GABA), a brain chemical which is the key inhibitory neurotransmitter of the central nervous system (Gottesmann, 2002). Other important brain structures include the thalamus, which sends information regarding sound and other sensations to the cerebral cortex, and the pineal gland, which receives information from the SCN and increases production of the hormone melatonin, and the basal forebrain, where the chemical adenosine is released. These processes all help synchronize the body’s sleep-wake cycle (Fuller et al., 2006).

1.1.1 Sleep-wake regulation

The two-process model, first introduced by Borbély and colleagues in 1982 (Borbély, 1982) and described more recently by Crowley et al. (Crowley et al., 2014), explains how two biological mechanisms work together to regulate the sleep-wake cycle (Figure 1). In this model, Borbély labelled the homeostatic sleep-wake component as Process S and the circadian component as Process C. Independent of each other, they both influence the amount and timing of sleep and, combined, they are probably the most important players when explaining the depth and timing of sleep (Deboer, 2018). The coordination of the sleep homeostatic and circadian systems account for typical daily schedules among normal healthy adults that entail 16 hours of constant wakefulness during the day, followed by 8 hours of consolidated sleep at night (Dijk & Czeisler, 1995).

In Figure 1.1, sleep pressure is on the y-axis and time of the day is on the x-axis. In this example, the grey shades are used to represent the ideal sleep duration of 9 hours, which takes place from 10 p.m. to 7 a.m. The upward-facing arrow set at 9 p.m. shows the onset of melatonin production (termed the dim-light melatonin onset, or DLMO), which typically happens before bedtime. Process C (red curve) shows sleep pressure changing with a cycle length of 24 hours, where the pressure to sleep is highest approximately 7 hours after DLMO and sleep pressure is lowest just before DLMO (Crowley et al., 2014). As the schematic representation of the model shows, Process S (blue curve) depends on the timing and duration of sleep and being awake, with sleep pressure highest shortly before sleep onset and then resolving over the course of active sleep and thus, lowest at the beginning of the waking day. Ideally, the two processes interrelate to maintain sleep at night and alertness during the day.

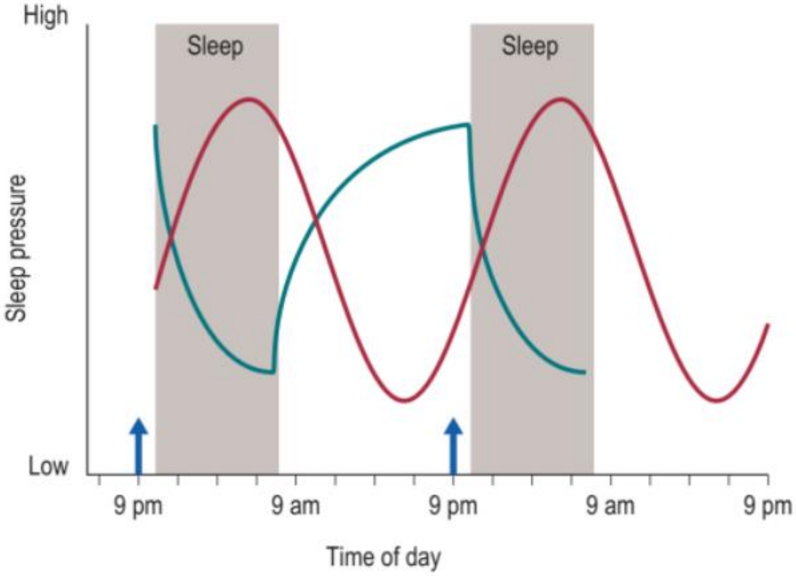

Figure 1.1 A schematic representation of the Two Process Model of Sleep Regulation. Sleep pressure in its broad concept is illustrated on the y-axis as a function of time spanning over 2 days. Ideal sleep duration of 9 hours, from 10 p.m. to 7 a.m. is presented with shaded grey rectangles. At 9 p.m. the upward-facing arrow explains the time of melatonin onset (DLMO phase), that usually takes place 1 to 2 hours before bedtime. The sleep pressure change of cycle length (24 hours) is Process C (red curve) where the pressure to sleep is highest around 7 hours after DLMO phase and sleep pressure lowest before bedtime or just before DLMO phase. Process S (blue curve) is dependent on the timing and duration of sleep and wake. At sleep onset, sleep pressure is highest but over the course of sleep it disperses. Sleep pressure is lowest at the beginning of the waking day but accumulates throughout the day and is highest later in the evening. Preferably, the two processes interrelate to maintain sleep at night and alertness during the day.

Figure from (Crowley et al., 2014).

The homeostatic drive can be explained as “a process whereby the ‘pressure’ for sleep increases the longer an individual has been awake” (Foster & Kreitzman, 2014). In general, the sleep-wake homeostasis keeps track of sleep needs and reminds the body to sleep. Studies have shown that when sleep is lost, humans can compensate by prolonging the duration of sleep the following night (Deboer, 2018) but can only sustain this sleep deprivation for a short period of time. Current research suggests that the status of one’s sleep-wake homeostasis can be quantified using physiological correlates such as electroencephalography (EEG) monitoring (Deboer, 2018). However, the specific neurochemical and neuroanatomical factors involved in the homeostatic sleep drive are not completely understood (Crowley et al., 2014; Foster & Kreitzman, 2014).

The circadian rhythm describes the cyclical biological changes that occur over a period of roughly 24 hours, including changes in body temperature, blood pressure, and hormone levels (e.g. cortisol, melatonin, etc.). Further, this biological clock can drive and alter our sleep patterns, alertness, physical strength and even mood and behavior (Foster & Kreitzman, 2014). Unlike the homeostatic sleep-wake system, the circadian system is self-sustaining (Crowley et al., 2014). This internal biological system is observed in almost all living beings from cyanobacteria to plants and humans. It arises from the expression and activity of genes and gene products (Konopka & Benzer, 1971) and is controlled by external cues, mainly light and darkness (King & Takahashi, 2000). Biological clocks composed of specific molecules interact with cells to help produce the circadian rhythm and regulate their timing (Foster & Kreitzman, 2014). In mammals, this time-keeping system, or the master circadian pacemaker, is located in the SCN of the hypothalamus. The pacemaker organizes multiple circadian biological rhythms and regulates according to external cues, most often light/dark conditions that are transmitted through the eye (Reppert & Weaver, 2002). The SCN uses these neuronal and hormonal signals to co-ordinate the circadian physiology and behavior and thus synchronize the local clocks within the cells of most organs and tissues (Dibner et al., 2010). Although the circadian rhythm mainly uses cues from the environment, they continue in the absence of cues, resulting in low alertness levels in the middle of the night (Kreitzman & Foster, 2011). Hormone secretion for signaling wake and sleep is coordinated with the internal clock starting with cortisol release that begins at sunrise and causes natural awakening. However, the most reliable marker of the human circadian system is the start of the melatonin secretion (Klerman et al., 2012), or DLMO (Lewy & Sack, 1989), as the secretion of the sleep hormone melatonin increases throughout the day (Klein & Moore, 1979), peaking in the evening when the body is ready to go to sleep.

In theory, the timing of the two processes help maintain wakefulness and alertness during the day and promote sleep during the night. The circadian rhythm and sleep-wake system involves a complex interaction of multiple brain regions, neurotransmitter systems and modulatory hormones, making it vulnerable to disruption (Foster & Kreitzman, 2014). Prolonged circadian rhythm disruption is associated with declines in memory, reduced motivation, depression, metabolic abnormalities, obesity, and greater risk of cancer (Wulff et al., 2010). Common examples of circadian disruption include nightshift work and travel between time zones, usually referred as jet lag. These conditions cause a mismatch between the internal clock and the actual clock (Weingarten & Collop, 2013) and can lead to deleterious health effects (Drake et al., 2004). The term “social jet-lag” has been used to describe a substantial shift in the timing of the mid-point of sleep between workdays and free-days (Roenneberg et al., 2012). It stems from the demanding schedule of modern society when school, work, or the social calendar greatly influences the sleep-wake cycle (Roenneberg et al., 2012; Wittmann et al., 2006), and has been shown to be associated with negative health problems (Wong et al., 2015). Similarly, the ideal balance of the “Two Process Model” of sleep regulation is confronted during adolescence when both processes are altered with bioregulatory changes, societal demands and lifestyle choices such as increased academic workload and extra-curricular activities (Carskadon, 2011; Crowley et al., 2014).

2 Sleep during adolescence

Adolescence, the transitional phase between childhood and adulthood, is a period of dramatic change due to considerable physical and mental development (Crone & Dahl, 2012; Curtis, 2015), increased independence, and an altered educational and social environment during the transition from primary to secondary school (Zeedyk et al., 2003). The stage is usually marked by pubertal onset and development, where the process of sexual maturation and reproductive competence occurs. Puberty is also the period when the hypothalamic-pituitary-gonadal axis is re-activated after an inactive period during childhood (Sisk & Foster, 2004). In addition, the adolescent brain undergoes structural reorganization with a sharp decline in cortical synapses ("pruning") that lead to a decline in cortical grey matter volume which impacts sleep physiology (Crowley et al., 2014).

Although, sleep needs remain stable throughout adolescence (Crowley et al., 2018), a delay in sleep onset commonly observed in older adolescents can be attributed in part to two biological mechanisms: a shift in the circadian rhythm and a slower accumulation of sleep pressure. Thus, the onset of adolescence brings sudden changes to the timing and composition of sleep (Colrain & Baker, 2011) partly caused by these biological developments.

2.1 Biological causes for sleep change during adolescence

2.1.1 Sleep-wake system changes during adolescence

During puberty, the dynamics of the homeostatic system are altered, and older and more mature adolescents find it easier to stay awake longer. Thus, studies have found that the accumulation of sleep pressure seems to slow down during puberty (Carskadon, 2011) and, despite experiencing the same deleterious effects of sleep deprivation, older adolescents do not notice it as readily as younger adolescents and are less likely to alter their sleep schedule accordingly. For instance, a laboratory-based study demonstrated that more mature adolescents had a longer sleep latency compared to their younger, less mature counterparts following a period of extended waking hours (Taylor et al., 2005).

The biological shift that occurs with pubertal maturation is demonstrated in Figure 2.1, where the process S of the younger, immature adolescent (blue solid line) increases faster during the waking day than the older, more mature adolescent (blue dashed line). Thus, at bedtime (around 10 p.m. in this example) the two individuals have not reached the same level of sleep pressure (Crowley et al., 2014). However, as mentioned above, the dissipation of process S does not change across adolescent development and, thus, the sleep recovery process, or sleep "need", remains the same for older and younger adolescents (Oskar G Jenni et al., 2005; Tarokh et al., 2012).

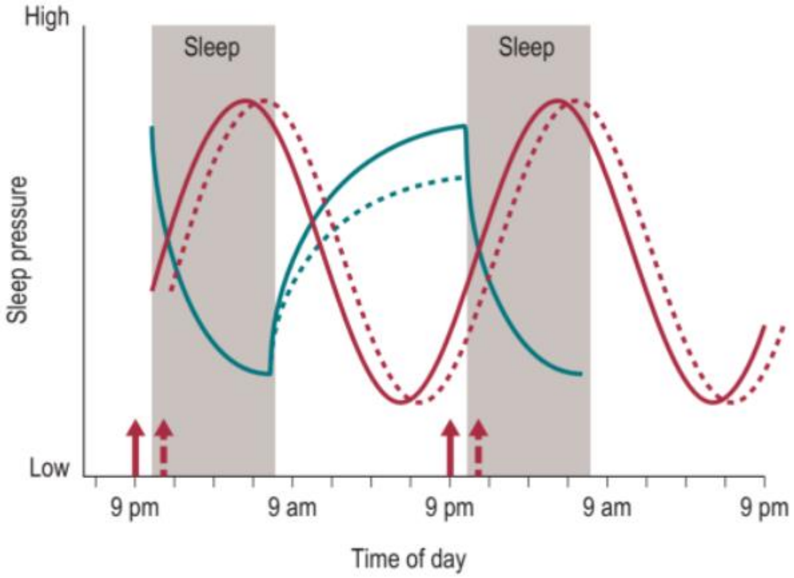

Figure 2.1. A schematic representation illustrating the relative change to process C and process S with maturation. Symbols and explanation are same as in Figure 1. Older and more mature adolescents are shown in dashed line and younger, immature adolescents are shown in solid lined. The dissipation of Process S is shown as a solid blue line for both mature and immature adolescents since this recovery process shows little change across adolescence. A delayed Process C and a slower accumulation of Process S promote later sleep times with maturation.

Figure from (Crowley et al., 2014).

2.1.2 Circadian rhythm during adolescence

Early research in adolescents showed that the circadian timing system also undergoes a phase delay during puberty (Andrade et al., 1993) which is similar to the shift observed in several other mammalian species (Hagenauer et al., 2009). Thus, the primary cause of the circadian phase delay seems to stem from a biological process rather than from social and/or behavior factors. This change in circadian rhythm makes the internal day longer for adolescents than adults (Carskadon et al., 1999) and was confirmed in a laboratory study conducted by Carskadon et al., which concluded that older adolescents have a later phase of melatonin-secretion than their younger peers (Carskadon et al., 1997). The developmental change in Process C and DLMO experienced by older and more mature adolescents is visible in Figure 2.1 as the dashed red curve and arrow, respectively, which are both shifted later than those of young adolescents (solid red curve and arrow). In general, this shift means that the greatest pressure for sleep dictated by the circadian system in more mature adolescents is closer to wake-up time (Figure 2.1), and the nadir in circadian system sleep pressure shifts later into the evening (Crowley et al., 2014).

2.2 External causes of sleep change during adolescence

Over, the last two decades, adolescents in the United States are sleeping for increasingly shorter durations (Keyes et al., 2015) and now less than 30% of US teens report achieving the recommend amount of sleep (Wheaton et al., 2018). Other countries have documented reductions in sleep with age during adolescence as well (Olds et al., 2010), including the Icelandic population (Rögnvaldsdóttir et al., 2017; Thorleifsdottir et al., 2002). This decline in sleep could be due in part to the biological changes during puberty discussed in the previous section (Andrade et al., 1993; Carskadon, 2011; O. G. Jenni et al., 2005; Tarokh et al., 2016). However, psychosocial and societal factors could also play a role. For instance, a general reduction in parental supervision, specifically parent-set bedtimes (Short et al., 2013), could lead to increased night-time media usage (Hrafnkelsdottir et al., 2018; Scott & Woods, 2018) which push bedtimes later and displace time for sleep. Increased participation in extra-curriculum activities, earlier school start times, more demanding academic load, and employment are all factors that contribute to the shorter sleep duration observed at this age (Short et al., 2013).

2.2.1 Changes in sleep

Studies that have examined the change in sleep over both shorter (months) and longer (years) periods report that average adolescents sleep decreases with age (Olds et al., 2010). A longitudinal, self-reported study from Switzerland found that sleep duration decreased from an average of 9.0 hours per day at age 13 to 8.1 hours at age 16 (Iglowstein et al., 2003). Similarly, a self-reported study from Portugal documented a drop in mean sleep duration from 9 hours at age 13 to 8.25 hours at age 17 (Paciência et al., 2016). Two self-reported studies from America show a similar decline in sleep between ages 14 to 17 where average sleep decreased from ~8.5 hours per day at age 14, to an average of 7.5 hours per day by age 17 (Lytle et al., 2013; Mitchell et al., 2013).

Interestingly, a detailed meta-analysis of objectively measured sleep parameters from childhood to adolescence found that sleep duration decreased with age, but only on school days. On non-school days the duration remained the same from childhood to the end of adolescence (Ohayon et al., 2004). The authors note that the different measurement techniques are likely to yield different results when studying the sleep patterns of healthy children and adolescents, making comparisons between studies employing the different techniques difficult (Ohayon et al., 2004).

2.2.2 School start times

The influence of school start time on adolescent sleep has been researched for over 20 years. Children spend about 13,000 hours in school from kindergarten through 12th grade (Crowley et al., 2018), thus, the school environment is an influential societal factor on adolescent sleep patterns. Carskadon et al., examined the effects on sleep patterns, sleepiness, and circadian phase when students in 9th grade transitioned to earlier school start time in grade 10 (Carskadon et al., 1998). The study reported that students did not go to sleep earlier in 10th grade, but they had to wake up significantly earlier and thus obtained less sleep. This earlier start was associated with increased daytime sleepiness and significant sleep deprivation (Carskadon et al., 1998). Moreover, their study revealed that the melatonin onset phase for the 10th grade students was 40 minutes later than in 9th grade and, thus, biologically, the adolescents should have been sleeping when they were required to wake up to attend classes (Carskadon et al., 1998).

Following this landmark study, several interventional studies were able to demonstrate that this inverse situation – delaying the start of the school day – was a useful tool to mitigate short sleep amongst adolescents (Boergers et al., 2014; Wheaton et al., 2016). More recently, a meta-analysis of previous studies has shown that delaying school start times is associated with longer sleep duration (Bowers & Moyer, 2017), which can lead to enhanced cognitive performance, improved attention levels, and greater academic success (Owens & Adolescent Sleep Working Group, 2014). Further, studies that have examined the association between sleep parameters (mainly sleep duration and efficiency) and register-based school absence have shown that a 30 minute delay in school start time can improve attendance, decrease tardiness and sleepiness, reduce motor vehicle crashes, and improve grades (Hysing et al., 2015; Wheaton et al., 2016).

2.3 The perfect storm model

The short and ill-timed sleep that older adolescents experience is most likely a combination of many factors that have been discussed above. The primary factors thought to contribute to these changes include psychosocial factors, such as reduction in parent-set bedtimes (Loessl et al., 2008), increased screen time, and increased academic pressure (Adam et al., 2007). Along with biological development, which promotes later bed- and rise-times through a delay in circadian timing (Crowley et al., 2007), a slowing of the accumulation of homeostatic sleep pressure (O. G. Jenni et al., 2005), and a delay in melatonin release (Carskadon et al., 1997). The combination of these bioregulatory and psychosocial interactions are shown with arrows in Figure 2.2. It seems that these psychosocial and biological changes by themselves may not affect the duration of sleep. However, when they are combined with societal pressures, such as early school start times which force early rise times, it results in sleep reduction for older adolescents (Owens & Group, 2014; Tarokh et al., 2016). Carskadon first described this combination of factors as a “perfect storm” (Carskadon, 2011), leading to insufficient adolescent sleep. The model provides a theoretical basis for understanding the behavior in sleep changes during adolescence and the many factors that come into play.

The current thesis builds on this general model but also considers the influence of the school system transition, the effects of different school scheduling systems on sleep, and the potential consequences of late bedtimes and short and inconsistent sleep on academic performance and cognitive development (Figure 2.2).

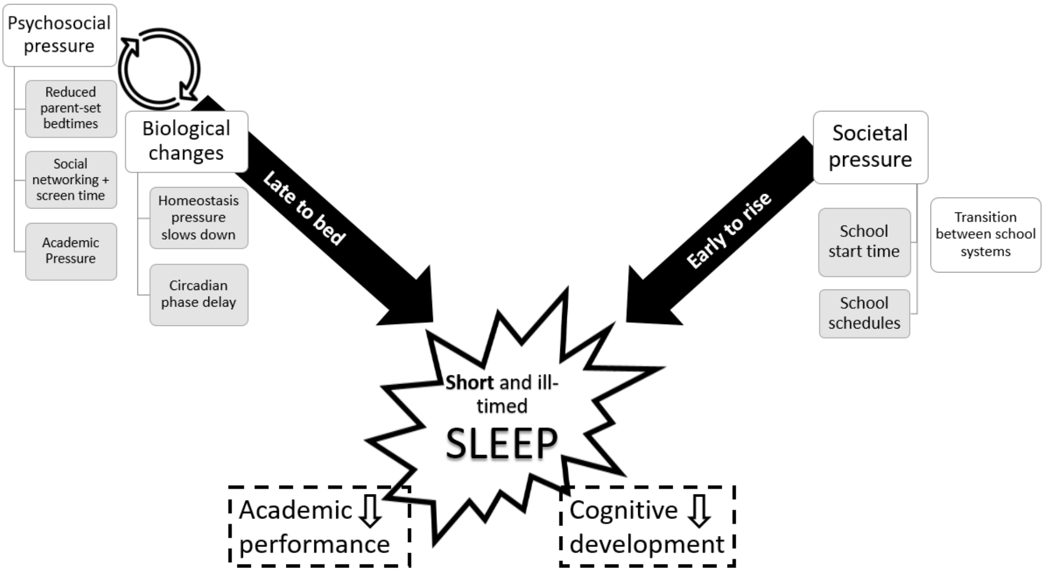

Figure 2.2. Adolescent development and sleep: Building on the perfect storm model first proposed by (Carskadon, 2011), the figure illustrates the different factors described in the text that can contribute to the change in sleep behaviour and can contribute to shortened and ill-timed sleep during adolescence. Due to bioregulatory changes on homeostatic sleep system and the circadian timing system, sleep onset and thus bedtime is shifted later. Psychosocial factors probably enhance the delayed sleep. The circled arrows show the likely interaction between the bioregulatory and psychosocial pressures that stems from social factor and academic pressure that can push bedtimes later. Further, these activities (e.g. light exposure from screens) during a time that delays circadian rhythms can amplify late sleep onset, but also feedback on the systems regulating sleep and wake. However, sleep only seems to be affected when these factors blend with societal pressure (i.e. early school start time) that forces youth to wake up earlier than they would prefer. The figure also illustrates the possible negative associations that short and ill-timed sleep can have on academic performance and cognitive development.

Figure is based on illustration from: “An update on adolescent sleep: New evidence informing the perfect storm model“ (Crowley et al., 2018).

2.4 The consequences of insufficient, poor quality, inconsistent, and ill-timed sleep for adolescents

Partial sleep deprivation occurs when an individual sleeps less than the recommended duration, without recovery sleep for multiple nights (Banks, 2007). Findings from randomized clinical studies show that partially sleep deprived participants, from 1-7 nights, has a deleterious effect on a wide range of cognitive functions including alertness (Lo et al., 2016), sustained attention (Agostini et al., 2017), reaction speed, cognitive processing speed (Louca & Short, 2014), and memory (Jiang et al., 2011). Similarly, laboratory-based and cross-sectional studies demonstrate that insufficient sleep is associated with higher prevalence of obesity (Garaulet et al., 2011), a blunted immune response (Bryant et al., 2004), and lower academic achievement (Hysing et al., 2016).

Previous research has mainly focused on sleep duration, but short sleep duration is not the only indicator of insufficient sleep (Brand et al., 2009). Poor sleep quality is also associated with increased risk of obesity and diabetes (Markwald et al., 2013), reduced academic performance (Dewald et al., 2010), and increased symptoms of depression (Sivertsen, Pallesen, et al., 2014) and anxiety (Xu et al., 2012). Furthermore, high nightly variability in sleep is known to negatively impact body composition (Golley et al., 2013), perceived health, development of white matter in the brain (Telzer et al., 2015) and cognitive function. Similarly, recent cross-sectional data in college-aged students and adolescents have demonstrated that later bedtimes associate with poorer grade point average (Hysing et al., 2016; Urrila et al., 2017) and less consistent sleep is associated with poorer academic performance (Díaz-Morales & Escribano, 2015; Haraszti et al., 2014; Okano et al., 2019). Thus, sleep quantity, quality, consistency, and timing all seem to be important to health and cognition (Gruber et al., 2014).

Studies have reported that in order to compensate for short weekday sleep, weekend catch-up sleep is prominent during adolescence (Carskadon, 2011). Unfortunately, increased catch-up sleep has been associated with poor performance on attention tasks (Kim et al., 2011), and is reported to negatively affects abilities to sustain attention and maintain alertness (Agostini et al., 2017). Clinical studies have reported that some cognitive measures do not fully recover even after 2 nights of recovery sleep (Agostini et al., 2017; Kim et al., 2011).

2.4.1 Effects of insufficient, irregular, and ill-timed sleep on academic performance

Adolescence is viewed as an important period in the development of both cognitive function and academic skill (Andersen, 2016; Patton & Viner, 2007). Nevertheless, the importance of sleep habits to school performance was not widely examined until approximately two decades ago, when Wolfson and

Carskadon published a comprehensive review of the available data (Wolfson & Carskadon, 2003) which indicated that students who slept less than their peers had lower school grades. However, the authors highlighted methodical limitation and recommended that future studies incorporate multiple sources of measurements and consider confounding factors (social status, age, sex) when interpreting their results (Wolfson & Carskadon, 2003). More recent studies of large European and American cohorts based on self-reported data demonstrated that shorter than recommended sleep duration can negatively affect academic performance amongst teenagers (Hysing et al., 2016; Roberts et al., 2009; Titova et al., 2015). Along with duration, sleep timing and consistency may also play a role in the cognitive function and academic performance of adolescents. Late bedtimes are common amongst teenagers (Fukuda & Ishihara, 2001; Rögnvaldsdóttir et al., 2017) and there is both cross-sectional (Hysing et al., 2016; Urrila et al., 2017) and longitudinal (Asarnow et al., 2014) evidence that those with later bedtimes are more likely to perform worse in school than those who go to bed earlier. Likewise, highly irregular sleep schedules, well documented amongst older adolescents (Telzer et al., 2015) and college students (Haraszti et al., 2014; Okano et al., 2019), are also associated with lower academic achievement (Díaz-Morales & Escribano, 2015; Haraszti et al., 2014; Okano et al., 2019).

Most prior research on adolescents has relied on self-reported measures of sleep, academic performance, or both. According to validation studies, students typically report receiving better grades and test scores than they actually achieve (Escribano & Díaz-Morales, 2014; Frucgt & Cook, 1994; Kuncel et al., 2005) and self-reporting of sleep timing (Brychta et al., 2019), duration (Short et al., 2012), and quality (Werner et al., 2008) has repeatedly been shown to be difficult and prone to bias. Further, sleep questionnaires typically do not include a measure of sleep consistency and, as a result, variability of sleep remains under-explored, particularly in adolescents.

Few studies have tried to expand on the association by using objective measures of sleep and academic measures (Dewald et al., 2010; Shochat et al., 2014). A recent study from Spain found no relationship with academic performance when objective sleep duration or quality was explored but found a positive association between self-reported sleep quality and academic performance (Adelantado-Renau et al., 2019). Similarly, a large review on the influence of sleep duration and quality on school performance showed that subjective sleep measures had a stronger relationship with academic performance than objective measures (Dewald et al., 2010). Thus, more experimental and longitudinal studies with objective measures of both sleep and academic performance are needed to clarify their potential relationship (Dewald et al., 2010).

2.4.2 Cognitive development during adolescence and the relationship with sleep

Brain development continues during adolescence, especially in frontal and parietal regions that underlie various cognitive domains (Sowell et al., 2001). Beginning in the early 2000´s, magnetic resonance imaging (MRI) was used to demonstrate that significant brain maturation occurs during adolescence and early adulthood (Giedd et al., 1999; Sowell et al., 1999). More recent studies report that this brain development extends from 11 to 25 years of age (Giedd et al., 1999; Lebel & Beaulieu, 2011). During this maturation, neural pruning strengthens which makes them more efficient (Colver & Longwell, 2013), starting with the primary systems, such as motor and sensory, while executive systems, such as memory, planning, decision-making and emotional regulation, continue to mature into young adulthood (Colver & Longwell, 2013). An important area of this growth is in memory and attention (Giorgio et al., 2010; Jiang et al., 2015)

Brain development is one of the primary functions of sleep, particularly during periods of brain maturation (Dahl & Lewin, 2002; Feinberg & Campbell, 2013). Previous studies have reported a link between shortened sleep and impaired cognitive function (Durmer & Dinges, 2005) and a recent systematic review reported that short sleep may negatively impact the developing brain (Dutil et al., 2018). Further, high nightly sleep variability has also been shown to impair the development of white matter among 15 year old adolescents, potentially harming cognitive function and socioemotional well-being (Telzer et al., 2015). Similarly, a recent study among 14-year-olds found that shorter time in bed on school days and late weekend hours were correlated with smaller grey matter volume in the frontal, anterior cingulate, and precuneus cortex regions (Urrila et al., 2017). Although short and variable sleep has been associated with impairments in cognitive and brain development, a precise mechanism has been difficult to establish due to the variations in brain development during adolescence and the diversity of sleep and outcome variables investigated (Dutil et al., 2018).

1.1.1.1 Visual attention, memory and sleep in adolescents

One of the more consistent findings is that short sleep is associated with impairments to attention and memory (Dahl, 1996; Durmer & Dinges, 2005). A previous study exploring sleep restriction in a laboratory setting concluded that restricting sleep opportunity to 5 hours led to deterioration of sustain attention, executive function, working memory, and processing speed (Lo et al., 2016). A similar sleep restriction study was performed by Cohen-Zion et al, where the authors concluded that partial sleep restriction had significant effects on information processing speed compared to the well-rested condition (Cohen-Zion et al., 2016). A population based actigraphy study conducted by Steenari and colleagues found modest associations between performance on visual working memory tasks and sleep quantity and quality among schoolchildren aged 6-13 years, including a higher percentage of incorrect responses during the tasks with the highest cognitive load for those with shorter sleep durations (Steenari et al., 2003). Other studies have reported that reduced sleep duration might affect performance on demanding tasks more than that on simple memory tasks due to the enhanced working memory capacity and concentration required by more demanding tasks (Kopasz et al., 2010). Along these same lines, sleep extension has been shown to decrease daytime sleepiness and mood in habitually short-sleeping teens (Van Dyk et al., 2017) and sleeping after training on an n-back task significantly improved accuracy when the task was retaken compared to remaining awake before retaking the task (Kuriyama et al., 2008). Taken together, the result of these studies demonstrate that sleep is associated with impaired cognitive function, particularly in memory and attention, but the impairments are more evident in more difficult tasks.

2.5 Transition from compulsory to secondary education

Adolescence has been described as the transition phase where children merge into adulthood (Curtis, 2015) and is marked by significant increases in autonomy which extends to the educational and social environments. This increased autonomy can affect their engagement in school (Hafen et al., 2012) and raise the probability of dropout (Blondal & Adalbjarnardottir, 2009). In Iceland, this period also includes a transition from compulsory education to secondary education (Figure 2.3) which typically consists of reduced parental supervision, more recreational activities, greater academic demands, increased hours of homework (Adam et al., 2007), greater extracurricular commitments (Short et al., 2013), increased media usage (Hrafnkelsdottir et al., 2018), and potentially part-time employment.

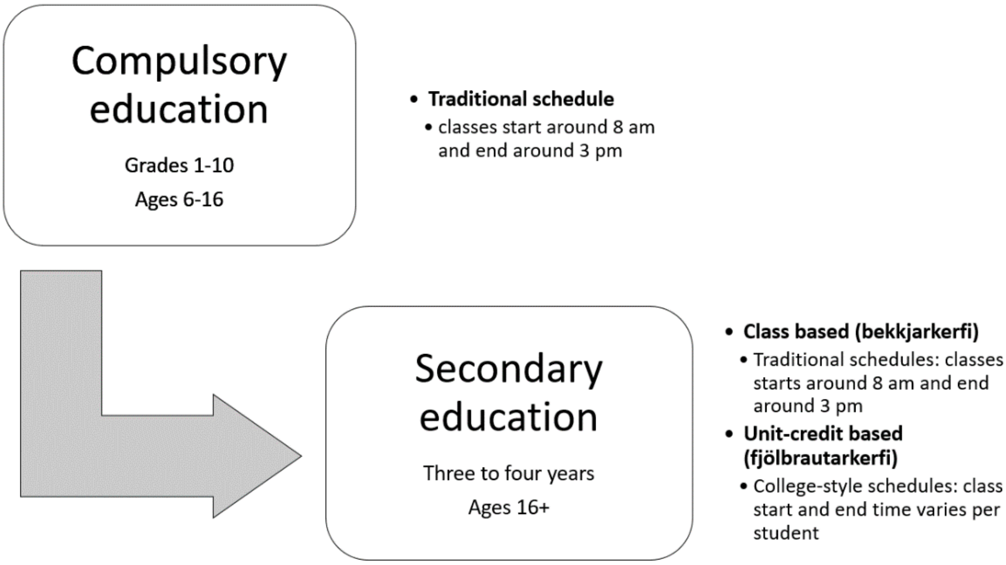

Figure 2.3. The Icelandic education system explained. Compulsory education starts at age 6 where students usually attend their neighborhood school for 10 years, until age 16 (grade 10). Compulsory education schools follow traditional schedule systems where classes start around 8-8:30 in the morning and conclude around 3 pm. At age 16, students can apply to an upper-secondary school with either a similar traditional schedule (class based) or a college-style scheduling system (unit-credit based) where individual student schedules can vary.

2.5.1 The Icelandic school system

The Icelandic school system consists of compulsory and secondary educational phases, as detailed in Figure 2.3 above. Compulsory education begins at age six and lasts ten years. The grades are formally divided into primary school (grades 1-4), middle school (grades 5-7), and lower secondary school (grades 8-10). Compulsory schools use a traditional schedule, which commences at approximately eight o´clock in the morning and concludes around three o´clock in the afternoon. After compulsory school, at age 16, students apply to secondary school to prepare for further studies and/or vocational training. In the last 10 years, over 90% of 16-year-olds have enrolled in upper secondary schools in Iceland (Statistics, 2021). Icelandic students can apply to an upper-secondary school with either a similar traditional schedule (class-based schools) or a college-style scheduling system (unit-credit based) (Figure 2.3). The Icelandic school system is similar in structure and theory to the Nordic School model (Oftedal Telhaug et al., 2006) and shares similarities with the school systems in other Scandinavian countries.

2.5.2 Icelandic secondary school scheduling

Class-based (traditional) upper secondary schools offer a single daily course schedule to all students, while unit-credit-based (college-style) upper secondary schools, students can choose from several offerings of the same course occurring at various times. Students are only required to be physically present at school during their scheduled course times. Thus, daily schedules of unit-credit students are more individualized, like those of college students in many countries, and school start times can vary from 08:30 to 16:00. Reasons for applying to schools of each type vary – some traditional schools are known for academic rigor and some college-style schools offer specialized academic concentrations. However, the college-style structure often gives students more opportunity to shape their school schedule.

2.5.3 Changes in sleep during school transition

Recent studies have explored changes in sleep during the transition from middle school (8th grade, ages 13-14) to high school (9th grade, ages 14-15) (Mitchell et al., 2020) and from high school (ages 15-16) into college (age 20) (Park et al., 2019). Both studies used actigraphy to measure sleep duration, latency, and efficiency and measured both school nights and non-school nights. During the transition from middle to high school there was a 25.8 min/night reduction in average sleep duration on school nights and the odds of sleeping the recommended ≥8 hours per night was reduced 42% (Mitchell et al., 2020). This reduction was mainly due to a 22.2-minute delay in sleep onset, as students went to bed at 23:01 in 8th grade and 23:24 in 9th grade. Similarly, Park et al. found that, in general, students sleep for shorter periods, are less efficient, and are less consistent in college at age 20 compared to when they were in high school at age 16 (Park et al., 2019). Interestingly, a recent systematic review of time spent in the movement behavior categories of sleep, physical activity, and sedentary behavior over 24h when students are transitioning from middle to high school reported a lack of studies documenting changes in sleep duration during this school transition (Chong et al., 2020). Thus, although limited previous research has documented meaningful changes in sleep during school transitions amongst older adolescents and young adults, sleep changes during school transitions during the critical developmental period from early adolescence into early adulthood remains understudied.

2.6 Methodological considerations

2.6.1 Subjective and objective sleep measures

Polysomnography (PSG) has been established as the gold standard to accurately and objectively measure sleep (Penzel & Conradt, 2000). This method uses multiple data streams including electroencephalography (EEG), muscle activity, heart rate, and blood oxygen level, to quantify physiologic changes that occur during sleep (Marino et al., 2013). However, in order to obtain this information, individuals are usually required to spend the night at the sleep clinic or laboratory under close supervision of a sleep technician, making the process too time and resources intensive for most large epidemiologic research. Further, due to the intensive instrumentation, supervision, and unfamiliar environment, lab based PSG assessments might not give a clear picture of typical at-home sleep (Mallinson et al., 2019). An alternative approach to objectively measure sleep patterns and quality in free-living conditions is wrist actigraphy (Weiss et al., 2010). Wrist-worn accelerometers have gained popularity over the past several decades as an objective sleep measure that is low in cost and causes minimal disturbance (Sadeh, 2011). The studies in this thesis measured sleep using the ActiGraph GT3X+, which is a watch-like accelerometer that collects raw accelerometer data on the wrist and detects sleep patterns through well-validated automatic detection algorithms (de Souza et al., 2003; Sadeh, 2011; Sadeh & Acebo, 2002; Sadeh et al., 1994). The devices record body movement over time and provide daily sleep-wake cycles, which can then be useful when evaluating and diagnosing clinical sleep disorders and treatment outcomes (Martin & Hakim, 2011). Nightly sleep periods and awakenings are detected with a scoring algorithm that is available in the software package (Martin & Hakim, 2011). The most commonly used algorithm for sleep-wake scoring in children and adolescents (age range 10–25 years) is the Sadeh algorithm (Sadeh et al., 1994). When compared against polysomnography, wrist actigraphy has demonstrated high sensitivity, but limited specificity (Marino et al., 2013), meaning that actigraphy can accurately detect periods of sleep, but tends to misidentify awakenings as sleep, leading to a potential to overestimation of sleep time and underestimation of wake time (Marino et al., 2013). However, the overall accuracy of wrist actigraphy is high (Slater, 2015 and Marino, 2013) and participant compliance to wrist-worn monitors is also high (Troiano et al., 2014). Thus, actigraphy has been a recommended measurement modality to characterize the sleep parameters of young adults in population-based studies (Zinkhan et al., 2014).

Despite the many advantages of objectively measured sleep via wrist actigraphy, the majority of studies that have examined the associations between sleep and cognition in this age group have relied on subjective, self-report measures (Carskadon, 2011). Self-reported measures of sleep include diaries/logs and single- or multi-item sleep questionnaires (Mallinson et al., 2019). Questionnaires are the most widely used tool to characterize sleep because they are cost effective and easy to administer to large populations (Ji & Liu, 2016). Numerous questionnaires and self-report metrics have been developed and validated, but the two most commonly used are the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989) and the Epworth Sleepiness Scale (ESS) (Johns, 1991). Sleep logs are daily paper- or electronic-based records of participant sleep schedules and/or sleep quality. Most often, participants are asked to report time of entering and exiting bed and, potentially when they fell asleep and woke up, although some sleep logs also require participants to report other sleep related issues, such as the number of nightly awakenings (Iwasaki et al., 2010; Westermeyer et al., 2007). While the questionnaire is well established as a measurement tool suitable for large populations (Ji & Liu, 2016; Wolfson et al., 2003), sleep logs can provide a more detailed assessment of day-to-day sleep patterns since they require participants to supply more information about sleep patterns and preferences than questionnaires (Lauderdale et al., 2008b). However, the additional information provided by sleep logs typically results in increased participant burden and lower compliance.

In general, studies comparing self-reported and objective measures of sleep during adolescence have demonstrated that self-report typically leads to earlier bedtimes (Brychta et al., 2019), longer sleep duration (Short et al., 2012), and fewer night-time awakenings (Werner et al., 2008). However, several studies suggest that agreement specifically between sleep logs and wrist actigraphy may be parameter-dependent. For instance, Thurman et al, found a strong agreement between the two methods for sleep onset and offset, but fairly poor agreement for variables related to wakefulness (Thurman et al., 2018). The authors suggested that combining the estimates from actigraphy and sleep logs should provide more accuracy of true sleep among participants in large studies than either method alone (Thurman et al., 2018). Thus, as suggested in a recent review of sleep data collection methodology, considering the strengths and limitation of each method and the idea that sleep assessment should rely on both subjective experience and objective measurement, the most practical practice to improve accuracy will likely combine various data types (Arnardottir et al., 2021).

2.6.2 Academic measures

A number of studies have examined the relationship between sleep and academic performance and concluded that short, disrupted sleep and later bedtimes are associated with poorer academic performance (Asarnow et al., 2014; Dewald et al., 2010; Hysing et al., 2016; Urrila et al., 2017). However, most studies of the association between sleep and academics have measured academic performance subjectively (Asarnow et al., 2014; Hysing et al., 2016; Stea et al., 2014). Subjective measures of academic performance include self-reported grade point average, parent or teacher reports on the student's grade, or reports on general school functioning, whereas objective methods consist of measures such as grade point averages from official school records and/or standardized tests scores obtained from the official administering institution (Dewald et al., 2010; Kuncel et al., 2005; Mayer et al., 2007). Self-reported academic performance is susceptible to both random and systemic error (Crockett et al., 1987; Kuncel et al., 2005). Random error does not have a specific directionality - meaning students can report better or worse performance - so it affects precision but not necessarily accuracy. For instance, random error can occur when students misinterpret the performance metric or measurement period in question (Teye & Peaslee, 2015). Systematic errors, however, have a consistent bias that differs from the truth in one direction - meaning students consistently report better (or worse) performance than truth - and this affects accuracy (Teye & Peaslee, 2015). According to validation studies, students typically report receiving better grades and test score than they actually achieve (Escribano & Díaz-Morales, 2014), likely in an effort to avoid social stigma or enhance their self-image (Bowman & Hill, 2011; Mayer et al., 2007; Zimmerman et al., 2002). According to 2010 review that looked at 26 studies, only two studies reported academic outcome with standardized test scores (Dewald et al., 2010). Thus, most studies of the association between sleep and academic function in adolescents have relied on self-reported measures of sleep, academic performance, or both. The current thesis focuses on objective measures of free-living sleep, with wrist actigraphy, and academic performance, with standardized national examination obtained from the Icelandic Directorate of Education, in order to address possible gaps in the literature and to help clarify their relationship between sleep and academic performance among adolescents.

2.6.3 Cognitive measures

Cognitive tests measure different cognitive areas such as memory, sustained attention, language skills, visual and spatial skills and other abilities that are related to mental functioning. The tests are normally used to measure the patient or participant cognitive abilities and/or to screen for cognitive impairments (Committee on Psychological Testing, 2015). There are numerous performance tests that are used to assess cognitive performance and sleep loss objectively (Basner et al., 2011) such as the psychomotor vigilance test (PVT) (Lim & Dinges, 2008), Sustained Attention to Response Task (SART) (Robertson et al., 1997), the n-back paradigm (Kirchner, 1958; Steenari et al., 2003), the Positive and Negative Affect Scale (PANAS) (Watson et al., 1988), Posner´s spatial cueing paradigm (Posner, 1980), the Amsterdam Neuropsychological Tasks program (Dewald et al., 2013), and the Symbol Digit Modalities Test (SDMT) (Smith, 1973) to name a few. Thus, when measuring cognitive function among adolescents, most studies incorporate a diverse range of cognitive tests (Esteban-Cornejo et al., 2015; Hoyland et al., 2009) and, with this variety, it can be difficult to compare between studies (Cohen et al., 2016). This dilemma was evident in a 2017 review conducted by de Burin et al., which identified forty-five unique cognitive tests, each measuring different aspects of cognition, amongst 16 different articles looking at the effects of sleep manipulation on the cognitive functioning of adolescents (de Bruin et al., 2017).

More recently, sleep researchers have employed neuroimaging techniques, such as positron emission topography (PET) (Hershey et al., 1991; Thomas et al., 2000) and functional magnetic resonance imaging (fMRI) (Beebe et al., 2009; Drummond et al., 2005; Habeck et al., 2004), to better quantitate the effects of sleep deprivation on the brain while participants perform different cognitive tasks. Although neuroimaging can provide more detail on the brain regions most affected by changes in sleep patterns, cognitive protocols during the measurements are still not standardized, can be demanding to complete, and the technology is expensive and requires trained personnel making it almost impossible to implement in large epidemiologic studies. As noted in several recent reviews, an alternative approach to study the complex association between sleep and cognition is to focus on tasks that are sensitive enough to measure sleep-related alterations in the cognitive function of healthy children and adolescents (Dutil et al., 2018; Kopasz et al., 2010).

The current thesis focuses on the relationship between objectively measured sleep and working memory and visual attention tasks in healthy adolescents since prior studies conducted in clinical settings have shown that sleep restriction affects these cognitive functions (Hudson et al., 2020). In order to address possible gaps in the methodologies used in previous research of the relationships between sleep and cognition, the current thesis measured free-living sleep using wrist actigraphy and previously validated working memory and visual attention tasks to quantitate cognitive performance.

3 Aims

The **overall aim** of this dissertation was to use objective measures to quantify the free-living sleep of Icelandic adolescents at ages 15 and 17, as they transition from compulsory to secondary education, and to determine whether their sleep patterns are associated with academic and cognitive outcomes.

The **specific aims** and corresponding research question of each paper were:

Aim I: To quantify changes in sleep in Icelandic students as they transition from the last year of compulsory school at age 15 to the second year of upper-secondary school at age 17.

Research questions:

a) During adolescence in Iceland, do bedtimes become later and does sleep duration decline as has been demonstrated in other countries?
b) Do changes in sleeping patterns differ by school scheduling system?

Aim II: To determine whether the quantity, quality, timing, and consistency of actigraphy-measured free-living sleep of 15-year-old Icelandic adolescents are associated with scores on standardized national examinations in Icelandic, English, and mathematics.

Research questions:

a) Are later bedtimes and shorter, more disrupted, and less consistent sleep associated with lower scores on the standardized national examinations?
b) Is there a sex difference in the association between sleep and academic performance?

Aim III: To determine whether the working memory and sustained attention of healthy 17-year-old adolescents is associated with objective free-living sleep duration and quality measured acutely, the night prior to testing, or cumulatively over an entire week.

Research question:

a) Is short and more disrupted sleep associated with poorer performance on short-term memory and visual attention tasks?

b) Does sleep the night before testing influence cognitive function differently than sleep over an entire week?

4 Materials and Methods

4.1 Research design

This thesis is based on a previous cohort originating from a longitudinal study conducted in 2006-2008 *"Lifestyle of 7-9-year-old children; intervention towards better health"* (LSOC). The project tracked the status and changes of various health and sleep parameters in the cohort born in 1999. The research used in the current thesis are from a follow-up study and part of a larger project entitled "Heilsuhegðun Ungra Íslendinga" or "*Health behavior of Icelandic youth*" (HHUI) that took place during spring 2015 and early 2017. The current study explored both longitudinal changes from age 15-17, as well as cross-sectional data from both time points. Figure 4.1 outlines the main parameters measured in the thesis.

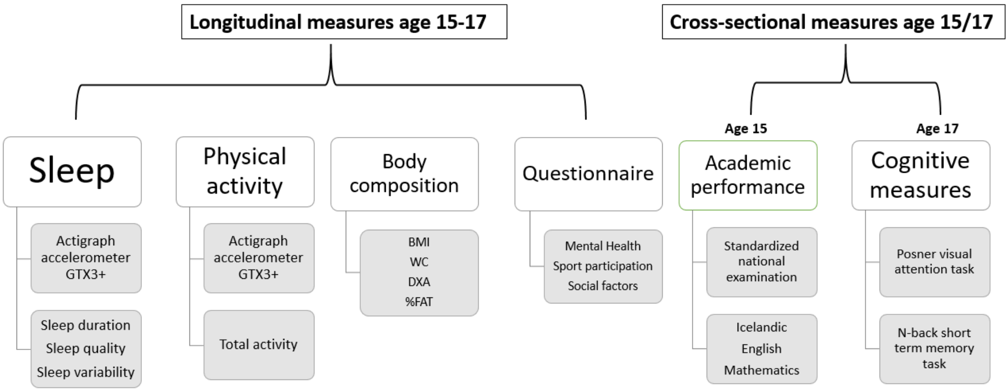

Figure 4.1. Longitudinal measures (age 15 and 17) and cross-sectional measures (age 15 or 17).
Abbreviations: BMI, body mass index, WC, waist circumference, DXA, dual energy X-ray absorptiometry.

4.2 Data collection and participants

In 2006, all students in second grade (born in 1999, age 7 - 8 years), from six of the largest primary schools in Reykjavik, Iceland, were invited to participate in the LSOC study, a longitudinal cohort examining health, cardiovascular fitness, and physical activity (invited N=320, 82% participation) (Magnusson et al., 2011). From April to June in 2015, all students in tenth grade (born in 1999, age

15-16 years) attending the same six schools, including 196 from the LSOC cohort studied in second grade, were invited to participate in a new round of data collection which included wrist actigraphy to measure free-living sleep (n=411); 315 agreed (response rate 77%) (Rögnvaldsdóttir et al., 2017). Students who did not attend school (sick or travelling) during days of measurements were excluded, although students who became ill within the week, while wearing the accelerometer were not excluded. Non-participation (n=104) was mainly due to absence from school during measurement days and lack of interest in the study. Of those who participated, 278 (167 girls) had valid sleep and body composition data and provided answers to the questionnaire.

Two years later, from February to April 2017, we were able to contact 420 individuals who had participated in any of the previous rounds of data collection and 236 (146 girls) agreed to participate (56% participation rate), 168 of which had participated in the 2015 data collection. Of the 168 who participated in both 2015 and 2017, 145 had complete sleep, activity, and body composition data at both time points and were included in the analysis for Paper 1.

Paper 2 is based on the cross-sectional data gathered in 2015, where 253 (150 girls) of the 278 with valid sleep and questionnaire data also had a valid score on at least one national examination. Paper 3 is based on the cross-sectional data gathered in 2017, where 199 (126 girls) of the 236 participants had valid sleep measurements over the week and answered the questionnaire. The subset of participants with valid weekly sleep measurements that took part in the cognitive testing was 188 (115 girls). However, due to schedule conflicts or non-compliance, 28 participants with valid weekly sleep measures did not have a sleep measurement the night prior to cognitive testing. Thus, the final sample for Paper 3 included 160 participants with valid sleep measures over the week and the night prior to cognitive tasks. A flowchart describing the overall participation at each time point and the subset analyzed for each paper is detailed in Figure 4.2.

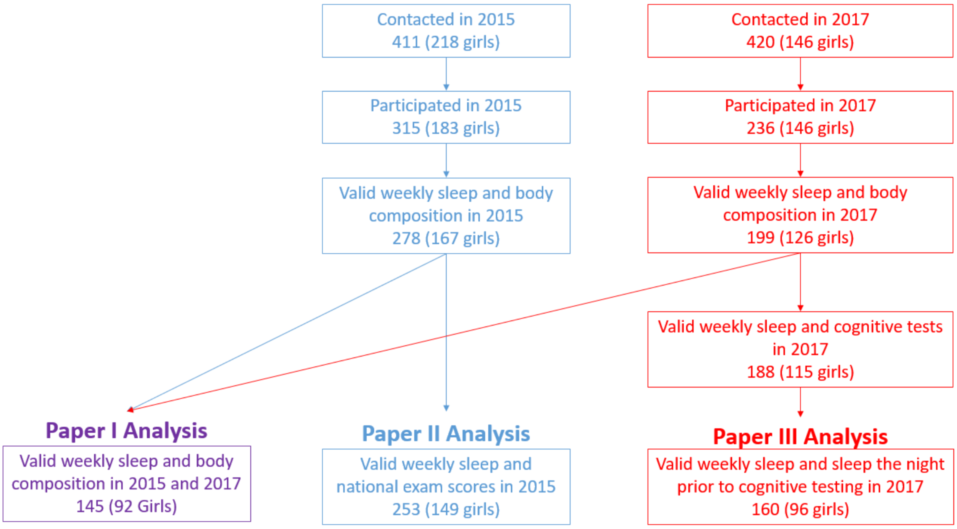

Figure 4.2. Participation and inclusion in the current research thesis, broken down and explained for each paper.

4.3 Sleep measures

4.3.1 Actigraphy

Participants were asked to continuously wear a small (3.8 cm x 3.7 cm x 1.8 cm), lightweight (27 g) accelerometer (model GT3X+, Actigraph Inc. Pensacola Florida) on their non-dominant wrist for one week. The GT3X+ model measures acceleration (change in velocity over time) in three different planes of motion: vertical (VA), antero-posterior, and medio-lateral. The combination of the three planes results in a composite triaxial accelerometer measure, defined as vector magnitude (VM) Tri-axial accelerometer data recorded at 80 samples/second was subsequently filtered and aggregated into one-minute activity counts with Actilife software version 6.13.0 (Actigraph, Pensacola, FL, USA). Periods of sixty or more consecutive minutes of zero counts on all axes were identified as non-wear by customized programs in Matlab version R2016B (Mathworks, Natick, MA, USA). Each night was considered valid if the device was worn for ≥14 h from 12 noon to 12 noon the next day and the longest detected sleep period beginning within that interval was analyzed. As detailed previously (Rögnvaldsdóttir et al., 2017), nightly sleep periods and awakenings were detected in the Actilife software with the Sadeh algorithm validated for adolescents (Sadeh et al., 1994). When necessary, two expert scorers adjusted the auto-detected rise- and bedtimes based on visual inspection and participant sleep diaries. For each night of sleep the midpoint of sleep, minutes of wakefulness after sleep onset (WASO), the time spent asleep (total sleep time), the duration between bedtime and rise time (time in bed), their ratio (sleep efficiency = total sleep time/time in bed x 100%), and social jetlag (non-school day midpoint of sleep minus school day midpoint of sleep) were computed for the primary nightly sleep period. Participants with valid sleep data on ≥3 week/school nights (Sunday-Thursday) and ≥1 weekend/non-school night (Friday, Saturday, and nights prior to school holidays) were included in the analyses. Participants were also required to have valid sleep measured the night prior to cognitive testing for inclusion in the analysis for paper 3.

4.3.2 Sleep diary

Participants were verbally instructed to complete a paper-based auto each morning and evening concurrent with actigraphy. The sleep log was labelled for each day of the week and included the time of going to bed, the time of sleep onset, the time of awakening, the time getting out of bed, and ratings (scale 1-4) for ease of falling asleep, daytime sleepiness, and daily mood. Participants filled out a sleep diary at both time points, 2015 and 2017.

4.4 Academic performance

4.4.1 National Examinations

The Icelandic Directorate of Education administers standardized national examinations in Icelandic, English, and mathematics to all tenth-grade students (age 15) annually in October. The Icelandic exam assess reading, writing, and grammar in the native language. It involves reading comprehension, writing short stories, multiple-choice questions, and correctly using words. The English exam has similar structure to the Icelandic exam but the focus shifts from native language to second language as described in the national curriculum (Menningarmálaráðneyti, 2014). The structure involves listening, reading comprehension, grammar, and writing (Skulason, 2020). The mathematics exam assesses knowledge of operations, geometry, and numerical understanding with multiple choice, word problems, and sentence completion (Skulason, 2020). Scores are nationally normalized to a mean of 30, standard deviation of 10, and range from 0-60 (Sævarsson et al., 2019). An average exam score was computed for participants with valid scores in all three topics and used as the primary outcome variable in paper 2.

4.5 Cognitive measures

Short-term working memory and visual attention were assessed with previously validated software-based tasks in E-prime 2.0 (standard version, Psychology Software Tools, Inc., Pittsburgh, PA). Tasks were administered on a 13.3" laptop computer in a quiet corner while wearing noise-cancelling headphones. Before each task, participants were given verbal instructions and provided with a short practice session to make sure they understood the instructions. Response time and response accuracy, the proportion of correct responses to total stimuli presented, were the outcome measure for each stimulus category (Irgens-Hansen et al., 2015; Jacola et al., 2014; Wengaard et al., 2017). Erroneous responses consisted of commission errors (i.e. wrong button pushed) and omission errors (incorrect rejections and responses provided ≤149 ms after target appearance) (Wengaard et al., 2017).

4.5.1 Visual attention task

Visual attention was evaluated using a Posner cue-target paradigm task (Irgens-Hansen et al., 2015; Posner, 1980; Posner & Cohen, 1984). Participants were instructed to focus on a cross centered on the screen between two rectangles (Figure 4.3a) and respond as quickly as possible by pressing "d" or "l" on the keyboard when the target stimulus (an asterisk) appeared in the left or right rectangle, respectively. The task consisted of a pre-determined sequence of three possible cue presentations: "valid cue", "invalid cue", and "no cue". "Valid cue" presentation (Figure 4.3b) occurred when a rectangle frame thickened (cue) 200 or 400 milliseconds (ms) before the target stimulus appeared at its center. "Invalid cue" presentation (Figure 4.3c) occurred when a rectangle frame thickened as the target stimulus appeared inside the opposite rectangle. "No cue" presentation (Figure 4.3d) was the absence of either rectangle frame thickening during target stimulus appearance (Irgens-Hansen et al., 2015; Wengaard et al., 2017). Participants were instructed to ignore the cues and respond only to the target stimulus appearance. Each stimulus was presented for 500 ms with inter-stimulus-intervals between 600 and 1400 ms for a total task duration of approximately 9 minutes. A total of 336 target stimuli were presented, 224 (67%) with a valid cue, 56 (17%) with an invalid cue, and 56 (17%) with no cue (Wengaard et al., 2017). The sequence and timing of cue and target stimulus presentations were the same for all participants.

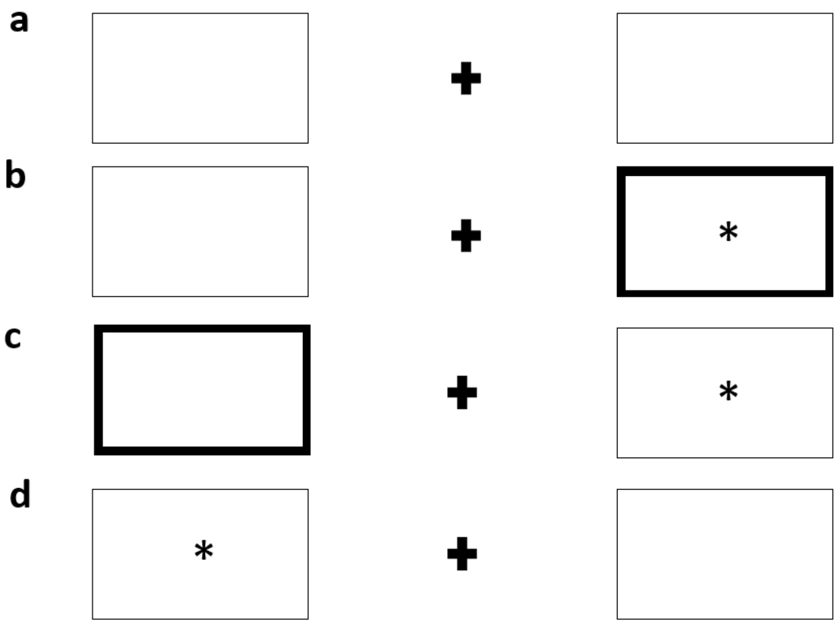

Figure 4.3. Posner cue target task for visual attention. (a) Screen appearance prior to cue presentation and stimulus appearance - central cross with rectangles to the right and left. (b). Valid cue presentation - thickened boarders (cue) prior to target stimulus appearance inside the rectangle. (c) Invalid cue presentation - target stimulus appears opposite to cue rectangle. (d) No cue presentation prior to target stimulus appearance.

4.5.2 Short term memory task

A numeric-based version of the n-back task was used to assess short-term working memory (Figure 4.4). Positive, single-digit integers (i.e., 1-9) appeared one at a time in the center of the screen in a fixed sequence. Participants were instructed to respond by pressing the spacebar as quickly and accurately as possible whenever the current digit was the same as the one presented n positions back in the sequence, where n varied from 1-3, with higher numbers representing greater working memory load. Each digit was presented for 500 ms with an inter-stimulus-interval of 1000 ms. The task was comprised of three sessions with the working memory load condition increasing from 1-back to 3-back (Cohen et al., 1997). Sixty-three digits were presented for each session with ten correct answers. Each session lasted a little under 2 minutes and participants were given a maximum 2-minute break between sessions with a total of ~12-minute task duration.

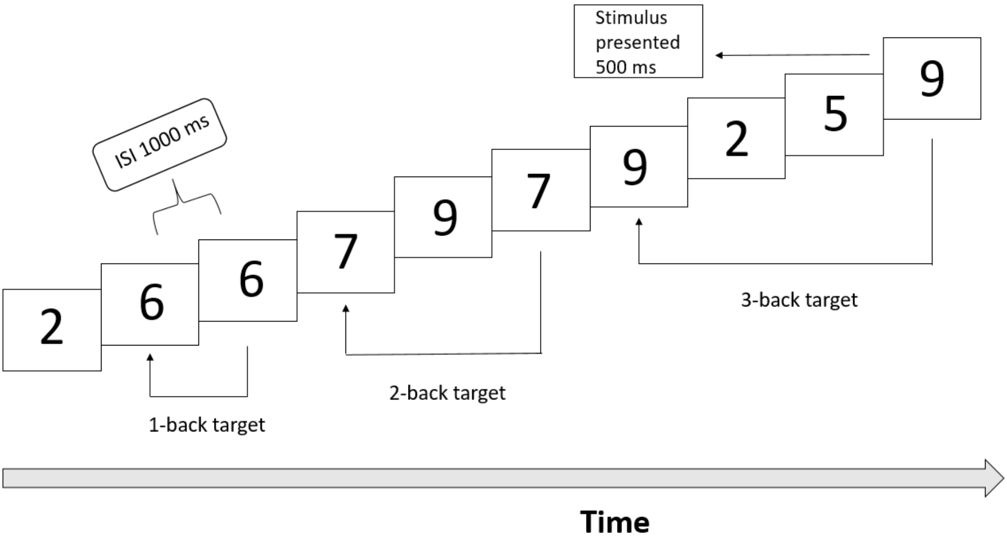

Figure 4.4. Schematic representation of the n-back task for short-term working memory. Sixty-three digits were presented one at a time for each session of one working memory load condition, which varied from 1-back (least difficult) to 3-back (most difficult). Each stimulus was presented for 500 ms with an inter-stimulus-interval of 1000 ms. Participants had a break between conditions. ISI: inter-stimulus-interval.

4.6 Body composition

Body mass index (BMI) was calculated from height and weight measured by trained personnel at the Icelandic Heart Association. Body fat percentage was measured with dual energy X-ray absorptiometry (DXA) (Lunar, GE Healthcare, Madison, WI, USA) which has been validated against direct imaging methods such as magnetic resonance imaging to detect longitudinal changes in adolescent body composition (Bridge et al., 2011).

4.7 Covariates

Covariates for each aim were chosen based on previous publications from our own lab, from publications on related topics, and, in some cases, in response to the peer review process. For aims I and II, the parental educational attainment of each participant was reported by answering a tablet-based questionnaire and used as a proxy for socioeconomic status (Hrafnkelsdottir et al., 2018; Sævarsson et al., 2017). Previous studies have reported that lower socioeconomic status can correlate with sleep problems in adolescence

(Johnson et al., 2004) and adolescents living in lower socioeconomic conditions have a higher risk at experiencing poorer sleep outcomes (Marco et al., 2012). Students provided the educational attainment of both mother and father from the following options (presented in Icelandic): 1 = “elementary degree”, 2 = “secondary degree”, 3 = “trade school degree”, 4 = “university degree”, 5 = “other”, 6 = “do not know”, 7 = “do not want to answer”. Responses were recoded into a binary variable: 1 = “parent with a university degree” or 0 = “no parent with a university degree or did not answer”, as described previously (Hrafnkelsdottir et al., 2018; Stefánsdóttir et al., 2020)

Similarly, participants answered their self-reported videogame use and presence or absence of a clinical diagnosis of ADHD on the questionnaire. Presence or absence of a clinical diagnosis of ADHD and weekly videogame usage were included in all regression models for aim III, since the presence of ADHD and extensive videogame use have previously been associated with cognitive performance in visuospatial tasks (Green & Bavelier, 2003; McDonald et al., 1999). Videogame use was reported using a seven-point scale with the following response options presented separately for weekdays and weekends: 1 = “none”, 2 = “about ½ h”, 3 = “1 up to 2 h”, 4 = “2 up to 3 h”, 5 = “3 up to 4 h”, 6 = “4 to 5 h” and 7 = “more than 5 h”. For aim III, the weighted average was computed from the weekday and weekend responses using the midpoints of each response category or 0.5 h/day for the “about half an hour” response option and 5.5 h/day for the “more than 5 h” response option (only four participants selected this response). Participants reported clinical diagnosis of ADHD by answering yes or no to the question “Have you been clinically diagnosed with ADHD?”

4.8 Ethics

The National Bioethics Committee and the Icelandic Data Protection Authority approved the study (Study number: VSNb2015020013/13.07). Written informed consent was obtained from participants and guardians of underage participants. Full confidentiality was ensured, and each individual study was conducted in agreement with the guidance provided in the Declaration of Helsinki.

4.9 Statistical analyses

All three manuscripts use analyses that were conducted using RStudio (v1.0.153 Boston, Massachusetts, USA) with R (v3.4.2, https://www.r-project.org/) and GraphPad Prism (v7, La Jolla, California). For each aim, all variables were first visually inspected for the presence of outliers and their distributions were examined for normality. Normally distributed variables are reported as mean ± standard deviation and were assessed using parametric statistics. Non-normally variables were reported as median [interquartile range], assessed with non-parametric statistics, and transformed prior to regression analyses. P-values less than 0.05 were considered significant.

Since all sleep variables were continuous, we elected to employed continuous analyses when possible, as continuous analyses provide greater information than categorical analyses. Categorical analyses and application of cut-points were used sparingly and only to support findings from continuous analyses and mainly implemented in response to peer review requests.

The sample population in the current thesis was longitudinal and part of a previous project powered for a different purpose. The analyses conducted were not pre-planned prior to data collection. Therefore, we sought to use more stringent methods to correct for multiple testing for primary analyses (i.e. Bonferroni correction) in each paper (or aim) and use a false discovery rate for additional, exploratory analyses. Mixed-effect models were used to examine longitudinal changes and multiple linear regression models were used to assess associations between cognitive measures and sleep at each time point.

Lastly, each paper topic was comprised of slightly different populations since not every student had measures at both time points and standardized national tests and cognitive testing were conducted only at one time point each (at age 15 and 17, respectively). Thus, each topic required a separate type of analysis to answer the research questions.

Below is a brief summary of analyses conducted for each thesis aim, but further detail is available in each paper.

4.9.1 Paper 1

Aim I examined the longitudinal changes in sleep from age 15 to 17 with the transition to upper secondary school. Paired analyses carried out with mixed-effect models adjusted for sex and parental education with post-hoc tests corrected for multiple comparisons using the Bonferroni method were used to assess within subject differences from age 15 to 17 and from school days to non-school days at each age.

Similarly, paired comparisons were used to test for within subject difference from age 15 to 17 separately by school structure at follow-up, while unpaired analyses adjusted for sex and parental education were used to test for differences between school structures at each measurement. These analyses also employed mixed-effect models with post-hoc tests corrected for multiple comparisons using the Bonferroni method.

An additional exploratory analysis to determine whether the sex distribution, socioeconomic status, body composition, and activity of participants with and without complete follow-up data differed at age 15 used chi-squared tests and unpaired t-tests. Chi-squared tests were also used to assess differences in sex distribution and parental education between students attending schools of each schedule type at follow-up.

4.9.2 Paper 2

Aim II addressed the relationship between sleep and academic performance cross-sectional at age 15. In that dataset, the midpoint of sleep, rise time, WASO, sleep efficiency, and total sleep time variability had non-normal, asymmetric distributions and are reported as median [interquartile range]. *T*-tests and Mann-Whitney tests were used for comparisons between sexes for normal and non-normally distributed variables, respectively.

Linear regression models adjusted for school and parental education were used to assess the strength of association between sleep parameters (predictor variables) and standardized exam scores (response variables), with results reported as standardized β and 95% confidence intervals. To investigate the association between exam scores and different dimensions of sleep while limiting the number of comparisons, bedtime, total sleep time, and total sleep time variability over all nights were used as representative measures of sleep timing, duration, and consistency, respectively, while WASO and sleep efficiency were used to represent sleep quality and the average exam score over the three topics (Icelandic, English, and mathematics) was used for the primary analysis.

Prior to regression analyses, log-transformation was applied to WASO and total sleep time variability and arcsine transformation (i.e., arcsine of the square root of the proportion variable) was applied to sleep efficiency. Three sets of regressions were performed: one set for all students controlled for sex and separate sets for boys and girls. *P*-values for the primary regression analysis were adjusted using the Bonferroni method across sleep parameters. The relationship between average national exam scores and sleep parameters computed over school nights and non-school nights were also performed using similar procedures and included in the supplemental material for completeness.

An additional exploratory analysis of the association between the sleep parameters and test scores in each topic was also conducted. A Benjamini–

Hochberg analysis (Benjamini & Hochberg, 1995) with a 0.20 false discovery rate (Q) of the 54 regression models performed in the exploratory analysis determined that all *P*-values less than or equal to the critical *P*-value of 0.049 could be considered significant.

4.9.3 Paper 3

The association between sleep and cognitive function at age 17 was evaluated in Aim III. In this dataset, response times, response accuracies, sleep efficiency and the weekly variability in time in bed and sleep duration all had non-normal distributions and were reported as median ± interquartile range.

Correlations between response times and response accuracies were assessed using the non-parametric Spearman method. Prior to outlier detection and regression analyses, log-transformation was applied to response time variables and the variability time in bed and sleep duration and arcsine transformation was applied to response accuracies and sleep efficiencies. Values that exceeded 3 standard deviations above or below the mean were considered outliers and excluded.

Mixed-effect models with post hoc tests with Bonferroni correction for multiple comparisons were performed to evaluate differences in transformed response times and response accuracy across stimuli on the visual attention task and across cognitive load on the working memory task. Linear regression models adjusted for baseline cognitive responses (i.e. 1-back or valid cue response time or accuracy), clinical diagnosis of ADHD, and time spent playing video games (Wengaard et al., 2017) were used to assess associations between sleep parameters and cognitive task performance, with results reported as standardized β with 95% confidence intervals.

Two sets of regression analyses were performed, the first with sleep parameters from the night prior to cognitive testing as predictor variables and the second with average weekly sleep parameters and sleep variability parameters as predictor variables.

In an additional, exploratory analysis of the relationship between total time in bed and working memory was tested to see whether participants with a total time in bed of 7 h or less performed differently on the task than those with greater than 7 h. The threshold value of 7 h of total time in bed was selected since it was the group mean for the participants in this study and previously used as an indicator of short sleep (Mi et al., 2019; Wheaton et al., 2018). Categorical analyses were also adjusted for baseline cognitive responses, clinical diagnosis of ADHD, and reported weekly video game use.

5 Results

5.1 Participant characteristics at age 15 and 17

Characteristics for all participants with valid sleep data at age 15 and all participants with valid sleep data at age 17 are presented in table 5.1. In 2015, 280 participants had valid sleep data with mean age 15.9±0.3 years. Two years later, 199 participants had valid sleep data with a mean age of 17.7±0.3 years. The current thesis examined both longitudinal changes from age 15 to 17 and cross-sectional data from each time point. Results of the analysis for each aim of this thesis are presented in the following subchapters. The analysis for each aim included only the subset of participants with valid data for all criteria measures related to that aim.

5.2 Sleep characteristics for all participants with valid sleep data at age 15 and 17

Sleep characteristics for all participants with valid sleep data at age 15 and all participants with valid sleep data at age 17 are presented in Table 5.2. Over all measured nights, Icelandic adolescents go on average late to bed (00:49 at age 15, 01:19 at age 17) and their total sleep time in short (6.6 h/night at 15, 6.2 h/night at age 17). Further, total sleep time variability is quite high at both time points (1.3 h/night and 1.4 h/night, respectively). Few significant sex differences were found for the cohort, although girls go to bed and rise earlier than boys at age 15 and age 17(Table 5.2).

More detailed statistical comparisons between sleep measures at age 15 and 17 were carried out using participants with complete sleep data at both time points in the subsequent section pertaining to Aim I.

Table 5.1. Characteristics for all subjects with valid sleep data at the 2015 cohort and the 2017 cohort.

	All	**Boys**	**Girls**	**Boys vs Girls p-value**
Cohort 2015				
n (%)	**278 (100)**	**111 (40)**	**167 (60)**	
Age (y)	15.9 (0.3)	15.8 (0.3)	15.9 (0.3)	0.07
Parent with university degree, N (%)	194 (70%)	81 (73%)	113 (68%)	0.56
Height (cm)	171.4 (8.0)	178.3 (6.0)	166.9 (5.7)	**<0.001**
Weight (kg)	64.8 (11.3)	69.0 (11.7)	62.0 (10.2)	**<0.001**
BMI (kg/m^2)	22.0 (3.2)	21.7 (3.3)	22.2 (3.2)	0.17
Cohort 2017				
n (%)	**199 (100)**	**73 (37)**	**126 (63)**	
Age (y)	17.7 (0.3)	17.6 (0.3)	17.7 (0.3)	**0.019**
Parent with university degree, N (%)	140 (70%)	53 (73%)	87 (69%)	0.71
Height (cm)	173.3 (9.2)	182.6 (5.7)	168.0 (6.0)	**<0.001**
Weight (kg)	68.4 (13.7)	74.8 (12.5)	64.7 (13.0)	**<0.001**
BMI (kg/m^2)	22.8 (4.1)	22.4 (3.4)	23.0 (4.5)	0.23

Results presented as mean ± standard deviation, unless otherwise noted. The p values are the result of t tests comparing boys and girls. Boldface type indicates significant differences.

Abbreviations: n, number; BMI, body mass index.

Table 5.2. Sleep characteristics averages for all nights by sex for all participants with valid data at both age 15 and 17.

	All	**Boys**	**Girls**	**Boys vs Girls p-value**
Cohort 2015				
n (%)	**278 (100)**	**111 (40)**	**167 (60)**	
Rise time (clock time ± min)	08:23 ± 44.1	08:30 ± 47.6	08:18 ± 40.9	**0.02**
Mid-sleep time (clock time ± min)	04:35 ± 43.8	04:43 ± 45.8	04:30 ± 41.7	**0.01**
Bedtime (clock time ± min)	00:49 ± 52.4	00:58 ± 53.2	00:43 ± 51.1	**0.03**
Time in bed (h/night)	7.5 ± 0.7	7.5 ± 0.8	7.6 ± 0.7	0.23
Total sleep time (h/night)	6.6 ± 0.7	6.5 ± 0.7	6.6 ± 0.6	0.12
Sleep efficiency (%)	87.8 ± 4.2	87.5 ± 3.9	87.9 ± 4.3	0.47
Wakening after sleep onset (min)	54.5 ± 20.7	55.5 ± 18.9	53.8 ± 21.9	0.49
Total time in bed variability (min)	1.4 ± 0.6	1.5 ± 0.7	1.3 ± 0.6	**0.03**
Total sleep time variability (h)	1.3 ± 0.6	1.3 ± 0.6	1.2 ± 0.5	0.17
Cohort 2017				
n (%)	**199 (100)**	**73 (37)**	**126 (63)**	
Rise time (clock time ± min)	08:29 ± 64.0	08:45 ± 73.5	08:20 ± 55.6	**0.01**
Mid-sleep time (clock time ± min)	04:53 ± 61.7	05:10 ± 69.3	04:44 ± 54.6	**0.004**
Bedtime (clock time ± min)	01:19 ± 66.9	01:35 ± 71.9	01:09 ± 61.9	**0.01**
Time in bed (h/night)	7.1 ± 0.8	7.1 ± 0.8	7.1 ± 0.8	0.1
Total sleep time (h/night)	6.2 ± 0.8	6.2 ± 0.8	6.2 ± 0.7	0.1
Sleep efficiency (%)	88 ± 4.4	88 ± 4.1	88 ± 4.7	0.9
Wakening after sleep onset (min)	50.8 ± 20.2	50.1 ± 18.0	49.9 ± 21.4	0.95
Total time in bed variability (min)	1.5 ± 0.7	1.5 ± 0.7	1.5 ± 0.7	0.61
Total sleep time variability (h)	1.4 ± 0.6	1.4 ± 0.6	1.3 ± 0.6	0.69

Results presented as mean ± standard deviation, unless otherwise noted. The p values are the result of t tests comparing boys and girls. Boldface type indicates significant differences.
Abbreviations: WASO wake after sleep onset.

5.3 Aim I: Overall changes in sleep from age 15 to 17

There were 145 students (63% females) who had valid sleep data at both time points. Over all measured nights, time in bed decreased from 7.5 ± 0.7 h/night at age 15 to 7.1 ± 0.8 h/night at age 17 and sleep duration decreased from 6.6 ± 0.7 h/night to 6.2 ± 0.8 h/night from age 15 to 17 (both P< .001; Table 5.3). On school nights, time in bed and total sleep time did not change from age 15 to 17. However, at age 17, students went to bed and rose later (both P< .01) and increased intraindividual variability (i.e., within subject standard deviation) of time in bed and total sleep time (both P< .001; Table 5.3). On non-school nights at age 17, students went to bed later (P< .001) but did not change their rise time from age 15, resulting in shorter total sleep time (P< .001; Table 5.3).

Sleep quality measures (i.e., nightly awakenings, WASO, and sleep efficiency) did not change from age 15 to 17 on school nights, but awakenings and WASO were both lower on non-school nights at age 17 (*P*< .05, Table 5.3). Students went to bed later, rose later, slept longer, and had greater awakenings and WASO on non-school nights than school nights during both measurements (all *P*< .001, Table 5.3), with the increase in WASO being directly proportional to the increase in sleep duration (~5.5 minutes of WASO/hour of sleep; *P*< .001).

Chi-squared tests and unpaired T-tests showed no differences in the sex distribution, socioeconomic status, body composition, or activity of participants with and without complete follow-up data at age 15 (Appendix Table A1). Participants who completed follow-up had slightly less sleep time variability on school nights (−10 min), and slightly better sleep quality on non-school nights (2 fewer awakenings/night) than those who did not, but otherwise did not differ in sleep at age 15 (Appendix Table A1).

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Table 5.3. Sleep for all participants on school days and non-school days at age 15 and 17

	School Days			Non-School Days			School vs non-school	
	2015	**2017**	**p(15 vs. 17)**	**2015**	**2017**	**p(15 vs. 17)**	**p (2015)**	**p (2017)**
Rise Time (Clock time ± min)	07:25 ± 37.40	07:47 ± 61.46	**0.01**	10:04 ± 76.74	10:15 ± 89.74	0.71	**<0.001**	**<0.001**
Mid-Sleep Time (Clock time ± min)	03:52 ± 36.13	04:20 ± 57.00	**<0.001**	05:49 ± 64.02	06:19 ± 78.51	**<0.001**	**<0.001**	**<0.001**
Bed Time (Clock time ± min)	00:20 ± 47.46	00:53 ± 62.01	**<0.001**	01:36 ± 70.65	02:24 ± 84.06	**<0.001**	**<0.001**	**<0.001**
Time In Bed (h/night)	7.06 ± 0.76	6.80 ± 0.86	0.17	8.33 ± 1.36	7.80 ± 1.33	**<0.001**	**<0.001**	**<0.001**
Total Sleep Time (h/night)	6.23 ± 0.66	5.98 ± 0.82	0.13	7.33 ± 1.25	6.89 ± 1.22	**<0.001**	**<0.001**	**<0.001**
Sleep Efficiency (%)	88.37 ± 4.36	87.99 ± 4.84	1.00	88.01 ± 4.99	88.43 ± 4.88	1.00	1.00	0.91
Wakening after sleep onset (min)	48.5 ± 21.5	48.1 ± 21.2	1.00	59.6 ± 28.0	52.8 ± 24.7	**0.1**	**<0.001**	**0.03**
Total Time in Bed Variability (h)	0.9 ± 0.6	1.3 ± 0.8	0.30					
Total Sleep Time Variability (h)	0.8 ± 0.5	1.1 ± 0.8	**<0.001**					

5.4 Aim I (b): Changes in sleep by school schedule-type

Over all measured nights, time in bed decreased from age 15 to 17 from 7.61 ± 0.66 to 7.02 ± 0.73 h/night for traditional schedule students and from 7.45 ± 0.72 to 7.13 ± 0.79 h/night for college-style students (both *P*≤ .001). Similarly, total sleep time over all nights declined from 6.73 ± 0.59 to 6.22 ± 0.77 h/night for traditional schedule students and from 6.54 ± 0.69 to 6.25 ± 0.74 h/night for college-style students (both *P*≤ .001). However, the magnitude of these reductions did not differ by schedule type. On school nights, students of both school types went to bed later at age 17 compared to age 15 (+25 minutes for traditional, + 40 minutes for college-style, both *P*< .01; Figure 5.1A), but those in college-style schools rose later at age 17 (*P*< .001; Figure 5.1A). As a result, time in bed and total sleep time on school nights was reduced at age 17 for traditional schedule students but did not change for students with college-style schedules (appendix Table A2, Figure 5.1B). On non-school nights, students of both school schedule types went to bed more than 40 minutes later (both *P*< .001) but did not differ in rise time at age 15 and 17 (Figure 5.1C). Time in bed and sleep duration on non-school nights did not change for traditional schedule student between ages 15 and 17, but both were reduced for college-style students (both *P*< .05) - perhaps indicating a reduction in catch-up sleep (appendix Table A2 and Figure 5.1D).

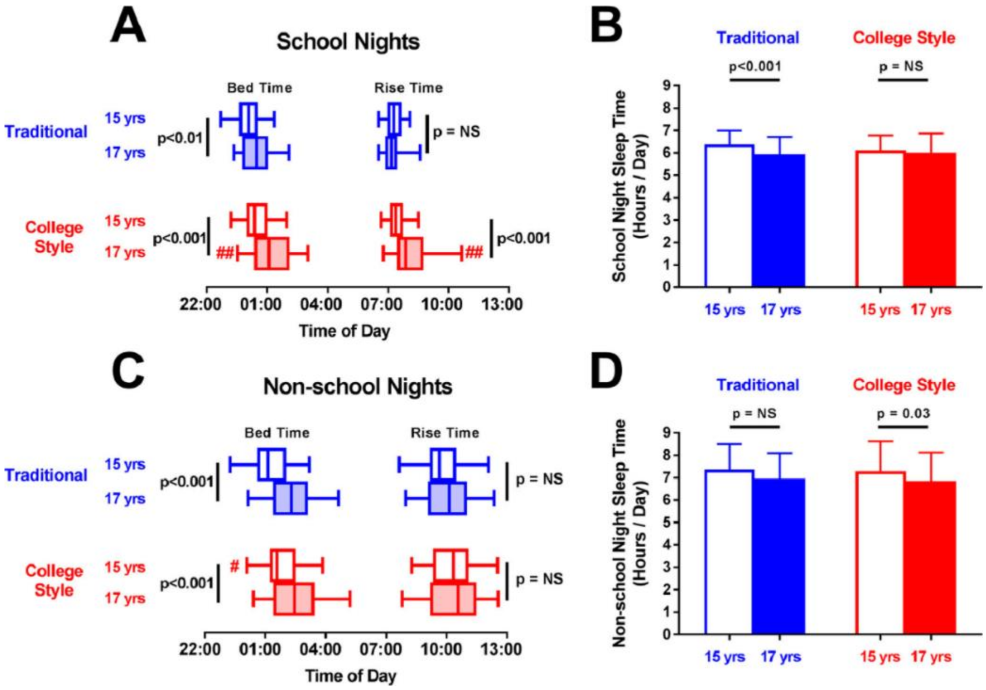

Figure 5.1. Sleep schedule and duration on school nights and non-school nights by age 17 school-schedule type. (A, B) On school nights, both traditional (blue) and college-style (red) students went to bed later at 17 (filled) vs. 15 (unfilled), but college-style student rose later at age 17 (A). Thus, only traditional-school students reduced sleep duration at 17 (B). (C, D) On non-school-nights, both traditional and college-style students went to bed later and rose at the same time at age 17 vs. 15 (C), but only college-style students reduced sleep duration (D). Box (median with first and third quartile) and whiskers (95% confidence interval) are used for bed- and rise-times; mean (boxes) with standard deviation (error bars) is used for sleep duration. *P* values with black bars indicate paired, within school-type comparisons between ages 15 and 17. # ($P < .05$) and ## ($P < .01$) indicate significant differences between traditional and college-style students at age 15 or 17. All comparisons adjusted for sex, parental education, and multiple comparisons.

5.5 Aim II: Association between sleep and academic performance at age 15

5.5.1 National exam scores

Characteristics and exam scores for the 253 participants in paper 2 that had valid sleep data and exam scores in at least one topic are presented by sex in appendix Table B1. The average age of participants was 15.9 ± 0.3 years, with a BMI of 22 ± 3.2 kg/m^2. The average score in Icelandic for all participants was 33.5 ± 9.6, but it was higher for girls (34.9 ± 9.6) than boys (31.7 ± 9.2, $p = 0.01$). Average scores in mathematics (32.5 ± 9.9), English (32.9 ± 9.4), and the average of all three topics (33 ± 8.6) did not differ by sex. Average scores for all three examination topics were highly correlated with one another (all $r > 0.65$, $p<0.001$), suggesting that students who scored highly in one topic also did so in the other two.

Participants with and without complete sleep and national exam data did not differ in terms of sex distribution, parental education, age, body composition, exam scores, or sleep measures (appendix Table B2).

5.5.2 Sleep measures

Average weekly sleep parameters for participants with both valid sleep data and national examination scores at age 15 are summarized by sex in Table 5.4. Students (n=253, 59% females) spent 7.5 ± 0.7 h/night in bed and slept 6.6 ± 0.7 h/night, with an efficiency of 88.1 [5.3] % (median [interquartile range]) and night-to-night variation in sleep duration of 1.2 [0.7] hours, none of which varied by sex. On average, participants went to bed at 00:49 ± 51.8 and rose at 08:20 [57.6], but girls had an earlier schedule than boys, averaging 17-minute earlier bedtimes and 8- minute earlier rise times ($p<0.05$).

Detailed table presenting sleep parameters averaged for all nights, school nights, and non-school nights are summarized by sex in paper 2, Table 2.

Table 5.4. Average weekly sleep characteristics for participants with both valid sleep data and national examination scores at age 15

	All (n=253)	**Boys (n=103)**	**Girls (n=150)**	***P*-value**
All Nights				
Rise time (clock time ± min)[a]	08:20 ± 57.6	08:25 ± 56.1	08:17 ± 53.2	**0.03**
Mid-sleep time (clock time ± min)[a]	04:31 ± 56.2	04:38 ± 63.4	04:26 ± 46.1	**0.02**
Bedtime (clock time ± min)[b]	00:49 ± 51.8	00:59 ± 51.8	00:42 ± 50.4	**<0.001**
Time in bed (h/night)[b]	7.5 ± 0.7	7.5 ± 0.8	7.6 ± 0.7	0.2
Total sleep time (h/night)[b]	6.6 ± 0.7	6.5 ± 0.7	6.7 ± 0.6	0.1
Sleep efficiency (%)[a]	88.1 ± 5.3	87.9 ± 4.9	88.3 ± 5.4	0.3
Wakening after sleep onset (min)[a]	52.4 ± 25.0	53.6 ± 24.7	49.4 ± 24.4	0.2
Total sleep time variability (h)[a]	1.2 ± 0.7	1.2 ± 0.7	1.2 ± 0.7	0.5
Social jetlag (min)[b]	122.9 ± 56.4	134.1 ± 63.6	115.4 ± 49.7	**0.01**

[a] Results presented as median (interquartile range) due to skewed distribution.

[b] Results presented as mean (SD); p values are the result of comparisons between boys and girls with t tests for normally distributed variables and Mann-Whitney tests for skewed variables. Boldface type indicates significant differences.

5.5.3 Regression analysis between sleep and academic performance at age 15

The association between the average national exam scores across the three topics and sleep duration, quality, and variability are shown in Table 5.5. After controlling for the schools attended and parental education, there is an inverse relationship between bedtime and average exam scores (Figure 5.2A), indicating that those with earlier bedtimes had a higher average exam score. When analyses were separated by sex, the association persisted for boys, but not girls (Table 5.5). Additional exploratory analysis demonstrated that the trends were present in national exam scores in Icelandic and mathematics, but not English (appendix Table B3). Variability in sleep duration was also negatively associated with the average exam score (Figure 5.2B) but did not persisted for either sex when analyses were conducted separately. The exploratory analysis by individual test topic showed that variability in sleep duration was also significant for Icelandic and mathematics, but not for English, and persisted for both sexes (appendix Table B3). The exploratory analysis also showed that longer total sleep time was associated with higher scores in Icelandic. However, this relationship was not significant for either sex when separate analyses were conducted for boys and girls (appendix Table B3). When school night sleep parameters were used in place of average sleep measures over all nights, the inverse association between bedtime and average national exam score persisted, suggesting that school night bedtimes specifically may play an important role in academic performance (appendix

Table B4). In contrast to sleep variability over all night, however, sleep variability on school nights was not related to average national exam scores (appendix Table B4), perhaps due to the reduced variation in school night sleep resulting in a smaller range of values. Non-school night sleep parameters were not related to the average national exam score (appendix Table B4).

Table 5.5. Results of multiple linear regression analyses between sleep parameters and national standardized exam scores averaged over all topics presented for all participants with valid sleep and exams scores at age 15 and separately for boys and girls.

	All*	**Boys**	**Girls**
	β [95% CI] (*p*)	β [95% CI] (*p*)	β [95% CI] (*p*)
Bedtime	-0.17 [-0.29, -0.05] (**0.04**)	-0.29 [-0.48, -0.10] (**0.02**)	-0.10 [-0.26, 0.06] (0.99)
Total sleep time	0.08 [-0.05, 0.20] (0.99)	0.13 [-0.07, 0.34] (0.99)	0.04 [-0.13, 0.20] (0.99)
Wakening after sleep onset	0.03 [-0.09, 0.15] (0.99)	0.09 [-0.10, 0.28] (0.99)	-0.02 [-0.18, 0.15] (0.99)
Sleep efficiency	-0.01 [-0.13, 0.11] (0.99)	-0.07 [-0.26, 0.12] (0.99)	0.03 [-0.13, 0.19] (0.99)
Total sleep time variability	-0.18 [-0.30, -0.07] (**0.01**)	-0.19 [-0.38, -0.001] (0.3)	-0.19 [-0.34, -0.03] (0.1)
Social jetlag	-0.06 [-0.19, 0.06] (0.99)	-0.02 [-0.22, 0.18] (0.99)	-0.11 [-0.26, 0.05] (0.99)

β, standardized beta value; CI, confidence interval; All regressions adjusted for school and parental education. *Additionally adjusted for sex. Wakening after sleep onset, sleep efficiency, and total sleep time variability were transformed prior to analysis due to skewed distributions. P-values adjusted for multiple comparisons. Boldface type indicates significant differences.

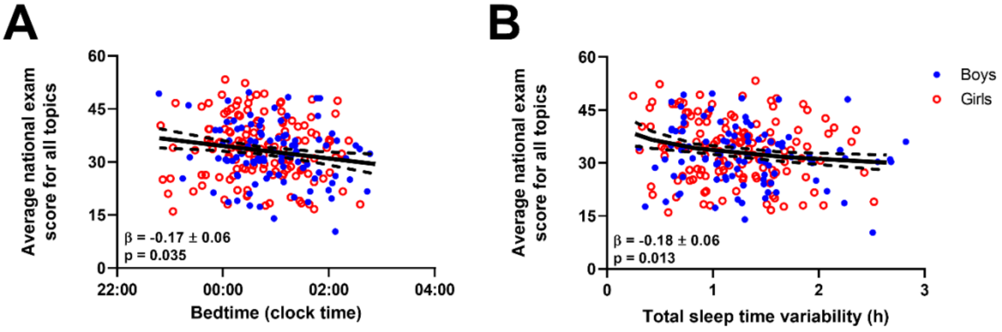

Figure 5.2. Relationship between average national exam scores and bedtime (A) and variability in total sleep time (B). Filled blue circles and unfilled red circles are used to indicate data for boys and girls, respectively. The solid and broken black lines respectively indicate regression and 95% confidence intervals adjusted for school and parental education. P-values were adjusted for multiple comparisons. Total sleep time variability was log-transformed prior to analysis due to skewed distributions; inverse transformation was applied for display in (B).

5.6 Aim III: Associations between sleep and cognitive measures at age 17

5.6.1 Descriptive statistics for cognitive performance measures at age 17

The analysis for Aim III included 160 participants that completed the cognitive tasks, answered the questionnaire, met the criteria for a valid week of wrist actigraphy-measured sleep, and had valid sleep measures the night prior to cognitive testing. The characteristics of these participants are presented in appendix Table C1. Participant's average age was 17.7± 0.3 years, with a BMI of 22.7 ± 3.9 kg/m^2. Only 4.3% of participants reported having a clinical diagnosis of ADHD.

5.6.2 Cognitive measures

Performance on the n-back task was quantified using response time, or the time between stimulus appearance and participant response, and response accuracy, defined as the proportion of correct responses (i.e., the sum of correct button presses and correct rejections divided by total stimuli), as shown in Table 5.6. Response time and accuracy varied predictably across cognitive load: response time gradually increased while accuracy decreased in a dose–dependent manner from the 1-back to the 2-back and 3-back conditions (all $p < 0.05$).

Response time and accuracy on the visual attention task varied significantly across conditions (all $p < 0.001$; Table 5.6). However, trends across cue presentations for response time differed from those of response accuracy. The no cue presentation elicited the slowest but most accurate responses. During the valid cue presentation, responses were fastest, but accuracy was intermediate between no cue and invalid cue presentations. On the other hand, during the invalid cue, responses were least accurate, but response times were intermediate between the valid and no cue presentation.

Table 5.6. Cognitive measures for participants with valid weekly sleep and valid sleep measured the night prior to cognitive testing.

	Response time (ms)	**Response accuracy (proportion correct)**
Working memory task[a]		
1-back	409.1 ± 73.6	0.98 ± 0.02
2-back	522.8 ± 133.8[b]	0.95 ± 0.06[b]
3-back	538.0 ± 150.6[b,c]	0.87 ± 0.08[b,c]
Visual attention task[a]		
Valid cue	307.2 ± 31.9	0.94 ± 0.05
Invalid cue	360.2 ± 40.6[d]	0.91 ± 0.09[d]
No cue	387.8 ± 45.6[d,e]	0.96 ± 0.04[d,e]

Results presented as median ± interquartile range due to skewed distributions. [a]Differences evaluated using mixed effect regression of transformed variables with Bonferroni post hoc correction for multiple comparisons. [b]Significantly different than 1-back load. [c]Significantly different than 2-back load. [d]Significantly different than valid cue presentation. [e]Significantly different than invalid cue presentation.

Response times for all three memory loads were positively correlated with one another (all $p \leq 0.01$; appendix Table C2), suggesting those who responded rapidly on lower memory load also did so on higher memory loads. Correlations between response accuracies were less consistent, with a positive correlation only between 2-back and 3-back accuracies ($p \leq 0.05$). There was limited correlation between response time and accuracy for each cognitive load, with the exception of a negative correlations for the 3-back load ($p < 0.05$), suggesting those with faster responses were also more accurate for this load (appendix Table C2).

Response times for each cue presentation in the visual attention task were all highly positively correlated to one another (all $p < 0.001$, appendix Table C3). Similarly, response accuracies of all cue presentations were also all positively correlated (all $p \leq 0.01$). Taken together, these results suggest that those who responded rapidly and accurately on one cue presentation did so on others. As in the working memory task, correlations between response time and response accuracy were inconsistent by cue presentation. While response time was directly correlated to response accuracy during the invalid cue presentation ($p = 0.03$), it was inversely correlated to accuracy during the no cue presentation ($p < 0.001$) and unrelated to accuracy for the valid cue presentation.

5.6.3 Sleep measures

A summary of all sleep parameters for participants with valid weekly sleep and valid sleep measured the night prior to cognitive testing are presented in Table 5.7. Average weekly time in bed and sleep duration was 7.1 ± 0.8 h/night and 6.2 ± 0.7 h/night, respectively. Intra-individual nightly variation (1.2 ± 0.7 h) over the week was also quite high. Sleep quality over the entire week was measured with sleep efficiency (88.5 ± 4.8%), and WASO (51.8 ± 20.5 min/night). The average weekly mid-sleep time, a marker of sleep timing, was 04:48 ± 1.0 h.

With the exception of an earlier mid-sleep time (04:19 ± 1.0 h, $p < 0.001$), sleep parameters on the night prior to cognitive testing were not significantly different than the weekly averages (Table 5.7).

Table 5.7. Sleep measures for participants with valid weekly sleep and valid sleep measured the night prior to cognitive testing.

	Sleep the night prior to cognitive testing	**Weekly sleep**	***p*-value**
Mid-sleep time (clock time ± h)	04:19 ± 1.2	04:48 ± 1.0	**<0.001**
Total rest time (h/night)	7.0 ± 1.4	7.1 ± 0.8	0.15
Total sleep time (h/night)	6.1 ± 1.4	6.2 ± 0.8	0.11
WASO (min/night)	51.4 ± 28.5	51.9 ± 20.5	0.71
Sleep efficiency (%)[a]	88.4 ± 7.1	88.5 ± 4.8	0.63
Total rest time variability (h)[a]		1.4 ± 0.8	
Total sleep time variability (h)[a]		1.2 ± 0.7	

Results presented as mean ± standard deviation, unless otherwise noted. *P*-values are the result of paired t-tests comparing sleep the night prior to cognitive testing to weekly sleep. Boldface type indicates significant differences. [a]Results presented as median ± interquartile range due to skewed distributions. WASO, wake after sleep onset.

5.6.4 Regression analyses between sleep and cognitive measures at age 17

Associations between cognitive measures and free-living sleep parameters were assessed using linear regression models. Response times and accuracies on higher cognitive loads of the working memory task (i.e. 2-back and 3-back response times) were adjusted for analogous measures on the 1-back task (Ciesielski et al., 2006; Schleepen & Jonkman, 2009). Similarly, response times and accuracies of the invalid and no cue conditions of the visual attention task were adjusted for the analogous measures on the valid cue condition.

When the association between working memory and sleep parameters measured the night prior to cognitive testing was explored, *p*-values below 0.05 were observed for the positive association between sleep efficiency and 2-back response time and the negative associations between total time in bed and sleep times and 3-back response times (Table 5.8). There were no associations between working memory and weekly averages of sleep parameters with *p*-values below 0.05 (Table 5.8).

Table 5.8. Results of linear regression between sleep parameters and response times and accuracies on the short-term working memory task at age 17.

	2-Back response time (ms) β [95% CI] (*p*)	**2-Back response accuracy (proportion correct) β [95% CI] (*p*)**	**3-Back response time (ms) β [95% CI] (*p*)**	**3-Back response accuracy (proportion correct) β [95% CI] (*p*)**
Sleep measures of the night prior to short-term memory task				
Total rest time (h)	-0.03 [-0.18, 0.11] (0.7)	-0.02 [-0.18, 0.15] (0.9)	-0.22 [-0.38, -0.07] (0.005)*	0.04 [-0.12, 0.20] (0.6)
Total sleep time (h)	0.02 [-0.13, 0.16] (0.8)	-0.06 [-0.22, 0.10] (0.5)	-0.19 [-0.34, -0.03] (0.02)	0.07 [-0.09, 0.23] (0.4)
Sleep efficiency (%)	0.15 [0.01, 0.29] (0.04)	-0.15 [-0.31, 0.00] (0.06)	0.03 [-0.13, 0.18] (0.8)	0.09 [-0.07, 0.25] (0.3)
WASO (min)	-0.13 [-0.27, 0.01] (0.06)	0.13 [-0.03, 0.29] (0.1)	-0.12 [-0.28, 0.04] (0.1)	-0.08 [-0.24, 0.08] (0.3)
Weekly sleep measures				
Total rest time (h/night)	-0.01 [-0.15, 0.13] (0.9)	-0.06 [-0.22, 0.10] (0.5)	-0.11 [-0.26, 0.05] (0.2)	0.11 [-0.05, 0.26] (0.2)
Total sleep time (h/night)	0.04 [-0.10, 0.18] (0.6)	-0.04 [-0.20, 0.12] (0.6)	-0.07 [-0.23, 0.09] (0.4)	0.13 [-0.03, 0.28] (0.1)
Sleep efficiency (%)	0.10 [-0.04, 0.24] (0.2)	-0.004 [-0.16, 0.16] (0.96)	0.06 [-0.10, 0.21] (0.5)	0.05 [-0.11, 0.20] (0.6)
WASO (min/night)	-0.10 [-0.24, 0.04] (0.2)	-0.06 [-0.22, 0.10] (0.5)	-0.08 [-0.24, 0.07] (0.3)	-0.05 [-0.20, 0.11] (0.6)
Total rest time variability (h)	0.01 [-0.13, 0.15] (0.9)	-0.04 [-0.20, 0.12] (0.7)	0.15 [-0.01, 0.30] (0.07)	-0.05 [-0.21, 0.11] (0.5)
Total sleep time variability (h)	0.002 [-0.14, 0.14] (0.98)	-0.02 [-0.18, 0.14] (0.8)	0.13 [-0.03, 0.28] (0.1)	-0.07 [-0.22, 0.09] (0.4)

*Significant after Benjamini-Hochberg analysis of all comparisons with 0.25 false discovery rate. All regressions adjusted for clinical diagnosis of attention deficit hyperactivity disorder and reported weekly video game use. 2-back and 3-back response time additionally adjusted for 1-back response times. 2-back and 3-back response accuracy additionally adjusted for 1-back response accuracy. Response times, response accuracies, sleep efficiency, total sleep time variability, and total rest time variability were transformed prior to analysis due to skewed distributions. β, standardized beta value; CI, confidence interval; WASO, wake time after sleep onset.

After controlling for possible type 1 error using the Benjamini-Hochberg method for false discovery rate, only the association between time in bed the night before cognitive testing and 3-back response time (p=0.005) fell below the critical p-value of 0.006. This suggests that less time in bed acutely, the night prior to the working memory task, was significantly associated with longer response times only on the most difficult cognitive load (Figure 5.3A), although no such relationship existed for average weekly time in bed (Figure 5.3C).

In an additional, exploratory analysis of the relationship between total time in bed and working memory was done in order test whether participants with a total time in bed of 7 h or less performed differently on the task than those with greater than 7 h. The analyses showed that the 82 students with a time in bed of 7 h or less the night prior to cognitive testing had longer 3-back response times on than the 78 students with a time in bed of greater than 7 h (median ± interquartile range: 551.7 ± 148.1 vs. 514.5 ± 138.2 ms, *p* = 0.04; Figure 5.3B, appendix Table C4). Similarly, the 66 participants who averaged 7 h or less total time in bed over the week had longer 3-back response times than the 94 participants who did not (570.3 ± 135.7 vs. 511.3 ± 143.7 ms, *p* = 0.03; Figure 5.3D appendix Table C4). Results of the categorical analysis support the finding that short, acute total time in bed prior to cognitive testing is associated with longer response times on the most difficult cognitive task.

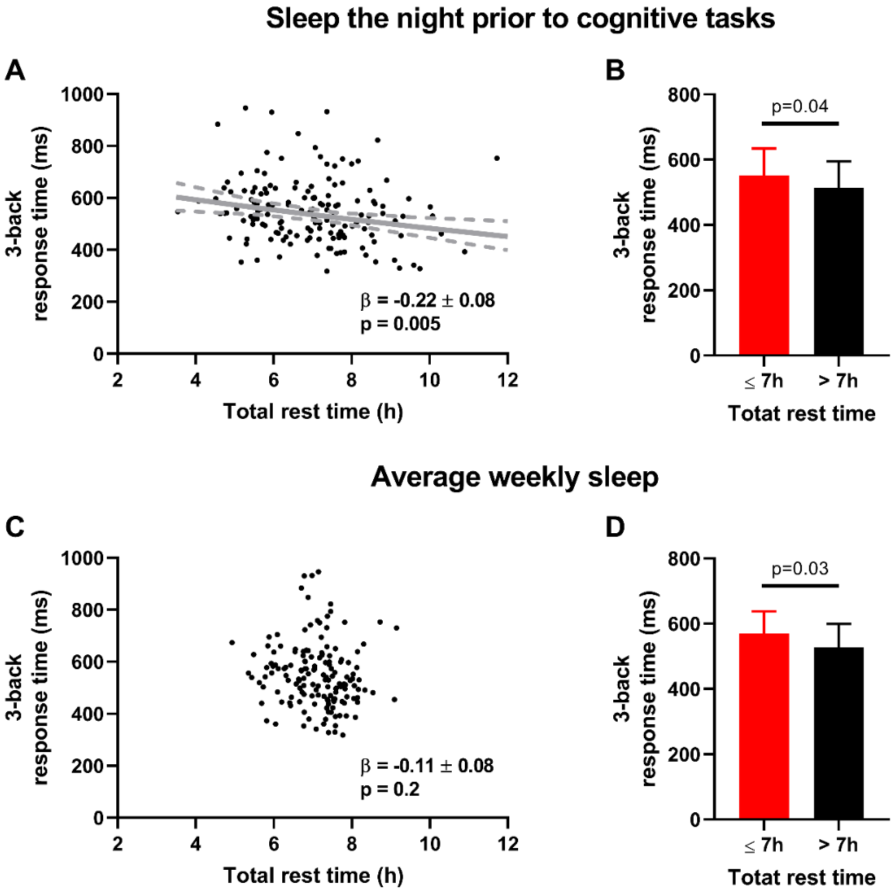

Figure 5.3. Relationship between response time on the most difficult (3-back) work memory load and total time in bed. (A) The solid grey line demonstrates the inverse correlation between total time in bed the night prior to the cognitive task and 3-back response times. Broken grey lines indicate the 95% confidence intervals. (B) Participants with 7 hours or less total time in bed (in red, N=82) had longer response times than those with greater than 7 hours (in black, N=78). (C) Average weekly total time in bed did not correlate with 3-back response times. (D) Participants that average 7 hours or less daily total time in bed over the week (N=66) had longer response times than those that averaged greater than 7 hours (N=94). All comparisons adjusted for clinical diagnosis of attention deficit hyperactivity disorder, reported weekly video game use, and 1-back response times. Response times were log-transformed prior to analysis due to skewed distributions; inverse transformation was applied for displayed in (A); bars and error bars in (B) and (D) are medians and interquartile ranges. β, standardized beta ± standard error.

No associations between response times on the visual attention task and sleep parameters measured the night prior to cognitive testing or over the entire week were found (Table 5.9). There were also no differences in the visual attention task performance of participants with 7 h or less total rest time compared to those with greater than 7 h (appendix Table C5).

Table 5.9 Results of linear regression between sleep parameters and response times and accuracies on the visual attention task.

	Invalid Cue response time (ms)	**Invalid Cue response accuracy (proportion correct)**	**No Cue response time (ms)**	**No Cue response accuracy (proportion correct)**
	β [95% CI] (*p*)	**β [95% CI] (*p*)**	**β [95% CI] (*p*)**	**β [95% CI] (*p*)**
Sleep measures of the night prior to short-term memory task				
Total rest time (h)	-0.05 [-0.14, 0.04] (0.3)	0.01 [-0.09, 0.11] (0.8)	0.04 [-0.05, 0.13] (0.3)	-0.08 [-0.24, 0.09] (0.4)
Total sleep time (h)	-0.06 [-0.15, 0.03] (0.2)	0.02 [-0.09, 0.12] (0.8)	0.03 [-0.06, 0.12] (0.5)	-0.07 [-0.23, 0.09] (0.4)
Sleep efficiency (%)	-0.05 [-0.14, 0.04] (0.3)	-0.01 [-0.11, 0.09] (0.9)	-0.02 [-0.11, 0.07] (0.6)	-0.02 [-0.18, 0.14] (0.8)
WASO (min)	0.02 [-0.07, 0.11] (0.7)	-0.01 [-0.11, 0.10] (0.9)	0.04 [-0.05, 0.13] (0.4)	-0.02 [-0.18, 0.14] (0.8)
Weekly sleep measures				
Total rest time (h/night)	0.01 [-0.08, 0.10] (0.8)	-0.01 [-0.11, 0.09] (0.9)	0.02 [-0.07, 0.10] (0.7)	0.04 [-0.12, 0.19] (0.7)
Total sleep time (h/night)	-0.02 [-0.11, 0.07] (0.7)	0.03 [-0.07, 0.13] (0.6)	0.01 [-0.08, 0.10] (0.8)	0.02 [-0.14, 0.18] (0.8)
Sleep efficiency (%)	-0.07 [-0.16, 0.02] (0.1)	0.07 [-0.03, 0.17] (0.2)	-0.01 [-0.1, 0.08] (0.8)	-0.05 [-0.21, 0.11] (0.6)
WASO (min/night)	0.07 [-0.02, 0.16] (0.1)	-0.07 [-0.17, 0.03] (0.2)	0.01 [-0.08, 0.09] (0.9)	0.04 [-0.12, 0.20] (0.6)
Total rest time variability (h)	-0.001 [-0.09, 0.09] (0.98)	0.03 [-0.07, 0.13] (0.6)	-0.07 [-0.16, 0.01] (0.1)	0.03 [-0.13, 0.18] (0.7)
Total sleep time variability (h)	-0.01 [-0.1, 0.08] (0.8)	0.05 [-0.05, 0.15] (0.3)	-0.06 [-0.15, 0.02] (0.2)	-0.003 [-0.16, 0.16] (0.97)

All regressions adjusted for clinical diagnosis of attention deficit hyperactivity disorder and reported weekly video game use. Invalid cue and no cue response time additionally adjusted for valid cue response times. Invalid cue and no cue response accuracy additionally adjusted for valid cue response accuracy. Response times, response accuracies, sleep efficiency, total sleep time variability, and total rest time variability were transformed prior to analysis due to skewed distributions. β, standardized beta value; CI, confidence interval; WASO, wake time after sleep onset.

6 Discussion

The overall aim of this dissertation was to use objective measures to quantify the free-living sleep of Icelandic adolescents at ages 15 and 17, as they transition from compulsory to secondary education, and to determine whether their sleep patterns are associated with academic and cognitive performance. It was observed that, in general, the sleep of Icelandic adolescents was characterized by short durations, late bedtimes, and high night-to-night variability. However, from age 15 to 17, average weekly time in bed and sleep duration became shorter and school night sleep became even later and more varied. Further, later bedtimes and less consistent sleep schedules at age 15 were associated with lower standardized exams scores and shorter time in bed the night prior to cognitive testing at age 17 was associated with poorer performance on the most challenging short-term memory task. These results, obtained with objective methods, support the idea that later bedtimes, and shorter and less consistent sleep, may negatively impact cognitive functioning. It was also observed that students who switched to a college-style schedule at age 17 rose later and thus, had less reduction in school night sleep. Although results were modest and further follow-up is needed to determine if different schedules lead to meaningful long-term differences in sleep behavior, these data suggest that modifications to school schedule may be a potential pathway for policymakers to positively impact student sleep.

6.1 Aim 1. Changes in sleep from age 15 to 17

The longitudinal aspect of this thesis measured the changes in sleep in Icelandic students from age 15 to 17 as they transitioned from compulsory to secondary education. The results revealed that only 10.9% of Icelandic adolescents spent the recommended 8 h/night in bed on school nights (Hirshkowitz et al., 2015) at age 15, with an average sleep duration of 6.2 hours per school night. At age 17, school night sleep duration remained low, at 6.0 h/night, and the percentage of students getting the recommended amount of sleep on school nights dropped to 6.9%. Although, the shortened sleep duration from age 15 to 17 is in line with previous findings of a 14 min/year decline in sleep during adolescence (Olds et al., 2010; Owens & Group, 2014) and has previously been reported in adolescent populations (Matthews et al., 2014), these findings suggest a widespread and consistent pattern of short sleep.

The sleep reduction observed from age 15 to age 17, stems from a 30 min/night later bedtime which was not compensated by a similar shift in rise times. Thus, a late bedtime routine was the primary contributor to the insufficient sleep among Icelandic adolescents, as the average weekly bedtime for students was 00:49 at age 15 and 01:19 at age 17. Although previous studies have reported late bedtimes for older adolescents (Olds et al., 2010) and found later bedtimes in Europe than in North America - 22:46 vs. 22:06 (Gradisar et al., 2011), Icelandic adolescent bedtimes are notably later than the reported bedtimes of similarly aged groups from other countries (Hysing et al., 2013; Knutson & Lauderdale, 2009).

There are several possible explanations for this change in sleep timing and reduction in sleep. One potential explanation is a change in external psychosocial influences, such as a reduction in parent-set bedtimes (Loessl et al., 2008), increases in night-time social media use (Scott & Woods, 2018), recreational activities, and/or academic pressure, or possible employment (Adam et al., 2007). As discussed previously, another contributing factor to later bedtimes might be a shift in circadian rhythm caused by delayed melatonin release (Carskadon et al., 1998) and slower accumulation of sleep pressure (Crowley et al., 2018) at this stage of puberty. Previous work has also demonstrated that older adolescents are less sensitive to sleep pressure than younger adolescents and adults (O. G. Jenni et al., 2005; Tarokh et al., 2012).

Several additional factors specific to the Icelandic population may exacerbate the late bedtime and short sleep demonstrated in the Aim I analysis. Clock misalignment, i.e., the ~1.5 hour mismatch between Iceland's geographical position and its adopted time-zone of Greenwich Meantime (GMT), may partly explain the late bedtimes reported here and in other Icelandic age groups (Thorleifsdottir et al., 2002). Iceland has adhered to GMT year-round since 1968, even though portions of it are geographically located nearly 2 time zones west of London. This means that solar noon, the time at which the sun reaches its highest point in the sky, is delayed by 1.5 hours in Reykjavík, occurring at 13:30 GMT rather than at 12:00. This time shift can cause a delay in the morning light from the sunrise that has shown to be vital in synchronizing information for the internal clock and bodily functions (Duffy & Czeisler, 2009). Furthermore, studies on geographical locations have shown that people living in the western part of a time zone have both later bedtimes and shorter sleep durations than people in the eastern area of a time zone (Giuntella & Mazzonna, 2019; Roenneberg et al., 2007).

The latitudinal position of Iceland, far north of the equator, may also cause misalignment in sleep timing due to a delay (or absence) of daylight in winter months and an excess of daylight in summer months, resulting in an extreme case of a condition known as “clock fatigue” (Heilbrigðisráðuneyti, 2018). Previous studies have explored the impact of day length on sleep. One study using self-reported sleep measures demonstrated that adolescents living in Norway (mean age 15.7y), who experienced shorter day length, went to bed 18 min later and slept 29 min less than peers in Australia, the Netherlands, and Canada (Bartel et al., 2017). Data was collected during the winter months in Norway, Netherlands and Canada, and during the summer months in Australia (October to May). However, a recent study of the adolescent cohort measured in this thesis did not find a relationship between day length and total sleep time (Rognvaldsdottir et al., 2017). Similarly, a study of older Icelandic men and women found no difference in total sleep time, WASO, or sleep efficiency, between winter and summer, indicating that inhabitants of Iceland are well-adapted to the extreme change in daylight across seasons (Brychta et al., 2016).

It should also be noted that the students measured in this project, born in 1999, were the first class to experience a shortened secondary education in Iceland, where the average time to matriculation was reduced from four years to three years (Menningarmálaráðuneyti, 2020). In a recent report, the Icelandic Minister of Education, Science and Culture reported that since the shortening of the time to matriculation there has been 0.5% decrease in dropout rate among first year students and participation in social activities and sports has remained stable, but employment amongst students has increased and student reported mental health has decreased (Menningarmálaráðuneyti, 2020). These statistics suggest that the organized leisure and sport participation of Icelandic students did not change even as academic demands increased as studies were condensed from four years to three years, which may have impacted their sleep schedules in upper-secondary school. The actigraphy data support this concept, as overall sleep decreased but weekend sleep became longer, indicating a greater need for weekend “catch-up” sleep to compensate for the short sleep on weekdays, when they were required to manage school and work on top of a busy schedule. These potential contributors to shorten overall sleep is of interest to policy makers and should be studied in greater detail in the future.

Sleep reduction on school nights was only seen in students who continued a traditional schedule and not in those who switched to a college-style scheduling system. On school nights, students of both school types went to bed later at age 17 compared to age 15, but students who attended schools with college-style course scheduling had later rise-times than those who continued in schools with traditional schedules, resulting in better preservation of total sleep time from age 15 to 17. These findings are in line with a study of similarly aged adolescents during which a 45 min delay in school start time resulted in a small delay in self-reported bedtimes, but also a considerable delay in self-reported rise times and, thus, an overall increase in sleep duration (Lo et al., 2018). Similarly, a large Canadian study of adolescents found that each 10-min delay in school start time corresponded to an additional 3.2 minutes of sleep (Gariépy et al., 2017). As a result, students attending schools with later start times were less tired in the morning and more likely to meet sleep recommendations (Gariépy et al., 2017). A recent meta-analysis also demonstrated that delaying school start times was associated with longer sleep durations (Bowers & Moyer, 2017), which can lead to improved academic performance (Hysing et al., 2016), enhanced cognitive function (Dewald-Kaufmann et al., 2013), students feeling less tired (Gariépy et al., 2017), and improvements in alertness and well-being (Lo et al., 2018). Taken together, these results support the idea that later school start times may be more suitable for the natural sleep patterns of older adolescents (Carskadon et al., 1998), and increases the chances of meeting sleep duration requirements by providing greater opportunity for morning sleep to accommodate their social and biological drive toward later bedtimes.

6.2 Aims II and III: The association between sleep and academic and cognitive performance

As highlighted in Aim I, the students measured in this thesis had short sleep, late bedtimes, and their sleep patterns were inconsistent. Thus, the next two aims were meant to address the possible repercussions of these trends on academic and cognitive performance.

The association between objectively measured sleep and performance on standardized national exams in 15-year-old Icelandic adolescents was examined in Aim II. The findings showed that earlier bedtimes, more consistent sleep schedules, and greater total sleep time were associated with higher standardized exams scores at age 15. There are no analogous standardized national examinations after age 15 in the Icelandic education system and thus, there are no similar academic metrics at age 17. However, since prior studies have demonstrated that sleep restriction affects cognitive function in laboratory settings (Hudson et al., 2020; Lo et al., 2016), Aim III sought to determine whether a similar association existed between objectively measured free-living sleep and performance on working memory and visual attention tasks at age 17, particularly after identifying the short sleep duration at both ages for the students measured in this thesis. The results demonstrated that shorter time in bed the night prior to the cognitive testing was negatively associated with performance on the most challenging short-term memory load, indicating that acute short sleep can affect short-term working memory, even in a healthy population measured in a free-living setting.

These findings are in line with previous studies that have focused on the deleterious effect short sleep has on academic and cognitive function. Cross-sectional and longitudinal data has demonstrated that shorter sleep is associated with poorer academic performance amongst adolescents (Dewald, Meijer, Oort, Kerkhof, & Bögels, 2010; Hysing, Harvey, Linton, Askeland, & Sivertsen, 2016). Further, a recent review paper discussed the deleterious effect short sleep has on health, behavior, and academic and cognitive performance (Alfonsi et al., 2020). Similarly, randomized clinical studies of adolescents have demonstrated that even partial sleep deprivation can deleteriously effect a wide range of cognitive functions including alertness (Lo et al., 2016), visual attention (Agostini et al., 2017), cognitive processing speed (Louca & Short, 2014), and memory (Jiang et al., 2011). Previous studies have also shown that sleep may be important for continued brain development during adolescence (Kopasz et al., 2010), especially in frontal and parietal brain regions since they underlie cognitive domains such as attention and memory (Sowell et al., 2001).

6.2.1 The relationship between sleep duration and cognitive and academic performance

Previous studies and most public health guidance have centered on sleep duration and highlighted the negative impact of short sleep on academic and cognitive performance (Curcio et al., 2006; Hirshkowitz et al., 2015; Lo et al., 2016). Additional, exploratory analysis for Aim II demonstrated that shorter total sleep time was associated with lower scores on the Icelandic exam score. These findings are in line with a large population-based survey from Norway, reporting that sleep duration had the highest odds compared to other sleep patterns when the association between sleep and grades was explored with official records (Hysing et al., 2016). Similarly, a German study based on self-report showed that students with sleep duration less than 8 hours a night had lower grades in the German language and mathematics courses compared to students who slept longer (Perkinson-Gloor et al., 2013). In the current thesis, however, there were no associations between sleep duration and the average exam score in the primary analysis nor were there associations between sleep duration and scores in individual topics when analyzed separately by sex. This limited association could suggest a more subtle relationship between objectively-measured free-living sleep duration and exam score compared to those identified in previous work, which are mostly based on self-reported sleep (Asarnow et al., 2014; Stea, Knutsen, & Torstveit, 2014). Although, it was not possible to fully understand why the association between free-living sleep duration and standardized exam scores in this thesis was less drastic than those seen in previous studies, one potential difference may be a floor effect of pervasive short sleep in the 15 year-olds measured for this aim, where >78% failed to achieve the recommended 8 h/night in bed and the 6.6 h/night sleep duration is amongst the shortest for this age range (Rognvaldsdottir et al., 2017).

Interestingly, when the association between sleep duration and cognitive function was tested in Aim III, the findings revealed that shorter time in bed the night prior to the cognitive testing was negatively associated with performance on the most challenging short-term memory load. A similar continuous association between weekly rest duration and short-term working memory was not observed, despite short average sleep duration and time in bed over the week. However, when an exploratory categorical analysis requiring less statistical power than continuous regression was used, participants with rest durations of 7 h or less, measured either acutely on the night prior to cognitive testing or averaged over the week, were found to have longer response times during the most difficult short-term memory load than those with greater than 7 h.

Despite strong previous evidence from clinical studies (Agostini et al., 2017; Lo et al., 2016), no association was found between sleep parameters and performance on the visual attention task. The contrasting results could be due in part to the visual attention task lacking the sensitivity needed to assess the effects of free-living sleep on the visual attention of our generally healthy, older adolescent population. Another potential explanation for the limited association between weekly sleep and cognitive function was that the participants were able to compensate for low sleep duration over the week. For instance, participants could have compensated for shorter amounts of sleep with caffeine intake, which we did not control for and is reportedly widespread amongst Icelandic adolescents (Kristjansson et al., 2011). The high intra-participant night-to-night variation in time-in-bed (1.4 h) is also indicative of compensatory nights of shorter and longer sleep over the week, which may have obscured or diluted associations between weekly sleep parameters and cognitive function. These potential compensatory behaviors may have led to a more subtle relationship between free-living sleep and cognitive function than those observed during clinical trials with greater control of diet and sleep schedules.

The great night-to-night variation in time in bed and sleep duration amongst participants in this thesis also suggests that a larger sample size or longer measurement period may be required to detect a correlation based on continuous measures of free-living rest or sleep duration and cognitive function in older adolescents.

6.2.2 The relationships between sleep timing and consistency and academic and cognitive performance

Despite the noted potential for highly varied sleep schedules to reflect a compensation for shortened sleep, irregular sleep patterns have also been shown to be associated with poorer academic performance in younger children (Kelly et al., 2013) and college-aged students (Phillips et al., 2017). Sleep timing may also be important to cognitive and academic performance of teenagers. There is both cross-sectional (Hysing et al., 2016; Urrila et al., 2017) and longitudinal (Asarnow et al., 2014) evidence that those with later bedtimes are more likely to perform worse in school than those that go to bed earlier. The results of Aim II of this thesis support these findings, as both bedtime and night-to-night variability in total sleep time were negatively associated with two of the three exam scores and the average score across all topics. These relationships reinforce the concept that sleep is multidimensional and aspects other than sleep duration may influence cognition and physical health. Further support for this notion come from previous studies of adults, which report that misalignment of sleep timing is associated with metabolic risk factors that can lead to diabetes and heart disease (Wong et al., 2015). Similarly, studies of adolescents have reported that sleep timing, particularly late bedtime, may independently influence BMI (Golley et al., 2013) and systolic blood pressure (Mi et al., 2019)

There was no association between national exam scores and “social jetlag” – an alternative measure of sleep schedule variability computed as the difference in the timing of the mid-point of sleep between weeknights and weekend nights. These results conflict with those of a previous study that found undergraduates with greater self-reported social jetlag had poorer weekly test grades (Haraszti et al., 2014). However, the disparity in these findings may have arisen from several factors including differences in study population age (21.2y for the undergraduates vs. 15.9y for the student for Aim

II), data collection method (questionnaire vs. wrist actigraphy), and/or test information (weekly tests vs. standardized exams). It should also be noted that while night-to-night variability quantifies changes in sleep duration over the entire week, social jetlag arises from weekend shifts in sleep schedule, duration, or both as students tend to compensate for the shorter sleep and earlier rise times on school days by sleeping longer and rising later on weekends (Collado et al., 2012). Thus, these two measures capture related, but slightly different information about the consistency of sleep schedule.

Despite high values for night-to-night variations of time-in-bed and sleep duration at age 17, they were not associated with any of the cognitive function tasks measured in Aim III. These results were surprising since a previous study using diffusion-tensor-imaging MRI reported that adolescents reporting sleep problems that had greater sleep variability one year prior to the scan had lower white matter integrity, suggesting that the greater sleep variability could potentially have long-term harmful effects on brain development, cognitive function, and well-being (Telzer et al., 2015).

Reasons for the differences in findings of this thesis compared to those of previous studies on the relationship between sleep variation and academic and/or cognitive performance remain unclear. However, as discussed previously, the high degree of variation amongst the participants in this thesis, as evidenced by the large night-to-night variability and social jetlag at both time points, suggests a larger sample size or longer measurement period may be required to detect associations between free-living sleep variability and cognitive function or academic performance.

6.2.3 The relationship between sleep quality and academic and cognitive performance

Contrary to some previous reports (Adelantado-Renau et al., 2019; Curcio et al., 2006; Dewald et al., 2010), and in contrast to the hypothesis of Aim II, there was no relationship between academic performances and sleep quality measures, i.e., sleep efficiency and WASO. There was also no significant association between sleep quality markers and performance on the cognitive tasks described in Aim III after controlling for the false discovery rate with Benjamini-Hochberg method.

A recent study using wearable activity trackers found that both better sleep quality, and greater sleep consistency were associated with better academic performance among college freshman students (mean age 18.19 years) (Okano et al., 2019). However, a recent study that used both subjective and objective methods demonstrated an association between academic performance and subjective sleep, but not when objective sleep quality were measured (Adelantado-Renau et al., 2019). The absence of an association in the current thesis may have resulted from studying a healthy population with >95% of participants averaging above 80% sleep efficiency and a limited prevalence of disorders known to cause sleep disturbances at both time points.

Further, large cross-sectional studies have found that poor sleep quality is associated with lower performance on tasks of working memory and executive functioning among young adolescents - mean age 9.9 and 12.3 years respectively (Kuula et al., 2015; Steenari et al., 2003). However, a recent study of healthy young adults (mean age 21) found no association between subjective sleep quality and working memory (Zavecz et al., 2020). Zavecz et al. suggest that the lack of association may have been due to a ceiling effect of studying a healthy population with limited prevalence of disorders known to cause sleep disturbances, which is also the case in the present thesis. These observations suggest that, compared to younger populations, free-living sleep quality may play a lesser role than sleep duration in the working memory task performance of healthy older adolescents and young adults.

6.3 Comparing the sleep patterns of Icelandic adolescents to those of adolescents around the world

Two of the most striking findings from our sleep measurement of Icelandic adolescents were their short sleep duration, 6.6 h/night at age 15 and 6.2 h/night at age 17 and late bedtime, 00:49 at age 15 and at 01:19 at age 17. It can be helpful to compare these sleep patterns to those of other populations of adolescents in order to provide a greater cultural context to the sleep of adolescents in Iceland. However, several factors confound direct comparisons of the sleep patterns between these Icelandic participants and those observed in other countries. First, most previous studies of sleep have relied on self-reported measures, which tend to report longer sleep duration (Short et al., 2012), and earlier bedtimes (Brychta et al., 2019) than those measured with actigraphy. In this regard, the “time in bed” measured in our cohort by wrist actigraphy (7.5 h/night at 15 and 7.1 h/night at 17) may be closer to self-reported sleep duration than the total sleep time, since many questionnaires and sleep logs measure the time between bedtime and rise time without accounting for nightly awakenings. Second, sleep amongst adolescents tends to change with age, with older adolescents going to bed later (Gariépy et al., 2020; Olds et al., 2010) and sleeping less (Galland et al., 2018), as evidenced in our own cohort. Thus, studies of sleep patterns in populations that are younger, older, or heterogeneous by age may not offer a fair comparison to those of the students measured for the current thesis, who averaged 15.9y during the first sleep measurement and 17.7y during the second sleep measurement. Finally, many studies report an average sleep duration across the week, although adolescents typically go to bed later but sleep longer on weekend nights to make up for short sleep on the weekdays, which can obscure weekly averages. This "catch-up sleep" phenomenon was also observed in our own cohort, as students shifted to a later sleep schedule and slept longer on non-school nights than school nights during both measurements.

Bearing in mind these limitations, it is still helpful to discuss how sleep amongst Icelandic adolescents fits into previous reports from around the world, since inter-national trends in sleep are apparent from the many large population studies using self-reported measures. In general terms, based on subjective sleep measures, Asian and American cohorts tend to report sleeping less than their European, Canadian, or Australian counterparts (Olds et al., 2010). For instance, a large population study comparing Australian and American students' sleep demonstrated that the Australian students (mean age 15.57y) reported sleeping an average of 8.28h on school nights, while American students (mean age 16.03y) reported sleeping 7.37h (Short et al., 2013). In similar large population studies, Canadian students (ages 11-16y old) reported sleeping 8.60h on weeknights (Gariépy et al., 2017), while Chinese students (mean age 15.6y) reported sleeping only 7.60h on weeknights (Chen et al., 2014). These findings are all in line with a large meta-analysis of self-reported sleep which found that, on average, Europeans sleep longer than Americans and Asians (Olds et al., 2010). However, the authors caution that making broad generalizations over the entirety of Europe can be difficult due to the considerable differences in geography and culture amongst European countries and the limited data from some countries (Olds et al., 2010). An additional regional analysis of European countries demonstrated that adolescents from Scandinavian countries tend to sleep about 14 min less per night than those from other European countries (Olds et al., 2010). Similarly, while a population survey from 10 European cities in Austria, Belgium, France, Germany, Greece, Hungary, Italy, Spain and Sweden (aged 12.5-17.5 years old) found that average daily sleep duration was around 8h (Garaulet et al., 2011), a Norwegian sample (mean age 17y) self-reported an average weekday sleep duration of 6.42h (Hysing et al., 2013), which is shorter than the self-reported sleep from many US and Asian cohorts and more in line with our finding that, on school nights, Icelandic adolescents spend about 7.1h in bed at age 15 and 6.8h in bed at age 17.

Objectively measured sleep data on adolescents is much less abundant than self-reported sleep measures, making inter-national comparisons of actigraphy-measured sleep more difficult. However, the data that are available seem to confirm a common finding of methodological studies that simultaneously employ both methods: that total sleep time measured by actigraphy is shorter than that measured by self-report. For example, an actigraphy-based study of older Italian students aged 18.14y found a mean weekly sleep of 6.64 h (Tonetti et al., 2015), shorter than most self-reported sleep durations from European countries (Olds et al., 2010), but notably longer than the 6.2h mean weekly sleep time of our Icelandic cohort at age 17.7y. Likewise, a study of Australian students with a mean age 16.18y reported total school night sleep time was 6.56 (Bei et al., 2014), which is 1.7h shorter than the self-reported school night sleep time in a similarly aged cohort (mean age 15.57y) from the same country of 8.28h (Short et al., 2013), and closer to the 6.23h average school night total sleep time of our Icelandic cohort at age 15.9y. Not surprisingly, objective studies of adolescent sleep also largely report longer sleep on weekends than on weekdays. In the same group of Australian students, objectively measured total sleep time increased by 0.59h to 7.15h on non-school nights compared to school nights (Bei et al., 2014), which is shorter than the 1.10h increase in total sleep time from school nights to non-school nights of our Icelandic cohort at age 15.9y.

Another trend that was generally consistent between self-reported and actigraphy-measured sleep was a decline in total sleep time with age throughout adolescence (Galland et al., 2018; Olds et al., 2010). However, neither the absolute sleep duration by age nor the magnitude of the decline was consistent, even in cohorts from the same country. In our Icelandic cohort, school night sleep declined from 6.23h at age 15.9y to 5.98h at age 17.7y, a reduction of about 8 min/y. A recent actigraphy-based study of American based students found a much more rapid drop in average school night sleep duration, from 6.72h in eighth grade (mean age 13.9y) to 6.29h in ninth grade (mean age 14.9y), or about 26 min/y (Mitchell et al., 2020). A similar objective study of American students' school night sleep at three different time points (mean age 16.39y at wave 1, 18.31y at wave 2, and 20.29y at wave 3) found a decline of about 6 min/y, from 7.56h at wave 1 to 7.16h (Park et al., 2019), which is more in line with the findings of the current thesis. Differences in these findings could reflect cultural/geographical differences in sleep declines, variations in sleep need changes during earlier versus later adolescence, or different sleep adaptations during various school transitions. It should be noted that eighth-to-ninth grade marks the transition from middle to high school in North America, 15y-to-16y is the transition from secondary to upper secondary school in Iceland, and 18y-to-20y is typically the transition from high school to college in the US. These objectively measured rates of adolescent sleep decline differ from those identified in the large meta-analysis of self-reported sleep from around the world, which found a 17 to 18 min/y rate of school night sleep reduction for Asia and the US and about 12 min/y decline in Europe and Australia (Olds et al., 2010). While differences in the rate of decline in adolescent sleep with age between actigraphy and self-report may partly be explained by methodological disparities, it is important to note that the two methods are known to be correlated (Lauderdale et al., 2008a) and there is much more data from self-reported methods.

As with sleep duration, disparities have been identified between actigraphy-measured and self-reported bedtimes, with actigraphy-measured bedtimes tending to be earlier when the two methods are employed concurrently (Brychta et al., 2019; Marino et al., 2013). Despite these differences, the bedtimes by actigraphy and self-report remain correlated (Brychta et al., 2019) and the two methods show similar overall age-based and inter-national trends across adolescent populations. For instance, previous studies using either method have consistently shown that older adolescents go to bed later (Galland et al., 2018; Gariépy et al., 2020; Ortega et al., 2010), which is likely a consequence of biology (Carskadon, 2011; Taylor et al., 2005) and increased independence (Short et al., 2013). Self-reported bedtimes also tend to be later in Europe than in North America (22:46 vs. 22:06) and even later amongst Asian countries (23:23) (Gradisar et al., 2011). However, the author of one large meta-analysis specifically noted that the self-reported bedtimes of Icelandic adolescents of all ages tend to be later than those of their peers from nearly all other countries (Gradisar et al., 2011), which supports our finding that the actigraphy-measured bedtimes of Icelandic adolescents are later than actigraphy-measured bedtimes of similarly aged groups from other countries (Bei et al., 2014; Galland et al., 2018; Tonetti et al., 2015). Notably, the bedtimes measured in this thesis at both time points (00:49 at age 15 and at 01:19 at age 17) were later than the upper 95% confidence bound (23:56) detailed in a large meta-analysis of actigraphy-measured sleep of adolescents aged 15-18y from around the world (Galland et al., 2018). Although these observations suggest a late bedtime pattern that is unique to Iceland, we should note that actigraphy-measured bedtimes in older adolescent populations is scarce, and there is some large multi-national, self-report evidence that suggest Icelandic bedtime patterns are closer to the European average than the extremes (Gariépy et al., 2020). Consequently, more widespread objective measures of sleep timing are needed at multiple seasonal time points throughout the year to make more definitive multi-national comparisons of adolescent bedtimes.

Thus, methodological and age-based differences present challenges to inter-national comparisons of adolescent sleep timing and duration. Despite these limitations, most evidence suggests that the sleep durations and bedtimes presented in this thesis at both measurement points are insufficient to meet the sleep needs of well-functioning adolescents (Gradisar et al., 2011). However, more objective data of sleep patterns from Icelandic adolescents and adolescent populations worldwide is needed to determine the causes of these late bedtimes and short sleep patterns and whether they are a cultural or geographical phenomenon that is unique to the Icelandic population.

6.4 Strengths and limitations

The central strength of the current thesis is the longitudinal design of the study and the diverse data collected at both age 15 and 17, which allowed for both cross-sectional and longitudinal comparisons during a change in educational structure. All three aims were also addressed using objective measures of sleep parameters and exposure outcomes, e.g. academic achievement and cognitive function. Previous studies of sleep in this age group have mainly relied on self- or parental-reports of typical time spent in bed, or bed- and rise-times. Compared to objective measures, adolescents tend to report earlier bedtimes (Brychta et al., 2019), longer sleep durations (Short et al., 2012), and fewer night-time awakenings (Werner et al., 2008). Thus, in order to prevent potential reporting bias, this research project instead measured free-living sleep using objective wrist actigraphy. The Actigraph accelerometer (Actigraph Inc. Pensacola Florida) is one of the most well validated and widely used actigraphy devices for sleep and activity research, especially in large population studies (Ekelund et al., 2001; Freedson et al., 2005; Trost et al., 2005). Epidemiological sleep studies benefit from using accelerometry in sleep research as it provides a more objective view on sleep than self-report and is less invasive and complicated than PSG (Ancoli-Israel et al., 2003; Meltzer & Westin, 2011; Morgenthaler et al., 2007).

Response variables were also measured objectively: standardized national examination scores were obtained from the Icelandic Directorate of Education to quantify academic performance for Aim II and short-term working memory and visual attention were assessed with previously validated software-based tasks for Aim III. Most previous studies of the relationship between free-living sleep and cognitive function that did not include laboratory-based sleep interventions have usually relied on self-reported sleep measures (Kopasz et al., 2010; Oginska & Pokorski, 2006). Those studies that have used objective measures usually examined younger students (Buckhalt et al., 2007; Sadeh et al., 2002; Steenari et al., 2003) or small (< 20 participants), selective samples (Patel et al., 2020).

Another strength of the current thesis is the high participation rate in the first round of data collection at age 15 (n=315, 77%). Since data was collected at the students' school and during school hours, there were few scheduled interferences and interest in the study was considerable. However, substantially fewer subjects (n=168) agreed to repeat the measure and only 145 had valid, complete data for both time points. The reason for the lower participation at age 17 could be due to scheduling conflicts, lack of interest in the study, or because subjects were unreachable for follow-up. Since actigraphy is more difficult to administer than questionnaire-based self-report, the sample size was limited, although it is larger than most clinical sleep studies and representatives of Reykjavík adolescents in this age group during the study period (a total of 1355 15-year-olds lived in Reykjavík in 2015 and 1382 17-year-olds lived there in 2017) (Statistics, 2018).

A limitation of the current thesis is that although wrist actigraphy has been shown to have high accuracy and sensitivity compared to PSG, its specificity is limited (Marino et al., 2013), meaning that actigraphy can accurately detect periods of sleep, but tends to misidentify awakenings as sleep, leading to a potential to overestimation of sleep time and underestimation of wake time (Marino et al., 2013). However, in population-based studies, sleep quality markers from wrist actigraphy, such as awakenings and WASO, correlate well with those from PSG and provide useful information about sleep in one's natural environment. Further, the analyses focus on the primary nightly sleep period since the parameters of the automated detection algorithm may have been insufficient to detect naps, and there is no accepted criterion for scoring actigraphy-assessed naps (Jakubowski et al., 2017). Participants were only explicitly instructed to log primary sleep periods and may not have thought to include naps in the diary. We cannot exclude that omission of naps could have affected our results, as napping has been shown to be a prominent behavior among this age group and is associated with both shorter and more disrupted night-time sleep (Jakubowski et al., 2017).

Another potential limitation was that age 15 measurements were collected from April to June and age 17 measurements from February to April due to schedule conflicts. Holiday periods and seasonal changes in day length and weather can affect sleep and activity (Brychta et al., 2016). More holidays occurred during the age 15 data collection period, resulting in fewer school nights and more non-school nights for some students at age 15 than at age 17. Day length and weather were also different during the age 15 and 17 measurement periods. However, there were few significant cross-sectional correlations between sleep and day length and only bedtime was inversely correlated to day length at age 17. Further, for Aim I**,** assignment to traditional and college-style schools at age 16 was not experimentally controlled. Thus, we could not control the gender distribution between different secondary school schedule systems. Similarly, students did not report reasons for secondary school preferences, and we cannot rule out other potential causes for differences in sleep schedule and duration changes between the two school types. For instance, we did not directly measure academic workload or participation in all extra-curricular activities and, thus, cannot assess how these factors may have impacted sleep. It should also be noted that the questionnaire used for the three studies in this thesis did not ask about participant´s smoking habits or alcohol and caffeine consumption. Further, the questionnaire did not ask participants to report if they have ever been clinically diagnosed with anxiety disorder and/or depression.

The national examinations used in Aim II were administered in October 2014, however, sleep was not measured until April-June 2015 because of scheduling conflicts. Due to this lengthy time interval, additional analysis of the longitudinal data was conducted and all sleep variables were highly correlated from age 15 to 17 ($p \leq 0.01$), with r values between 0.2 (for total sleep time variability) to 0.6 (for sleep efficiency). Thus, there seems to be relative consistency within the cohort for the actigraphy-based sleep measures over the two-year period, suggesting associations between test scores and sleep measures are likely to be reproducible if the interval between them were shorter. Further, the week of free-living sleep and the national exam scores only provide a snapshot of a student's typical sleep schedule and academic performance, respectively. Aims II and III were cross-sectional in nature, which limits study of the causal relationship between study parameters.

It was not feasible to control the time of day or day of week for cognitive testing used in Aim III due to the highly varied schedules of the participants in this age group, which is a considerable limitation. However, all tests were conducted on weekdays in the afternoon (starting from 12:30-19:00, with a mean start time of 15:43±1.3h) and in preliminary analyses, no correlation was found between cognitive response times and time of day or day of the week for testing.

Lastly, it should be noted that the participants in this thesis project were ethnically homogeneous, as most of the Icelandic population is of Norse and

Celtic origin, and generally healthy, with >95% of participants averaging above 80% sleep efficiency, a limited prevalence of disorders known to cause sleep disturbances, and few participants with overweight or obesity (14% at age 15 and 17% at age 17). The general good health of the population studied in this thesis may have been due to self-selection bias, since those who participated could have more interest in health behavior compared to non-participants, which could limit the generalizability of the findings.

7 Conclusion

The findings presented in this doctoral thesis indicate that short and insufficient sleep is a widespread problem among Icelandic adolescents. Further, students go to bed later and sleep less at age 17 compared to age 15. However, students attending schools with college-style systems with greater control of their school schedule showed less drastic change in sleep duration. The findings of the cross-sectional analyses demonstrated that students that went to bed earlier and had more consistent sleep schedules were more likely to score higher on standardized national academic exams at age 15 and that shorter time in bed the night prior to the cognitive testing was negatively associated with performance on the most challenging short-term memory load when students were 17 years old.

It is well established in the literature that short and insufficient sleep during adolescence can have deleterious effect on both physical and mental health (Tarokh et al., 2016). The findings of this doctoral study further deepen the knowledge about this association with longitudinal and cross-sectional studies conducted in a free-living setting with objective measures during a major developmental phase in young people's lives.

One of the key findings is that older adolescents go to bed later than younger adolescents but rise just as early, leading to a shortened total sleep time with age. This change was less drastic for students who enrolled in a secondary school with a college-style scheduling system at age 17, where they had greater control of their school schedule. These results suggest that school schedules can impact adolescent sleep patterns and, since sleep seems to be scarce during this period, it may be beneficial for the student's transition into adulthood to have greater control of their school schedules. However, further follow-up is needed to determine if different school schedules lead to meaningful long-term differences in health or sleep behavior.

The findings of this doctoral thesis also demonstrated that short sleep, late bedtimes, and a less consistent sleep schedule were associated with worse academic and cognitive performance, even in a healthy adolescent population. These findings suggest that public health guidance should highlight the importance of both early and consistent sleep schedules, in addition to appropriate sleep duration to enhance academic and cognitive performance.

8 Future perspectives

The findings presented in this thesis were based on objective measures of free-living sleep in healthy 15 and 17 year old adolescents. The need to continue the observations and follow the participants into adulthood might be of great interest in order to evaluate the prospective changes in sleep and the possible association with cognition. Although the research presented in this thesis tracked sleep at different time points, and explored longitudinal and cross-sectional association the possible harmful consciences of short sleep might take years to manifest and thus present itself later in adulthood. Further, future research should incorporate observation and measures that explore additional dimensions of the 24 hour timespan, where sleep, physical activity, leisure time, and school hours are covered in order to better inform recommendations and policy focused on helping students achieve goals, complete secondary education, socialize, and work while receive sufficient sleep during their hectic schedules.

Future studies should also measure objective sleep for longer periods since the daily schedule of adolescents can change drastically in a few short weeks. It would be of interest to measure each student for seven consecutive days at several time points during the calendar year. Alternatively, measuring students for longer bouts to gather weeks or months of free-living sleep data would provide more detailed information about adolescent sleep patterns allowing for better assumptions for associations between sleep duration, timing, and variability and various psychological and physical health outcomes. Recent advances in the technology of wrist worn actigraphs, including longer battery life, increased memory, and cloud-based platforms, have made longer data collections more feasible by increasing information storage and allowing for near-real time compliance checks, barriers that were difficult to overcome with the technology available even a few years ago.

As discussed previously, both the latitudinal location and the adoption of a more Easterly time zone provide the basis for several interesting natural experiments in Iceland. The current doctoral thesis measured students at age 15 and 17 during the spring months near the vernal equinox, but it could be beneficial to compare sleep data at different time points throughout the year. Additional information about how sleep patterns change longitudinally over the year may provide better explanation for the short and ill-timed sleep that was observed in the current thesis.

Findings of the current thesis suggest that students who went to bed earlier and had more consistent sleep schedules were more likely to score higher on standardized national academic exams. If feasible, future interventions should explore the impact of delayed school start time on academic and cognitive performance in both compulsory and secondary education students – which has not yet been systematically studied in the Icelandic education system. The findings of this thesis have demonstrated that multiple dimensions of sleep, including timing, duration, and consistency, are associated with various cognitive functions and should be considered when designing policy or future studies of free-living sleep.

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Paper I

Sleep Health 6 (2020) 749–757

Contents lists available at ScienceDirect

Sleep Health

Journal of the National Sleep Foundation

journal homepage: sleephealthjournal.org

Changes in sleep and activity from age 15 to 17 in students with traditional and college-style school schedules

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ARTICLE INFO

Article History:
Received 12 March 2019
Revised 8 April 2020
Accepted 23 April 2020

Keywords:
Accelerometer
Adolescents
Physical activity
Body composition
School schedule
Sleep duration

ABSTRACT

Objectives: Sleep duration and physical activity decline with age during adolescence. Earlier school schedules may contribute to these declines. The aim of this longitudinal study was to track changes in sleep and activity of Icelandic youth from primary to secondary school and compare students who enrolled in secondary schools with traditional and college-style schedules.

Methods: We measured free-living sleep and activity with wrist actigraphy and body composition by dual-energy x-ray absorptiometry in 145 students at age 15 and age 17, when 58% attended schools with college-style scheduling. Differences from 15 to 17 and between students of different school structures were assessed with mixed-effect models.

Results: Actigraphs were worn for 7.1 ± 0.4 nights at 15 and 6.9 ± 0.4 nights at 17. Overall, sleep duration decreased from 6.6 ± 0.7 h/night to 6.2 ± 0.7 h/night from age 15 to 17 ($P < .001$). Students with traditional schedules reduced school-night sleep duration 26 min/night at follow-up ($P< .001$), while sleep duration did not change for college-style students. All students went to bed later on school nights at follow-up, but only college-style students rose later. Sleep efficiency and awakenings did not differ by schedule-type. Neither sex changed body fat percentage, but average school-day activity decreased by 19% ($P< .001$) on follow-up and did not differ by schedule-type.

Conclusions: Over the 2-year period, adolescents decreased weekly sleep duration and activity, but only those continuing traditional schedules reduced school-night sleep. This suggests greater individual control of school schedule may preserve sleep duration in this age group, which may be beneficial during the transition into adulthood.

Introduction

Sleep and physical activity are important for health and maturation in young people.[1] Teenagers aged 14–17 years are recommended to sleep 8–10 hours each night[2] with a consistent schedule[3] and accumulate at least 60 minutes of vigorous activity 3 or more days each week.[4] Cross-sectional studies have shown that insufficient sleep is associated with higher prevalence of obesity,[5] lower academic achievement,[6] decreased cognitive function,[7] and increased symptoms of depression.[8] Laboratory-based sleep deprivation has also been shown to impair cognitive function,[9] cause increased daytime sleepiness,[10] and promote positive energy balance.[11] Poor sleep quality is also associated with increased risk of obesity and diabetes,[12] reduced academic performance,[13] and increased symptoms of depression[8] and anxiety,[14] indicating that sleep quantity and quality are important during this critical period of development. Both cross-sectional and longitudinal data demonstrate that physical activity is inversely correlated with body fat percentage and depressive symptoms and positively correlated with cardiorespiratory fitness.[15] During adolescence, sleep and activity are reported to decline markedly,[16] and behaviors formed during this stage are known to continue into adulthood.[17] Many factors are thought to contribute to these changes, including psychosocial factors, increased hours of homework,[18] and greater extracurricular commitments.[19] Biological development also likely contributes to changes in adolescent sleep, as older adolescents accumulate homeostatic sleep pressure more slowly[20] and are less sensitive to its effects[21,22] than younger adolescents. Melatonin release is also delayed in older adolescents relative

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Abbreviations: BMI, body mass index; WASO, Wake after sleep onset

The study was performed at the University of Iceland in Reykjavik, Iceland.

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https://doi.org/10.1016/j.sleh.2020.04.009
2352-7218/Published by Elsevier Inc. on behalf of National Sleep Foundation.

to their younger counterparts, creating a propensity towards later bed- and rise times.[23] However, early school start times often prohibit shifting rise times later, resulting in sleep curtailment for older adolescents.[1,22] Most studies of sleep and activity in this age group have relied on reported measures, which generally have earlier bedtimes than objective measures[24,25] and tend to over-report sleep duration[26] and physical activity,[11] while under-reporting nighttime awakenings.[27] Studies employing concurrent objective measurements of sleep and activity for this critical period of development are sparse.

In a previous study, we objectively measured sleep and activity in a cohort of 15-year-old Icelandic adolescents.[28] Sleep duration was found to be insufficient, particularly on school nights, when approximately 90% of participants spent less than the recommended 8–10 hours/night in bed. We postulated that this was due to late bedtimes (00:22 on average) combined with early school start times (08:10–08:20).[28] The late bedtimes are likely caused by a variety of biological and societal factors, including the drive toward later bedtimes in older adolescents[29] and an observed time-zone in Iceland that shifts sunsets 1.5 hours later than typically dictated by geography.[30] Alarmed by these results, we conducted a follow-up study to investigate whether this trend continued 2 years later. Interestingly, after attending compulsory school with traditional schedules (approximately 08:00–15:00) from ages 6 through 16, Icelandic students apply to upper-secondary schools with either similar traditional schedules or college-style scheduling systems – where school start times can vary from day-to-day.[31] Reasons for applying to schools of each type vary—some traditional schools are known for academic rigor and some college-style schools offer different academic concentrations. However, the college-style structure often gives students more opportunity to shape their school schedule. This transition presented a unique opportunity to test the hypothesis that adolescents enrolled in college-style systems have different changes in sleep and activity than those continuing traditional school schedules.

The aims of this study were to quantify changes in sleep and physical activity in Icelandic students as they transition from the last year of compulsory school at age 15 to the second year of upper-secondary school at age 17 and determine whether differences in school scheduling affect these changes. We hypothesized that sleep and physical activity would decline as reported in other adolescent populations, but that the greater control of class scheduling in the college-style system would curtail these declines.

Methods

Participants

All students in second grade, aged 7–8 years, in six of the largest primary schools in Reykjavik, Iceland were invited to participate in a longitudinal cohort studying health, cardiovascular fitness, and physical activity initiated in 2006 (N = 320, 82% participated).[32] At age 15, students from this cohort and all others who enrolled in these same schools were invited to participate (N = 411); 315 agreed (response rate 77%), and 281 had complete data for sleep and body mass index (BMI) and were reported on previously.[28] Five of these participants had incomplete data for physical activity or body fat percentage, leaving 276 with complete data for all measurements (Fig. 1). Two years later, 168 agreed to repeat the measurements and 145 had complete data, including 61 students (47 girls) attending secondary schools with traditional schedules and 84 (45 girls) attending secondary schools with college-style schedules. Nonparticipation was due to scheduling conflicts, lack of interest, or because subjects were unreachable for follow-up (n = 108).

The National Bioethics Committee and the Icelandic Data Protection Authority approved the study (Study number: VSNb2015020013/13.07). Written informed consent was obtained from participants and guardians of underage participants. Full confidentiality was ensured, and the study was conducted in agreement with the guidance provided in the Declaration of Helsinki.

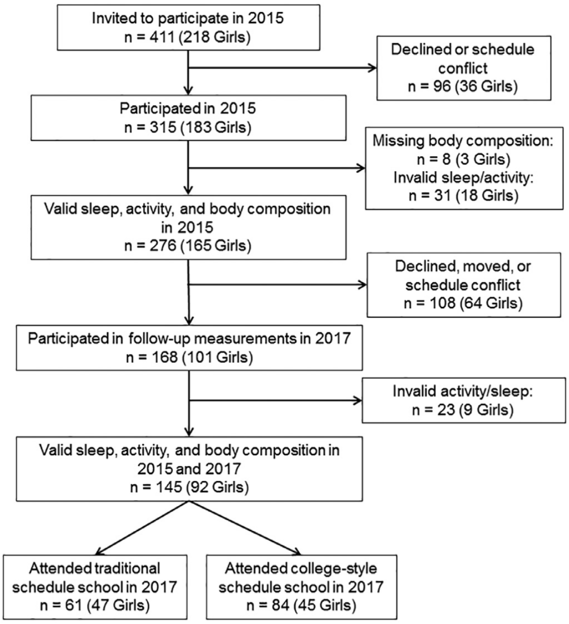

Fig. 1. Flowchart describing study participation.

Sleep and activity measurements

Participants were instructed to wear an ActiGraph GT3X+ accelerometer (ActiGraph Inc., Pensacola, Florida, USA) on their nondominant wrist, continuously, for 7 consecutive days. Due to holidays or schedule conflicts, some devices were collected after more than 7 days (8–12 days) and some students (23 at age 15, and 31 at age 17) continued to wear the device for the extended period. Conversely, battery failures occurred in three cases resulting in shorter recordings of 5–6 days. Raw tri-axial accelerometer data was recorded at 80 samples/s and subsequently filtered and aggregated into 1-minute activity counts with Actilife software (v6.13.0, ActiGraph, Pensacola, Florida, USA). Periods of 60 or more consecutive minutes of 0 counts in all axes were identified as nonwear[28] by customized programs in Matlab (R2016B, Mathworks, Natick, Massachusetts, USA). Data was considered valid if the device was worn for $\geq$14 hours on $\geq$3 school nights and $\geq$1 nonschool night for sleep assessment[33] and $\geq$ 4 days[34] with at least 1 nonschool day for activity analysis. Daily physical activity was represented by the tri-axial vector magnitude of each minute averaged from 12 midnight to 12 midnight the next day[34] and normalized for wear-time.[35]

Concurrent with the week of actigraphy, participants were verbally instructed to complete a paper-based sleep diary each morning and evening. The diary was labeled for each day of the week and included time getting in bed, time of sleep onset, time of awakening, time leaving bed, and ratings for ease of falling asleep, daytime sleepiness, and daily mood. At age 15, 84% of all participants returned the sleep log, including 82% (N = 119) of those with valid actigraphy and body composition data at both time points. At age 17, 80% of all participants returned the sleep log, which also included 82% of those with valid actigraphy data at both time points. Those with valid actigraphy data who returned the sleep log completed 6.7 ± 0.8 and 6.8 ± 0.6 days on average while wearing the actigraph at age 15 and 17, respectively.

Bed- and rise-times were detected from the actigraphy recording in the Actilife software with an algorithm validated for adolescents[36] and adjusted by two expert scorers based on visual inspection and participant sleep logs, when available.[33] The mid-sleep time (midpoint between bed- and rise-times), time in bed, total sleep time, number of awakenings, minutes of wakefulness after sleep onset (WASO), and sleep efficiency (percentage of the period spent asleep) were computed for each sleep period.[28,36] Averages of all valid school nights and nonschool nights are presented. We quantified intraindividual variability of bedtime, rise-time, time in bed, and sleep duration using the standard deviation of all valid school nights. The longest nightly sleep period from 12 noon until 12 noon the next day was used in the analyses.

Body composition measurements

BMI was calculated from height and weight measured by trained personnel[28] and converted to age- and sex-corrected z-score using the International Task Force for Obesity guideline.[37] Body fat percentage was measured with dual energy X-ray absorptiometry (Lunar, GE Healthcare, Madison, Wisconsin, USA) which has been validated against direct imaging methods such as magnetic resonance imaging to detect longitudinal changes in adolescent body composition.[38] Daily scans of a manufacturer-issued standard quality-assurance phantom for body composition measurement (IQA phantom, GE Healthcare) yielded a coefficient of variation of 0.19%.

Socioeconomic status

Participant-reported parental educational attainment was used as a proxy for socioeconomic status.[39] Students provided the educational attainment of both mother and father from the following options (presented in Icelandic): 1 = “elementary degree,” 2 = “secondary degree,” 3 = “trade school degree,” 4 = “university degree,” 5 = “other,” 6 = “do not know,” 7 = “do not want to answer.” For the current analysis, responses were recoded into a binary variable: 1 = “parent with a university degree” or 0 = “no parent with a university degree or did not answer,” as described previously.[40]

Sports participation

Students self-reported participation in sports at age 15 and 17 by answering the question “Do you participate in sports?” with the options: 1 = “Yes,” 2 = “No,” 3 = “I did, but I don’t anymore” (presented in Icelandic). For the current analysis, responses were recoded into a binary variable: 1 = “participating in sports” or 0 = “not participating in sports.”

Icelandic secondary school scheduling

Upper-secondary schools in Iceland can adopt 1 of 2 course-scheduling systems.[31] Class-based (traditional) schools offer a single daily course schedule to all students, which typically begins between 08:10 and 08:30 and finishes around 15:30, similar to compulsory schools. In unit-credit-based (college-style) schools, students can choose from several offerings of the same course occurring at various times. Students are only required to be present at school during their scheduled course times. Thus, daily schedules of unit-credit students are more individualized, like those of college students in many countries, and school start times can vary from 08:30 to 16:00.

National examinations

To determine whether secondary school types may have differed in academic rigor, we compared student scores on standardized national examinations in Icelandic, English, and mathematics. The examinations are administered by the Icelandic Directorate of Education to all tenth-grade students (age 15) and used as part of the application criteria for secondary schools. Icelandic and English exams assess reading comprehension, writing, and grammar using multiple choice, short answer, and essay questions. The mathematics exam assesses knowledge of operations, geometry, and numerical understanding with multiple choice, word problems, and sentence completion. Scores are nationally normalized to a mean of 30, standard deviation of 10, and range from 0 to 60.[41] We were unable to retrieve national exam information for 9 students with complete data for sleep, activity, and body composition, and 13 students were absent for testing in 1 or more subject area. Ultimately, test scores were available for 129 students (80 girls, 49 boys) in English, 129 students (82 girls, 47 boys) in Icelandic, and 126 (77 girls, 49 boys) in mathematics. No similar academic metrics could be included at age 17 since there are no analogous standardized national examinations after age 15 in the Icelandic education system.

Statistical analyses

Chi-squared tests and unpaired *t*tests showed no differences in the gender distribution, socioeconomic status, body composition, or activity of participants with and without complete follow-up data at age 15 (Table S1). Participants who completed follow-up had higher scores in English and mathematics, slightly less sleep time variability on school nights (−10 min), and slightly better sleep quality on nonschool nights (2 fewer awakenings/night) than those who did not, but otherwise did not differ in sleep or activity at age 15 (Table S1).

Chi-squared tests were also used to assess differences in sex distribution and parental education between students attending schools of each schedule type at follow-up. Mixed-effect models with Tukey’s post-hoc tests were used for all other comparisons. Paired comparisons adjusted for parental education were used to assess changes in body composition from age 15 to 17 for boys and girls separately. Using unpaired analyses, we found few sex differences in parental education, sport participation, test scores, sleep, or activity at either age; compared to boys, girls had greater nonschool day activity at 15,[28] and earlier school night bedtimes at 17 (Table S2). Therefore, data from both sexes were combined. Paired analyses, adjusted for sex and parental education, were used to assess within subject differences from age 15 to 17 and from school days to nonschool days at each age. Paired comparisons were again used to test for within subject difference from age 15 to 17 separately by school structure at follow-up, while unpaired analyses adjusted for sex and parental education were used to test for differences between school structures at each measurement. Linear regression was used to test for cross-sectional and longitudinal associations between body composition parameters and measures of sleep and physical activity. All regression models were adjusted for parental education. Age 17 cross-sectional models and all longitudinal models were additionally adjusted for age 17 school structure. All regression models involving body fat percentage were also adjusted for sex. All results are reported as mean ± standard deviation, unless otherwise noted. Bonferroni correction was used in all tests with multiple comparisons and corrected P-values $< .05$ were considered significant. Analyses were conducted using RStudio (v1.0.153 Boston, Massachusetts, USA) with R (v3.4.2, https://www.r-project.org/) and GraphPad Prism (v7, La Jolla, California).

Table 1
Body composition of all participants at age 15 and 17.

	Boys (N = 53)			Girls (N = 92)			Boys vs. girls	
	15 y old	17 y old	P (15 vs. 17)	15 y old	17 y old	P (15 vs. 17)	P (15 y)	P (17 y)
Age, years	15.8 ± 0.3	17.6 ± 0.3	<.001	15.9 ± 0.3	17.7 ± 0.3	<.001	.09	.33
Height, cm	178.8 ± 6.1	182.1 ± 5.9	<.001	167.3 ± 5.8	168.1 ± 5.8	.001	<.001	<.001
Weight, kg	69.2 ± 12.5	74.3 ± 12.1	<.001	62.1 ± 10.3	65.5 ± 12.6	<.001	<.001	<.001
Body mass index, kg/m^2	21.6 ± 3.5	22.4 ± 3.3	.003	22.2 ± 3.5	23.2 ± 4.3	<.001	1.00	1.00
Body mass index, z-score	0.53 ± 0.92	0.48 ± 0.92	1.00	0.52 ± 0.94	0.58 ± 1.03	.832	1.00	1.00
Body fat, %	17.9 ± 8.0	18.0 ± 7.3	1.00	29.9 ± 6.8	30.9 ± 7.5	.08	<.001	<.001

Results are means ± standard deviation. All statistical tests were controlled for multiple comparisons.

Results

Changes in body composition from age 15 to 17

Body composition measures are presented by sex in Table 1. Boys and girls were taller and heavier at age 17 than at age 15, but BMI z-scores and body fat percentage did not change. Boys were taller, heavier, and had lower body fat percentage than girls at both time points, but their BMIs did not differ. These results confirm expected growth patterns and known gender differences in this age group.[32,33]

Changes in sleep and activity from age 15 to 17

Over all measured nights, time in bed decreased from 7.5 ± 0.7 h/night at age 15 to 7.1 ± 0.8 h/night at age 17 and sleep duration decreased from 6.6 ± 0.7 h/night to 6.2 ± 0.8 h/night from age 15 to 17 (both $P < .001$). On school nights, time in bed and total sleep time did not change from age 15 to 17, although students went to bed and rose later (both $P < .01$) and increased intraindividual variability (i.e., within subject standard deviation) of time in bed and total sleep time at 17 (both $P < .001$; Table 2). On nonschool nights at age 17, students went to bed later ($P < .001$) but did not change their rise time from age 15, resulting in shorter total sleep time ($P < .001$; Table 2).

Sleep quality measures (i.e., nightly awakenings, WASO, and sleep efficiency) did not change from age 15 to 17 on school nights, but awakenings and WASO were both lower on nonschool nights at age 17 ($P < .05$, Table 2). Students went to bed later, rose later, slept longer, and had greater awakenings and WASO on nonschool nights than school nights during both measurements (all $P < .001$, Table 2), with the increase in WASO being directly proportional to the increase in sleep duration (~5.5 minutes of WASO/hour of sleep; $P < .001$).

Average activity decreased by 13.1% over all days (2042 ± 494 to 1773 ± 393 counts/min of wear/day, $P < .001$) and by 19.0% on school days ($P < .001$) from 15 to 17 (Table 2). However, there was no change in nonschool day activity from 15 to 17 (Table 2). At age 15 students were 18.5% more active on school days than nonschool days ($P < .001$); but 2 years later, activity on school days and nonschool days was not different (Table 2).

Changes in body composition, sleep, and activity by school schedule-type

Participants attending both secondary school systems did not differ in parental education, sports participation (Table 3), BMI z-score, or activity at either age (Fig. 2, Tables S3 and S4). Combined data from both sexes showed that body fat increased from 25.6 ± 8.4% to 26.9 ± 8.6% in students that continued traditional school schedules ($P = .04$) but did not change for students that switched to college-style schedules. However, there were no changes in body fat when boys and girls were analyzed separately (Fig. 2, Tables S3 and S4). At age 15, students who went on to attend traditional-schedule schools at age 17 scored higher than those who went on to attend college-

Table 2
Sleep and physical activity for all participants on school days and nonschool days at age 15 and 17.

	School days			Nonschool days			School vs nonschool	
	15 y old	17 y old	P (15 vs. 17)	15 y old	17 y old	P (15 vs. 17)	P (15 y)	P (17 y)
Sleep								
Time in bed, h/day	7.1 ± 0.8	6.8 ± 0.9	.115	8.3 ± 1.4	7.8 ± 1.3	<**.001**	<**.001**	<**.001**
Total sleep time, h/day	6.2 ± 0.7	6.0 ± 0.8	.09	7.3 ± 1.3	6.9 ± 1.2	<**.001**	<**.001**	<**.001**
Bed time, clock time ± min	00:20 ± 47.5	00:53 ± 62.0	<**.001**	01:36 ± 70.7	02:24 ± 84.1	<**.001**	<**.001**	<**.001**
Mid-sleep time, clock time ± min	03:52 ± 36.1	04:20 ± 57.0	<**.001**	05:49 ± 64.0	06:19 ± 78.5	<**.001**	<**.001**	<**.001**
Rise time, clock time ± min	07:25 ± 37.4	07:47 ± 61.5	**.008**	10:04 ± 76.7	10:15 ± 89.7	.5	<**.001**	<**.001**
WASO, min/night	48.5 ± 21.5	48.1 ± 21.2	1.0	59.6 ± 28.0	52.8 ± 24.7	**.01**	<**.001**	**.03**
Awakenings, number/night	18.2 ± 5.4	17.9 ± 5.6	1.0	21.9 ± 8.1	20.3 ± 7.3	**.03**	<**.000**	<**.001**
Sleep efficiency, %	88.4 ± 4.4	88.0 ± 4.8	1.0	88.0 ± 5.0	88.4 ± 4.9	1.0	.9	.6
Recorded Nights, N	4.7 ± 0.6	5.3 ± 0.7	<**.001**	2.5 ± 0.6	2.0 ± 0.3	<**.001**	<**.001**	<**.001**
Valid nights, N	4.6 ± 0.6	5.2 ± 0.8	<**.001**	2.5 ± 0.6	2.0 ± 0.3	<**.001**	<**.001**	<**.001**
Invalid nights, N	0.07 ± 0.33	0.08 ± 0.31	1.0	0.02 ± 0.14	0.03 ± 0.16	1.0	.3	.3
Sleep variability								
Time in bed variability, min	51.6 ± 34.8	76.8 ± 47.5	<**.001**					
Sleep time variability, min	47.3 ± 28.7	68.9 ± 43.5	<**.001**					
Bed time variability, min	45.0 ± 33.3	48.7 ± 26.8	.2					
Rise time variability, min	38.8 ± 40.8	56.8 ± 43.4	<**.001**					
Physical activity								
Activity, counts/wear min/day	2207 ± 529	1787 ± 382	<**.001**	1796 ± 556	1733 ± 575	.6	<**.001**	.6
Wear time, h/day	23.9 ± 0.5	22.2 ± 1.1	<**.001**	23.9 ± 0.5	23.7 ± 1.0	.5	1.0	<**.001**
Valid days, N	3.7 ± 0.6	5.4 ± 1.0	<**.001**	2.5 ± 0.6	2.0 ± 0.3	<**.001**	<**.001**	<**.001**

Results are means ± standard deviation, WASO = minutes of wakening after sleep onset, Comparisons adjusted for sex, parental education, and multiple comparisons.
Boldface indicates significaant P-value ($P<0.05$).

Table 3
Characteristics and sleep on school days and nonschool days at age 15 and 17 of students attending traditional and college-style schedule schools at age 17.

	Traditional schedule (N = 61, 77% female)			College-style schedule (N = 84, 53.6% female)			Traditional vs. college-style	
	15 yr old	17 yr old	*P* (15 vs. 17)	15 yr old	17 yr old	*P* (15 vs. 17)	*P* (15 yr)	*P* (17 yr)
Characteristics								
Parent with university degree, N (%)		47 (77%)			56 (67%)			.24
Organized sports participation, N (%)	48 (79%)	31 (51%)	<**.001**	53 (63%)	37 (44%)	**.005**	.1	1.0
National English exam[a,b,c]	35.76 ± 8.09			33.09 ± 9.19			.14	
National Icelandic exam[a,b,d]	38.69 ± 7.85			31.97 ± 8.22			<**.001**	
National mathematics exam[a,b,e]	38.25 ± 7.67			31.63 ± 8.56			<**.001**	
School nights								
Time in bed, h/day	7.2 ± 0.7	6.7 ± 0.8	<**.001**	7.0 ± 0.8	6.9 ± 0.9	1.0	.3	.9
Mid-sleep time, clock time ± min	03:42 ± 31.8	03:54 ± 40.4	.2	03:59 ± 37.6	04:38 ± 60.4	<**.001**	.1	<**.001**
WASO, min/night	47.7 ± 18.7	45.0 ± 17.4	1.0	49.1 ± 23.4	50.3 ± 23.4	1.0	1.0	.5
Awakenings, number/night	18.5 ± 4.7	17.2 ± 4.5	.2	18.0 ± 5.8	18.4 ± 6.2	1.0	1.0	.8
Sleep efficiency, %	88.7 ± 3.8	88.6 ± 4.3	1.0	88.1 ± 4.7	87.5 ± 5.2	.8	1.0	.6
Time in bed variability, min	47.4 ± 36.0	65.8 ± 48.9	**.04**	54.7 ± 33.8	84.7 ± 45.1	<**.001**	.9	**.02**
Sleep time variability, min	44.8 ± 31.4	57.5 ± 42.4	.2	49.2 ± 26.5	77.2 ± 42.7	<**.001**	1.0	**.002**
Bed time variability, min	40.6 ± 32.5	41.8 ± 26.1	1.00	48.2 ± 33.6	53.8 ± 26.2	.7	.7	.11
Rise time variability, min	27.7 ± 21.6	42.3 ± 37.5	.2	46.8 ± 49.0	67.3 ± 44.6	**.003**	**.02**	**.001**
Recorded nights, N	4.7 ± 0.6	5.3 ± 0.7	<**.001**	4.7 ± 0.6	5.3 ± 0.7	<**.001**	1.0	1.0
Valid nights, N	4.7 ± 0.6	5.2 ± 0.8	<**.001**	4.6 ± 0.6	5.2 ± 0.8	<**.001**	1.0	1.0
Invalid nights, N	0.03 ± 0.26	0.02 ± 0.15	.6	0.08 ± 0.38	0.07 ± 0.26	.5	1.0	1.0
Nonschool nights								
Time in bed, h/day	8.4 ± 1.2	7.8 ± 1.2	.053	8.3 ± 1.5	7.8 ± 1.4	**.01**	1.0	1.0
Mid-sleep time, clock time ± min	05:31 ± 59.1	06:08 ± 70.6	**.003**	06:03 ± 64.4	06:27 ± 83.3	**.04**	**.04**	.6
WASO, min	58.87 ± 25.7	50.0 ± 20.1	.1	60.1 ± 29.7	54.8 ± 27.5	.5	1.0	1.0
Awakenings, number/night	22.2 ± 7.6	19.6 ± 6.4	.1	21.8 ± 8.5	20.8 ± 8.0	1.0	1.0	1.0
Sleep efficiency, %	88.2 ± 4.7	88.8 ± 4.6	1.0	87.9 ± 5.2	88.2 ± 5.1	1.0	1.0	1.0
Recorded nights, N	2.6 ± 0.6	2.0 ± 0.3	<**.001**	2.5 ± 0.6	2.0 ± 0.3	<**.001**	.4	1.0
Valid nights, N	2.6 ± 0.7	2.0 ± 0.3	<**.001**	2.5 ± 0.6	2.0 ± 0.4	<**.001**	.9	1.0
Invalid nights, N	0.02 ± 0.13	0.02 ± 0.13	1.0	0.02 ± 0.15	0.04 ± 0.19	1.0	.9	1.0

Results are means ± standard deviation; All comparisons corrected for sex, parental education, and multiple comparisons; WASO = minutes of wakening after sleep onset. Boldface indicates significaant *P*-value ($P<0.05$).

[a] Nationally normalized (mean = 30, standard deviation = 10, maximum score = 60).

[b] National test scores available for: [b]55 traditional schedule students (13 boys, 42 girls).

[c] 74 college-style schedule students (36 boys, 38 girls).

[d] 74 college-style schedule students (34 boys, 40 girls).

[e] 71 college-style schedule students (36 boys, 35 girls).

style schools on national exams in Icelandic and mathematics (both $P< .001$; Table 3).

Over all measured nights, time in bed decreased from age 15 to 17 from 7.61 ± 0.66 to 7.02 ± 0.73 h/night for traditional schedule students and from 7.45 ± 0.72 to 7.13 ± 0.79 h/night college-style students (both $P\leq .001$). Similarly, total sleep time over all nights declined from 6.73 ± 0.59 to 6.22 ± 0.77 h/night for traditional schedule students and from 6.54 ± 0.69 to 6.25 ± 0.74 h/night for college-style students (both $P\leq .001$). However, the magnitude of these reductions did not differ by schedule type. On school nights, students of both school types went to bed later at age 17 compared to age 15 (+25 minutes for traditional, + 40 minutes for college-style, both $P< .01$; Fig. 3A), but those in college-style schools rose later at age 17 ($P< .001$; Fig. 3A). As a result, time in bed and total sleep time on school nights was reduced at age 17 for traditional schedule students but did not change for students with college-style schedules (Table 3, Fig. 3B). On nonschool nights, students of both school schedule types went to bed more than 40 minutes later (both $P< .001$) but did not differ in rise time at age 15 and 17 (Fig. 3C).Time in bed and sleep duration on nonschool nights did not change for traditional schedule student between ages 15 and 17, but both were reduced for college-style students (both $P< .05$) - perhaps indicating a reduction in catch-up sleep (Table 3 and Fig. 3D).

Sleep quality (awakenings, WASO, and sleep efficiency) did not differ by school schedule-type on either school nights or non-school nights at age 15–17 (Table 3). Students of both school types had increased variability of time spent in bed at age 17 compared to 15, but only college-style students also showed greater intraindividual

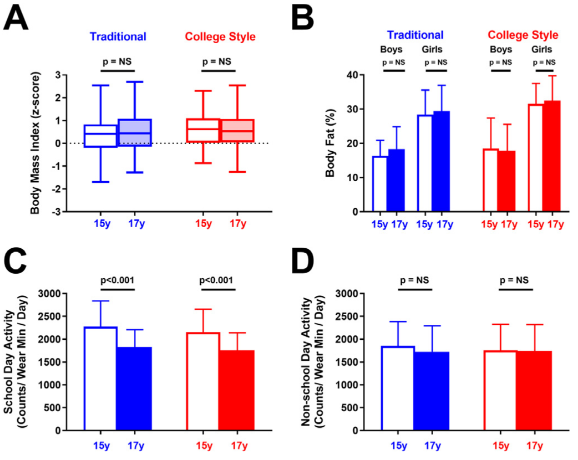

Fig. 2. Body composition and physical activity by age 17 school-schedule type. (A, B) Traditional (blue) and college-style (red) students showed no change in body-mass index z-score (A) or body fat percentage (B) from age 15 (unfilled) to 17 (filled). (C, D) Traditional and college-style students showed similar school day reduction in activity (C) and no change in nonschool day activity (D) from age 15 to 17. Box (median with first and third quartile) and whiskers (95% confidence interval) are used for BMI z-score in (A); all other results are means (boxes) with standard deviations (error bars). *P* values indicate paired, within school-type comparisons between ages 15 and 17 adjusted for sex, parental education, and multiple comparisons. (Color version of figure is available online)

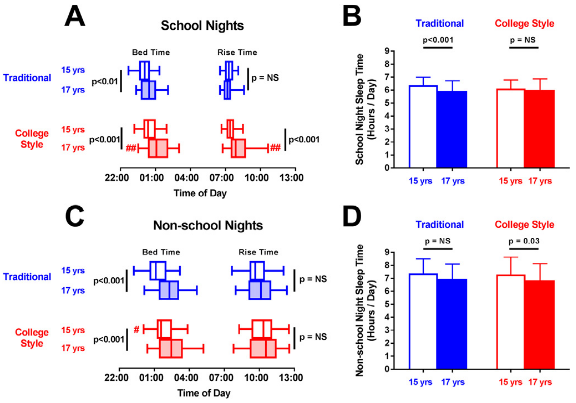

Fig. 3. Sleep schedule and duration on school nights and non-school nights by age 17 school-schedule type. (A, B) On school nights, both traditional (blue) and college-style (red) students went to bed later at 17 (filled) vs. 15 (unfilled), but college-style student rose later at age 17 (A). Thus, only traditional-school students reduced sleep duration at 17 (B). (C, D) On nonschool-nights, both traditional and college-style students went to bed later and rose at the same time at age 17 vs. 15 (C), but only college-style students reduced sleep duration (D). Box (median with first and third quartile) and whiskers (95% confidence interval) are used for bed- and rise-times; mean (boxes) with standard deviation (error bars) is used for sleep duration. *P* values with black bars indicate paired, within school-type comparisons between ages 15 and 17. # ($P < .05$) and ## ($P < .01$) indicate significant differences between traditional and college-style students at age 15 or 17. All comparisons adjusted for sex, parental education, and multiple comparisons. (Color version of figure is available online)

variability in rise time and total sleep time on school nights ($P \leq .02$ vs traditional schedule students; Table 3).

In sex-specific analyses, changes in sleep patterns from age 15 to 17 for girls from each schedule-type were similar to those of the entire group (Table S3). Changes in sleep for boys attending college-style schools were also largely similar to the entire group, with one notable exception - they did not increase variability in school day rise time at age 17 (Table S4). Conversely, the small number of boys attending traditional schools at age 17 in our sample (N = 14) had few significant changes in sleep from age 15 (Table S4).

Regression analysis of body composition vs sleep and activity

Linear regression was used to explore potential cross-sectional and longitudinal associations between body composition and sleep and activity (Table S5). Mean sleep duration over all nights was negatively correlated with BMI z-score at age 15 ($P = .03$), but this association did not persist at age 17 and change in sleep duration from age 15 to 17 was not associated with change in BMI z-score. There were no significant cross-sectional or longitudinal associations between sleep duration and body fat percentage or between sleep quality measures (e.g., sleep efficiency and WASO) and BMI or body fat percentage (Table S5).

After adjusting for sex and school schedule type, physical activity was negatively correlated to body fat percentage at age 17 ($P = .002$), but not at age 15. Physical activity did not correlate with BMI z-score at either age, and longitudinal changes in activity did not correlate with changes in body fat or BMI z-score.

Discussion

In this longitudinal study of Icelandic adolescents, we found that nightly sleep duration over the whole week decreased from age 15 to 17. However, on school nights, this reduction was only seen in students who continued a traditional schedule and not in those who switched to a college-style scheduling system. We also observed a profound reduction in school day activity at age 17, but it did not differ by school scheduling system.

Our previous study of 15-year-old Icelandic adolescents revealed that only 10.9% spent the recommended 8 h/night in bed on school nights, with an average sleep duration of 6.2 hours per school night,[28] which is among the shortest reported in this age group.[42,43] At age 17, school night sleep duration remained low, at 6.0 h/night, and the percentage of students getting the recommended amount of sleep on school nights dropped to 6.9%. These findings suggest a widespread and consistent pattern of short sleep, which is associated with problems in cognition,[7] obesity,[5] and poor academic achievement,[6] and may lead to continued sleep problems and other deleterious health effects in adulthood.[17]

The shortened sleep duration from age 15 to 17 is in line with previous findings of a 14 min/year decline in sleep during adolescence.[1,44] The sleep reduction observed here stems from a 33 min/night later bedtime which was not compensated by a similar shift in rise time. The later bedtime may be the result of a shift in circadian rhythm caused by delayed melatonin release[29] and a slower accumulation of sleep pressure[20] at this stage of puberty. Previous work has also demonstrated that older adolescents are less sensitive to sleep pressure than younger adolescents and adults.[21,22] Thus, despite experiencing the same deleterious effects of sleep deprivation, they do not notice it as readily and are less likely to alter their sleep schedule accordingly. Alternatively, changes in sleep timing and the reduction in sleep may be the result of external changes, such as increased media usage,[40] reduced parental supervision, more recreational activities, work, and/or increased academic demands. While some studies using objective methods have reported comparably short adolescent sleep durations,[42,45] the average bedtime of 01:19 at age 17 is notably later than the reported bedtimes of similarly aged groups from other countries.[43,46] This may be due in part to a 1.5 hour mismatch between Iceland's geographical position and its adopted time-zone of Greenwich Meantime.[30]

Students who attended schools with college-style course scheduling had later rise-times than those who continued in schools with traditional schedules resulting in better preservation of total sleep time from age 15 to 17. College-style students also reduced time in bed and total sleep time on nonschool nights while traditional schedule students did not, perhaps indicating reduced need for catchup sleep amongst college-style student. These finding supports the idea that later school start times may be more suitable for the natural sleep patterns of older adolescents. Meta-analysis of previous cross-sectional and longitudinal studies has demonstrated that delaying school start times by 15-130 minutes is associated with longer sleep durations,[47] which can lead to enhanced cognitive performance, improved attention levels, and greater academic success.[1] Although students of the two school types did not differ in sleep quality measures such as sleep efficiency and WASO, college-style students had more intraindividual night-to-night variability in total sleep duration and rise-times on school nights than their counterparts with traditional schedules. The higher variability in sleep schedule may be due to greater day-to-day variation in class schedule amongst college-style students, specifically more varied school day start times. High nightly variability in sleep is known to negatively impact body composition,[48] perceived health, and cognitive function. Thus, it is recommended that adolescents maintain a consistent sleep routine.[3]

Across the entire group, average activity declined by 13.1% over all measured days between age 15 and 17, explained mainly by a 19% reduction on school days. This substantial reduction in activity is in line with previous studies conducted in Iceland[49] and elsewhere[16,50] that suggest adolescent activity declines about 7% per year. These findings highlight the large impact school day activity has on overall activity in this age group.[51] Further study is needed to determine if changes to physical education policy can mitigate the reduction in school day activity.

Changes in activity and BMI did not differ between students attending traditional and college-style schools. Similarly, sex-specific comparisons demonstrated no significant changes in body fat percentage for either school type. These results suggest that changes in activity and body composition are likely due to factors in addition to school schedule type. Cross-sectional regression demonstrated that sleep duration and physical activity were inversely correlated with measures of body composition, but the trends were not consistent at both ages and there were no longitudinal associations between body composition and sleep or activity. However, a longer duration between baseline and follow up is likely needed to detect whether changes in sleep and/or activity habits are associated with meaningful changes in body composition.

To our best knowledge, this is the first longitudinal study to objectively measure changes in sleep and physical activity in a cohort of youth (age 15-17) during a change in educational structure. Most previous studies of sleep in this age group have relied on self- or parent-report of typical time in bed or bed- and rise-times and have observed average sleep durations of 7 hours or more, with a few notable exceptions, mostly from Asian countries.[52] Self-reported measures do not normally account for onset latency or brief awakenings during sleep[53] and tend to over-report sleep time.[26,53] In the current analysis, bedtimes and rise-times were detected in the actigraphy recordings and, thus, may be closer to sleep onset and awakening times rather than times of getting in and out of bed. For instance, over all nights for participants with concurrent actigraphy and sleep log information, actigraphy-measured bedtimes were closer to reported sleep onset times than reported time of entering bed. This methodological difference may partly explain the shorter sleep duration found in this study, although some studies of this age group with comparable objective measures have reported longer sleep durations.[45] However, longitudinal trends in bedtime over all measured nights were consistent whether using actigraphy-measured bedtime (00:46 ± 47 min at 15 y vs 01:12 ± 59 min at 17 y, $P< .001$), reported sleep onset time (00:40 ± 50 min at 15 y vs 00:58 ± 58 min at 17 y, $P< .001$), or reported time of entering bed (00:07 ± 47 min at 15 y vs 00:22 ± 55 min at 17 y, $P< .001$), and all three measures were highly correlated ($r > 0.76$ at both ages).

During this study, we focused our analysis on the primary nightly sleep period. Daytime naps were rare, with only 14 total naps identified in 8 different subjects.[28] A recent study demonstrated approximately 62% of their teenage participants reported taking naps and both actigraphy-detected and self-reported naps were associated with shorter and more disrupted night-time sleep.[54] However, although wrist actigraphy has high accuracy and sensitivity compared to polysomnography, its specificity is limited,[55] and there is currently no accepted criterion for scoring actigraphy-assessed naps.[54] We felt that the automated sleep detection algorithm may have been inadequate to detect naps and, although participants were instructed to log sleep periods, our sleep diary did not explicitly ask about napping. Thus, there were no validated automated methods or confirmatory logs to determine whether short periods of inactivity outside of the primary sleep period were naps.

We did not assess the prevalence of delayed sleep phase syndrome (DSPS) on school days following a weekend or holiday, when sleep schedules were likely shifted later. However, previous studies found a 2%-3% prevalence of DSPS in adolescents.[56,57] Thus, it is unlikely that the presence of DSPS significantly affected the results of our study.

Holiday periods and seasonal changes in daylength and weather can affect sleep and activity.[58] Due to schedule conflicts, age 15 measurements were collected from April to June and age 17 measurements from February to April. More holidays occurred during the age 15 data collection period, resulting in fewer school nights and more nonschool nights for some students at age 15 than at age 17. Daylength and weather were also different during the age 15 and 17 measurement periods. However, there were few significant cross-sectional correlations between either sleep or activity and daylength: activity was positively correlated to daylength at age 15 and bedtime was inversely correlated to daylength at age 17. The differences in daylength from the age 15 measurement to the age 17 measurement were similar for students of the 2 school schedule types. Thus, it was unlikely that changes in daylength alone could explain difference in sleep duration or schedule between the 2 school types.

Assignment to traditional and college-style schools at age 16 was not experimentally controlled. Thus, we could not control the gender distribution between different secondary school schedule systems. Similarly, students did not report reasons for secondary school preferences, and we cannot rule out other potential causes for differences in sleep schedule and duration changes between the 2 school types. For instance, we did not directly measure academic workload or participation in all extra-curricular activities and, thus, cannot assess how these factors may have impacted sleep and activity. However, students attending traditional-schedule schools had higher average national exam test scores at age 15, supporting the notion that these schools may have more selective academic entrance requirements. Conversely, participation in organized sports did not differ across school type at either age, suggesting factors other than school type contribute to a decline in sports participation. Future studies with the opportunity to randomized school assignment should consider these factors in experimental design.

Due to the longitudinal design, we did not power the study to detect a predefined difference. However, data from this study is useful to design intervention studies in the field of sleep and health in adolescents. Sample size was relatively small, although it was representative of Reykjavík students in this age group during the study period (i.e., 1355 15-year-olds in 2015 and 1382 17-year-olds in 2017).[59] Finally, the participants were Icelandic, generally healthy, and few were overweight or obese (14% at age 15 and 17% at age 17), potentially limiting generalizability.

Conclusions

From age 15 to 17, Icelandic adolescents reduced sleep duration, became less active, and shifted to a later bedtime. However, students attending schools with college-style systems with greater control of their school schedule showed less drastic change in sleep duration. These results suggest that school schedules can impact adolescent sleep patterns, but further follow-up is needed to determine if different schedules lead to any long-term differences in health or sleep behavior in adulthood.

Conflict of interest

The author has no conflicts of interest to disclose.

Acknowledgments

The authors would like to thank Hans Haraldsson for additional statistical support, Cindy Clark of the NIH Library Writing Center and the University of Iceland Writing Center for manuscript editing assistance, study participants and staff of participating schools, and master's students and researchers involved in data collection.

Funding

Primary funding was supplied by the Icelandic Centre for Research (RANNIS) (grant number: 152509-051). Additional support was provided by the Ministry of Education, Science and Culture; the Iceland Primary Health Care Research Fund, and doctoral grants from the University of Iceland Research Fund. KYC and RJB were funded by the National Institute of Diabetes and Digestive and Kidney Diseases intramural research program (Z01 DK071013 and Z01 DK071014).

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.sleh.2020.04.009.

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Paper II

Received: 15 December 2020 | Revised: 17 May 2021 | Accepted: 17 May 2021
DOI: 10.1111/jsr.13422

Journal of Sleep Research ESRS

RESEARCH ARTICLE

Sleep timing and consistency are associated with the standardised test performance of Icelandic adolescents

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Funding information
National Institute of Diabetes and Digestive and Kidney Diseases intramural research program, Grant/Award Number: Z01 DK071013 and Z01 DK071014; Icelandic Centre for Research, Grant/Award Number: 152509-051

Summary

Sleep has been shown to affect cognitive function in laboratory studies; however, its association to the academic performance of adolescents has largely been demonstrated using self-reported measures. Studies with objective measures of both sleep and academic performance are limited. The aim of the present study was to determine whether the free-living sleep quantity, quality, and timing of 15-year-old adolescents measured with wrist actiography are associated with their scores on national standardised examinations as an objective measure of academic achievement. We measured sleep with wrist actiography for 1 week in 253 (150 girls) Icelandic adolescents with a mean (*SD*) age of 15.9 (0.3) years. Multiple linear regression was used to assess associations between sleep parameters and combined standardised examination scores in mathematics, English, and Icelandic obtained from the Icelandic Directorate of Education. We found that students went to bed at 00:49 hours (± 51.8 min) and slept for a mean (*SD*) of 6.6 (0.7) hr/night, with a median (interquartile range) night-to-night variation in sleep duration of 1.2 (0.7) hr and an efficiency of 88.1 (5.3)%. Combined analyses adjusted for sex, demonstrated that both bedtime and night-to-night variability in total sleep time were negatively associated with the average score across all topics. Sex-specific associations did not indicate clear differences between boys and girls. These findings suggest that, in addition to appropriate sleep duration, public health guidance should also highlight the importance of early and consistent sleep schedules to academic achievement for both boys and girls.

KEYWORDS
academic performance, accelerometer, bedtime, free-living sleep, sleep habits, teenagers

1 | INTRODUCTION

Despite recommendations that teenagers should sleep 8–10 hr/night (Hirshkowitz et al., 2015), recent research suggests an overwhelming majority fail to do so (Wheaton et al., 2018). Cross-sectional data has shown that shorter and more disrupted sleep is associated with poorer academic performance amongst teenagers (Dewald et al., 2010; Hysing et al., 2016). Similarly, prospective interventions involving adolescents have shown that sleep restriction can have deleterious effects on a wide range of cognitive functions including sustained attention (Agostini et al., 2017), alertness (Lo et al., 2016), and memory (Jiang et al., 2011), while sleep extension improves academic performance (Curcio et al., 2006). Further, the need for sufficient sleep may be more critical during adolescence than in

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The study was performed at the University of Iceland in Reykjavik, Iceland.

adulthood, as sleep can influence proper development of the frontal and parietal brain regions that occurs at this age (Kopasz et al., 2010).

Along with duration, sleep timing and consistency may also play a role in the cognitive function and academic performance of teenagers. There is both cross-sectional (Hysing et al., 2016; Urrila et al., 2017) and longitudinal (Asarnow et al., 2014) evidence that those with later bedtimes are more likely to perform worse in school than those that go to bed earlier. In addition, a mismatch between social schedule and circadian clock, i.e. social jetlag, (Wittmann et al., 2006) has been reported to affect academic performance in high school and undergraduate students (Díaz-Morales & Escribano, 2015; Haraszti et al., 2014).

Despite prior research suggesting girls perform slightly better than boys academically (Cole, 1997; Steinmayr & Spinath, 2008) few studies have explored sex differences in relationships between sleep and academic achievement. Additionally, while some investigations have found evidence of sex differences in associations of sleep versus academics (Díaz-Morales & Escribano, 2015; Okano et al., 2019) the affected sex is inconsistent, and other studies note no differences (Eliasson et al., 2002; Hysing et al., 2016). Thus, further study of a potential role for sex in the relationship between sleep and academic achievement is warranted.

Most prior research in adolescents has relied on self-reported measures of sleep, academic performance, or both. According to validation studies, students typically report receiving better grades and test score than they actually achieve (Escribano & Díaz-Morales, 2014; Frucgt & Cook, 1994; Kuncel et al., 2005) and self-reporting of sleep timing (Brychta et al., 2019), duration (Short et al., 2012) and quality (Werner et al., 2008) has repeatedly been shown to be difficult and prone to bias. Further, sleep questionnaires typically do not include a measure of sleep consistency and, as a result, variability of sleep remains under-explored, particularly in adolescents. Studies employing objective measures of both sleep and academic performance could address these gaps and help clarify their relationship in adolescents.

The aim of the present study was to determine whether the quantity, quality, and timing of actiography-measured free-living sleep of 15-year-old Icelandic adolescents were associated with their scores on standardised national examinations in Icelandic, English, and mathematics and to explore whether these potential relationships differed by sex. We hypothesised that later bedtimes and shorter, more disrupted, and less consistent sleep would be associated with lower scores and that associations for girls and boys would not differ based on limited previous findings of such differences.

2 | METHODS

2.1 | Population and data collection

The present study is an exploratory analysis of the association between sleep and national examination scores, a secondary outcome from a longitudinal study of sleep and physical activity that has been reported on previously (Rognvaldsdottir et al., 2017; Stefansdottir et al., 2020). Six schools in Reykjavík, Iceland were included in the original study, and each of the 411 students aged 15–16 years attending those schools received an invitation letter to participate in this wave of the study. A total of 77% (*n* = 315) agreed to participate and 253 students (150 girls), or 18.7% of the 15 year-olds living in Reykjavik in 2015 (Statistics Iceland, 2015) had complete data for sleep parameters, a valid score on at least one national examination, and provided parental educational attainment on a questionnaire (Figure 1). Non-participation (*n* = 96) was mainly due to absence from school during measurements, schedule conflicts or lack of interest in the study. The national examinations were administered in the Autumn of 2014, and the sleep and characteristic data were collected in the Spring of 2015 (Rognvaldsdottir et al., 2017). Participants and their guardians provided written consent, and study procedures were conducted in agreement with the guidance provided in the Declaration of Helsinki. The National Bioethics Committee and the Icelandic Data Protection Authority approved the study (Study number: VSNb2015020013/13.07).

2.2 | Measures

2.2.1 | Academic performance

The Icelandic Directorate of Education administers standardised national examinations in Icelandic language, English, and mathematics to all 10th-grade students (age 15–16 years). Students' official grades were retrieved from The Directorate of Education and used to assess academic achievement. The Icelandic examination assesses reading, writing and grammar in the native language. It involves reading comprehension, writing short stories, multiple-choice questions, and correctly using words. The English examination has a similar structure to the Icelandic examination, but the focus shifts from native language to second language as described in the national curriculum (Education & Culture, 2014). The structure involves listening, reading comprehension, grammar, and writing (Skulason, 2020). The mathematics examination contains multiple-choice questions, word problems, geometry, operations, and numerical knowledge (Skulason, 2020). Scores are nationally normalised to a mean (*SD*; range) of 30 (10; 0–60). An average examination score was also computed for participants with valid scores in all three topics.

2.2.2 | Sleep measurements

Students wore a small (3.8 × 3.7 × 1.8 cm), lightweight (27 g) triaxial accelerometer (model GT3X+, Actigraph Inc., Pensacola, FL, USA) on their non-dominant wrist, continuously for 1 week. Data recorded at 80 samples/s and were subsequently filtered and aggregated into 1-min activity counts with Actilife software version 6.13.0 (Actigraph Inc.). Customised programs in Matlab version R2016B (Mathworks, Natick, MA, USA) identified non-wear time as periods of ≥60 consecutive minutes of zero counts on all axes. As described previously (Rognvaldsdottir et al., 2017), each night was considered valid if the device was worn for ≥14 hr from 12:00 to

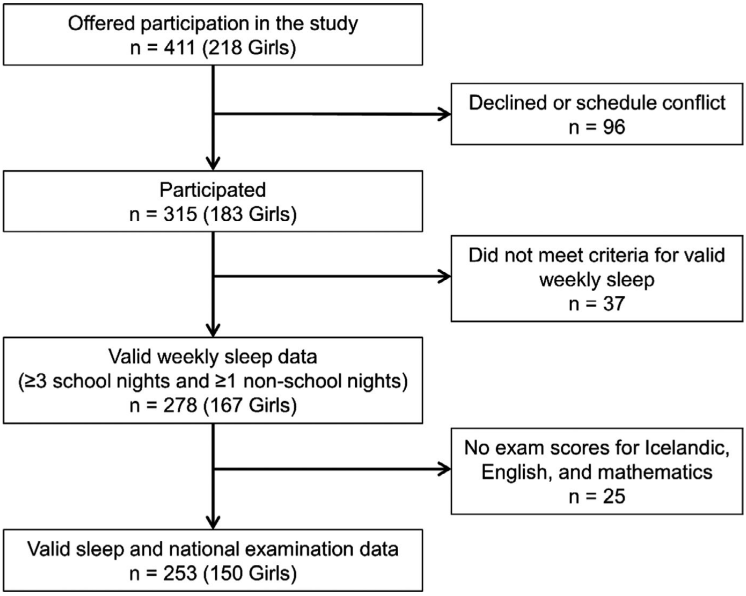

FIGURE 1 Study participant's flowchart

12:00 hours the next day. Participants with valid data on ≥3 school nights (non-holiday nights on Sunday–Thursday) and ≥1 non-school night (Friday and Saturday nights and nights prior to holidays) were used in this analysis (Stefansdottir et al., 2020). The wear time requirement was determined based on a recent systematic review of accelerometer data collection that recommends a wear time of 10 hr/day minimum, but also mentions that 24-hr assessment for sleep and activity may need longer wear time than studies who focus only on waking activity (Migueles et al., 2017). The criterion for the present study was selected to remain consistent with previous analyses of this data set, which looked at both sleep and activity in the 24-hr assessment (Rognvaldsdottir et al., 2017).

Sleep periods were detected by the Actilife software with the Sadeh algorithm validated for adolescents (Sadeh et al., 1994). Participants also completed a paper-based sleep diary each morning and evening simultaneous with the actiography. The sleep log was labelled for each day of the week and included time of entering bed, sleep onset, awakening to rise, and leaving bed. Two expert scorers adjusted the auto-detected rise- and bedtimes based on visual inspection and participant sleep diaries if needed. For each night of sleep the midpoint of sleep, minutes of wakefulness after sleep onset (WASO), the time spent asleep (total sleep time [TST]), the duration between bedtime and rise time (time in bed), their ratio (sleep efficiency = TST/time in bed × 100%), and social jetlag (non-school day midpoint of sleep minus school day midpoint of sleep) were computed for the primary nightly sleep period.

2.2.3 | Possible covariates

Ethnicity, race, and religion were not considered for the present analysis (Sigfúsdóttir et al., 2007), as the population in Iceland is largely of Norse and Celtic origin and in 2015, when data were collected, only 8% of 10th graders in Reykjavík were of non-Icelandic origin (Statistics Iceland, 2015). Participants parental educational attainment was reported by answering a tablet-based questionnaire and used as a proxy for socioeconomic status (Marco et al., 2012). Students provided the educational attainment of both mother and father from the following options (presented in Icelandic): 1 = "elementary degree", 2 = "secondary degree", 3 = "trade school degree", 4 = "university degree", 5 = "other", 6 = "do not know", 7 = "do not want to answer". Responses were recoded into a binary variable: 1 = "parent with a university degree" or 0 = "no parent with a university degree or did not answer", as described previously (Stefansdottir et al., 2020).

2.3 | Statistical analyses

The distributions of all variables were examined for normality to determine whether transformation was needed prior to regression analyses. The midpoint of sleep, rise time, WASO, sleep efficiency, and TST variability had non-normal, asymmetric distributions and are reported as median (interquartile range). Other variables were normally distributed and reported as mean ± standard deviation (*SD*). The *t* test and Mann–Whitney test were used for comparisons between sexes for normal and non-normally distributed variables, respectively, with $p < .05$ considered significant.

Linear regression models adjusted for school and parental education were used to assess the strength of association between sleep parameters (predictor variables) and standardised examination scores (response variables), with results reported as standardised β and 95% confidence intervals. To investigate the association between examination scores and different dimensions of sleep while limiting the number of comparisons, bedtime, TST, and TST variability over all nights were used as representative measures of sleep timing, duration, and consistency, respectively, while WASO and sleep efficiency were used to represent sleep quality and the average examination score over the three topics was used for the primary analysis. Prior to regression analyses, log-transformation was applied to WASO and TST variability and arcsine transformation (i.e. arc-sine of the square root of the proportion variable) was applied to sleep efficiency. Three sets of regressions were performed: one set for all students controlled for sex, and separate sets for boys and girls. The *p* values for the primary regression analysis were adjusted using the Bonferroni method across sleep parameters. The relationship between average national examination scores and sleep parameters computed over school nights and non-school nights were also performed using similar procedures and included in the supplemental material for completeness. An additional exploratory analysis of the association between the sleep parameters and test scores in each topic was also conducted. A Benjamini–Hochberg analysis (Benjamini & Hochberg, 1995) with a 0.20 false discovery rate (Q) of the 54 regression models performed in the exploratory analysis determined that all *p* values less than or equal to the critical *p* value of 0.049 could be considered significant. Analyses were conducted using R (version 3.4.2, https://www.r-project.org/) and GraphPad Prism (version 7, La Jolla, CA, USA).

3 | RESULTS

3.1 | Participant characteristics and national examination scores

Characteristics and examination scores for the 253 participants with valid sleep data and examination scores in at least one topic are summarised by sex in Table 1. The mean (*SD*) age of participants was 15.9 (0.3) years, with a mean (*SD*) body mass index of 22 (3.2) kg/m^2. The mean (*SD*) score in Icelandic for all participants was 33.5 (9.6), but it was higher for girls than boys, at 34.9 (9.6) versus 31.7 (9.2) ($p = .01$). Average scores in mathematics (mean [*SD*] 32.5 [9.9]), English (mean [*SD*] 32.9 [9.4]), and the average of all three topics (mean [*SD*] 33 [8.6]) did not differ by sex. Average scores for all three examination topics were highly correlated with one another (all $r > 0.65$, $p < .001$), suggesting that students who scored highly in one topic also did so in the other two. Participants with and without complete sleep and national examination data did not differ in terms of sex distribution, parental education, age, body composition, examination scores, or sleep measures (Table S1).

3.2 | Sleep measures

Sleep parameters averaged for all nights, school nights, and non-school nights are summarised by sex in Table 2. Students spent a mean (*SD*) of 7.5 (0.7) hr/night in bed and slept 6.6 (0.7) hr/night, with median (interquartile range [IQR]) efficiency of 88.1 [5.3]% and night-to-night variation in sleep duration of 1.2 (0.7) hr, none of which varied by sex. On average, participants went to bed at 00:49 hours (± 51.8 min) and rose at 08:20 hours (± 57.6) min, but girls had an earlier schedule than boys, averaging 17 min earlier bedtimes and 8 min earlier rise times ($p < .05$). On school nights, students went to bed ~1 hr earlier, rose 2.8 hr earlier, spent 1.4 hr/night less in bed, and slept 1.1 hr/night less than on non-school nights, resulting in a mean (*SD*) social jetlag of 122.9 (56.4) min. The mean (*SD*) sleep variability on school nights was 0.7 (0.7) hr, or ~30 min less than sleep variability over all nights when non-school nights were also included in the calculation.

TABLE 1 Participant characteristics and national examination scores by sex

	All (*n* = 253)	Boys (*n* = 103)	Girls (*n* = 150)	*p*
Mean (*SD*):				
Age, years	15.9 (0.3)	15.8 (0.3)	15.9 (0.3)	.2
Height, cm	171.5 (8.1)	178.3 (6.2)	166.8 (5.6)	**<.001**
Weight, kg	64.8 (11.2)	68.9 (11.5)	62.0 (10.2)	**<.001**
Body mass index, kg/m^2	22.0 (3.2)	21.6 (3.2)	22.2 (3.1)	.1
Parent with university degree, *n* (%)	178 (70.4)	74 (71.8)	104 (69.3)	.8
Mean (*SD*):				
English examination score[a]	32.9 (9.4)	32.2 (9.8)	33.4 (9.2)	.3
Icelandic examination score[b]	33.6 (9.5)	31.7 (9.2)	34.9 (9.6)	**.01**
Mathematics examination score[c]	32.6 (9.9)	32.7 (9.3)	32.5 (10.4)	.9
Average examination score[d]	33.1 (8.6)	32.3 (8.3)	33.7 (8.8)	.2

The *p* values are the result of *t* tests comparing boys and girls. Boldface type indicates significant differences.

[a] *N* = 243 (100 boys,143 girls).

[b] *N* = 248 (101 boys, 147 girls).

[c] *N* = 247 (99 boys, 148 girls).

[d] *N* = 236 (97 boys, 139 girls).

TABLE 2 Sleep characteristics averaged for all nights, school nights, and non-school nights by sex

	All (*n* = 253)	**Boys (*n* = 103)**	**Girls (*n* = 150)**	***p***
All nights				
Rise time, clock time ± min[a]	08:20 (± 57.6)	08:25 (± 56.1)	08:17 (± 53.2)	**.03**
Mid-sleep time, clock time ± min[a]	04:31 (± 56.2)	04:38 (± 63.4)	04:26 (± 46.1)	**.02**
Bedtime, clock time ± min[b]	00:49 (± 51.8)	00:59 (± 51.8)	00:42 (± 50.4)	**<.001**
Time in bed, hr/night[b]	7.5 (0.7)	7.5 (0.8)	7.6 (0.7)	.2
TST, hr/night[b]	6.6 (0.7)	6.5 (0.7)	6.7 (0.6)	.1
Sleep efficiency, %[a]	88.1 (5.3)	87.9 (4.9)	88.3 (5.4)	.3
WASO, min[a]	52.4 (25.0)	53.6 (24.7)	49.4 (24.4)	.2
TST variability, hr[a]	1.2 (0.7)	1.2 (0.7)	1.2 (0.7)	.5
Social jetlag, min[b]	122.9 (56.4)	134.1 (63.6)	115.4 (49.7)	**.01**
School nights				
Rise time, clock time ± min[a]	07:22 (± 40.3)	07:32 (± 38.9)	07:18 (± 34.6)	**.01**
Mid-sleep time, clock time ± min[a]	03:49 (± 46.1)	03:53 (± 47.5)	03:46 (± 44.6)	**.01**
Bedtime, clock time ± min[b]	00:22 (± 46.1)	00:32 (± 47.5)	00:16 (± 44.6)	**<.001**
Time in bed, hr/night[b]	7.0 (0.8)	7.0 (0.8)	7.1 (0.8)	.2
TST, hr/night[b]	6.2 (0.7)	6.1 (0.7)	6.2 (0.7)	.2
Sleep efficiency, %[a]	88.4 (5.5)	88.4 (5.3)	88.4 (5.6)	.98
WASO, min[a]	45.4 (27.0)	45.6 (27.4)	45.2 (24.5)	.9
TST variability, hr[a]	0.7 (0.7)	0.7 (0.5)	0.7 (0.6)	.96
Non-school nights				
Rise time, clock time ± min[a]	10:13 (± 102.2)	10:31 (± 113.8)	09:52 (± 109.4)	**.002**
Mid-sleep time, clock time ± min[a]	05:51 (± 92.2)	06:10 (± 99.4)	05:37 (± 80.6)	**.002**
Bedtime, clock time ± min[b]	01:42 (± 73.4)	01:58 (± 83.5)	01:31 (± 64.8)	**<.001**
Time in bed, hr/night[b]	8.4 (1.2)	8.4 (1.4)	8.4 (1.1)	.9
TST, hr/night[b]	7.4 (1.1)	7.3 (1.3)	7.4 (1.0)	.5
Sleep efficiency, %[a]	87.6 (5.7)	86.3 (5.3)	88.6 (5.8)	**.01**
WASO, min[a]	60.9 (34.3)	66.8 (30.3)	55.7 (30.8)	**.01**

TST, total sleep time; WASO, wakefulness after sleep onset.

[a] Results presented as median (interquartile range) due to skewed distribution.

[b] Results presented as mean (*SD*); *p* values are the result of comparisons between boys and girls with *t* tests for normally distributed variables and Mann-Whitney tests for skewed variables. Boldface type indicates significant differences.

3.3 | Association between sleep measures and national examination scores

The association between the average national examination scores across the three topics and sleep duration, quality, and variability are shown in Table 3. After controlling for the schools attended and parental education, we found an inverse relationship between bedtime and average examination scores (Figure 2a), indicating that those with earlier bedtimes had a higher average examination score. When analyses were separated by sex, the association persisted for boys, but not girls (Table 3). Additional exploratory analysis demonstrated that the trends were present in national examination scores in Icelandic and mathematics, but not English (Table S2). Variability in sleep duration was also negatively associated with the average examination score (Figure 2b) but did not persisted for either sex when analyses were conducted separately. The exploratory analysis by individual test topic showed that variability in sleep duration was also significant for Icelandic and mathematics, but not for English, and persisted for both sexes (Table S2). The exploratory analysis also showed that longer TST was associated with higher scores in Icelandic. However, this relationship was not significant for either sex when separate analyses were conducted for boys and girls (Table S2). When school night sleep parameters were used in place of average sleep measures over all nights, the inverse association between bedtime and average national examination score persisted, suggesting that school night bedtimes specifically may play an important role in academic performance (Table S3). However, in contrast to sleep variability over all nights, sleep variability on school nights was not related to average national examination scores (Table S3), perhaps due to the reduced variation in school night sleep resulting in a smaller range of values. Non-school night sleep parameters were not related to the average national examination score (Table S3).

TABLE 3 Results of multiple linear regression analyses between sleep parameters and national standardised examination scores averaged over all topics presented for all participants and separately for boys and girls

	All[a]	Boys	Girls
	β [95% CI] (*p*)	β [95% CI] (*p*)	β [95% CI] (*p*)
Bedtime	−0.17 [−0.29, −0.05] (**.04**)	−0.29 [−0.48, −0.10] (**.02**)	−0.10 [−0.26, 0.06] (.99)
TST	0.08 [−0.05, 0.20] (.99)	0.13 [−0.07, 0.34] (.99)	0.04 [−0.13, 0.20] (.99)
WASO	0.03 [−0.09, 0.15] (.99)	0.09 [−0.10, 0.28] (.99)	−0.02 [−0.18, 0.15] (.99)
Sleep efficiency	−0.01 [−0.13, 0.11] (.99)	−0.07 [−0.26, 0.12] (.99)	0.03 [−0.13, 0.19] (.99)
TST variability	−0.18 [−0.30, −0.07] (**.01**)	−0.19 [−0.38, −0.001] (.3)	−0.19 [−0.34, −0.03] (.1)
Social jetlag	−0.06 [−0.19, 0.06] (.99)	−0.02 [−0.22, 0.18] (.99)	−0.11 [−0.26, 0.05] (.99)

CI, confidence interval; β, standardised beta value; TST, total sleep time; WASO, wakefulness after sleep onset.

All regressions adjusted for school and parental education.

[a] Additionally adjusted for sex. Wakening after sleep onset, sleep efficiency, and TST variability were transformed prior to analysis due to skewed distributions. *p* values adjusted for multiple comparisons. Boldface type indicates significant differences.

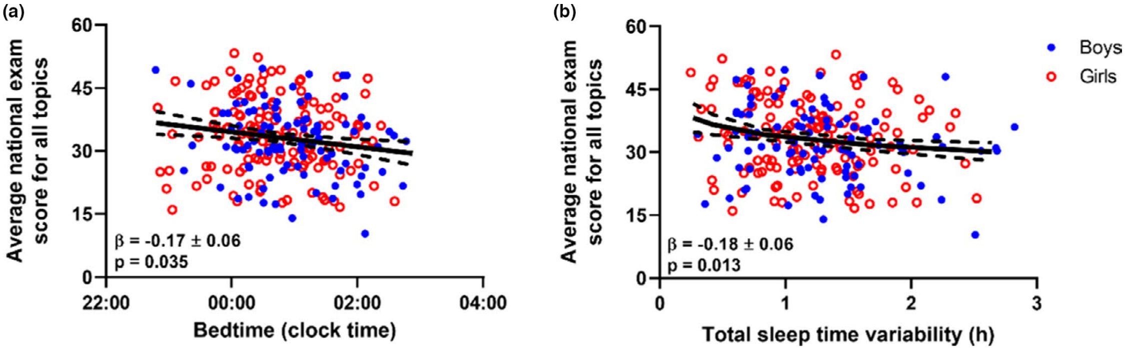

FIGURE 2 Relationship between average national examination scores and bedtime (a) and variability in total sleep time (b). Filled blue circles and unfilled red circles are used to indicate data for boys and girls, respectively. The solid and broken black lines respectively indicate regression and 95% confidence intervals adjusted for school and parental education. *p* values were adjusted for multiple comparisons. Total sleep time variability was log-transformed prior to analysis due to skewed distributions; inverse transformation was applied for display in (b)

4 | DISCUSSION

We examined the association between objectively measured sleep and performance on standardised national examinations in 15-year-old Icelandic adolescents and found that earlier bedtimes and more consistent sleep schedules were associated with higher standardised examinations scores. When girls and boys were analysed separately, the relationships between sleep variability and examination scores were not consistent across sex. Although associations between bedtime and examination scores persisted for boys but not girls, on average boys had later bedtimes than girls did. Taken together, these sex-specific observations do not support a clear role for sex in relationships between examination scores and sleep measures.

Most public health guidance and previous academic study has centred on sleep duration and highlighted the negative impact of short sleep on cognition and academic performance (Curcio et al., 2006; Hirshkowitz et al., 2015). Although our present finding of an association between TST and Icelandic examination scores support that message, the absence of associations with scores in sex-specific analyses and with scores in other topics or the average examination score in the primary analysis suggests a more subtle relationship than those identified in previous work mostly based on self-reported sleep (Asarnow et al., 2014; Stea et al., 2014). This may have resulted from a floor effect of pervasive short sleep in this population, where >78% failed to achieve the recommended 8 hr/night in bed and the 6.6 hr/night sleep duration is amongst the shortest for this age range (Rognvaldsdottir et al., 2017). Alternatively, the considerable intra- and inter-participant variation in sleep duration associated with our actiography-based sleep measurement also indicates that longer observation periods may be required to achieve further clarity on the relationship between objectively measured sleep duration and standardised test scores.

The relationships between academic performance and sleep timing and consistency were more pronounced than that for sleep duration, as both bedtime and night-to-night variability in TST were negatively associated with the average score across all topics. These findings are consistent with recent cross-sectional data in college-aged students and adolescents demonstrating that later bedtimes associate with poorer grade point average (Hysing et al., 2016; Urrila et al., 2017) and less consistent sleep associates with poorer academic performance (Díaz-Morales & Escribano, 2015; Haraszti et al., 2014; Hysing et al., 2016; Okano et al., 2019). While boys and girls had similar TST variability, bedtimes were later for boys than girls, differences which may partly explain why the relationship between bedtime and academic performance was only significant for boys. Taken together, these findings add to the emerging evidence that dimensions of sleep other than duration, such as timing and consistency, may play a role in the academic performance of adolescents, but do not suggest clear differences in these relationships by sex.

Contrary to some previous reports (Adelantado-Renau et al., 2019; Curcio et al., 2006; Dewald et al., 2010), we did not observe a relationship between academic performances and sleep quality measures, i.e. sleep efficiency and WASO. We also failed to detect a significant association between social jetlag and academic performance in the present population, which is not consistent with a previous study (Haraszti et al., 2014). The conflicting results may reflect differences in the information captured by objective and subjective measures, as most previous studies have used self-reported sleep and a study employing both methods only identified an association between subjective sleep quality and academic performance (Adelantado-Renau et al., 2019). Alternatively, the absence of an association may result from studying a healthy population with >95% of participants averaging >80% sleep efficiency and a limited prevalence of disorders known to cause sleep disturbances.

Most previous studies of this age group have relied on self-reported measures of sleep, academic performance, or both. Compared to objective measures, adolescents tend to report earlier bedtimes (Brychta et al., 2019) longer sleep durations (Short et al., 2012), and fewer night-time awakenings (Werner et al., 2008), and higher academic achievement (Escribano & Díaz-Morales, 2014; Frucgt & Cook, 1994; Kuncel et al., 2005). To prevent potential reporting bias, we instead measured free-living sleep using wrist actiography, which has high accuracy and moderate sensitivity compared to polysomnography (Slater et al., 2015), and obtained standardised national examination scores from the Icelandic Directorate of Education to quantitate academic performance. It is important to note that in Iceland the standardised tests are held in students' regular classrooms during normal school hours in order to minimise stress. Although examinations are nationally standardised, graduation from compulsory education is not contingent upon the scores and scores are used in combination with average school grades when applying to upper secondary schools.

Despite efforts to reduce reporting biases, our present study does have some other limitations. Naps were not included in our sleep analysis, as the automated sleep detection algorithm has not been validated to detect naps, there is currently no accepted criteria for scoring actiography-assessed naps (Jakubowski et al., 2017), and our participant sleep diaries did not clearly state to record napping behaviour. It should be noted that the exclusion of naps could have affected our present results, as a recent study stated that 62% of the youth participants reported taking naps (Jakubowski et al., 2017). National examinations were administered in October 2014; however, sleep was not measured until April–June 2015 because of schedule conflicts. Due to this long time interval, we performed additional analysis of our longitudinal data from the same cohort (Stefansdottir et al., 2020) and found all sleep variables to be highly correlated from age 15–17 years ($p \le .01$), with r values between 0.2 (for TST variability) and 0.6 (for sleep efficiency). We interpret this as a relative consistency within the cohort for the actiography-based sleep measures over the 2-year period, although there was individual variation between the measurements, as, on average, students went to bed later and maintained less consistent sleep schedules at age 17 years. It should also be noted that during pubertal development around this age, adolescents tend to stay awake longer in part because they accumulate homeostatic sleep pressure more slowly (Carskadon, 2011; Jenni et al., 2005) and may be less sensitive to its effects (Jenni et al., 2005; Tarokh et al., 2016). It is not clear whether these factors may have led to changes in sleep patterns or the effects of sleep on daytime functioning in the 6–8 months between the examinations and the sleep measurements. Further, both the week of free-living sleep and national examination scores only provide a snapshot of a student's typical sleep schedule and academic performance. Additional studies over a longer duration and in closer proximity to the examination date are needed to better differentiate how both chronic and acute sleep trends might affect examination scores.

The sample, although representative of Reykjavik adolescents in this age group (Statistics Iceland, 2015), is reasonably small and quite homogenous, which could potentially limit the generalisability of our present findings. Lastly, the cross-sectional design and exploratory nature of the present analysis contribute to the small effect sizes and makes it difficult to determine the directionality of the relationships. Thus, it should be repeated with a prospective design.

5 | CONCLUSION

Students that went to bed earlier and had more consistent sleep schedules were more likely to score higher on standardised national academic examinations. These findings suggest that public health guidance should highlight the importance of both early and consistent sleep schedules to enhance academic performance. Future studies with longer observation periods, longitudinal designs, and interventional components could further clarify the relationship between sleep and academic performance in adolescents.

ACKNOWLEDGEMENTS

We would like to thank Sigurgrímur Skúlason for the helpful input, the participants and staff at participating schools, and the Master's students and researchers involved in the data collection. Primary funding supplied by the Icelandic Centre for Research (RANNIS) (grant number: 152509-051). Additional support provided by the Ministry of Education, Science and Culture, the Iceland Primary Health Care Research Fund, and doctoral grants of the University of Iceland Research Fund. KYC and RJB were funded by the National Institute of Diabetes and Digestive and Kidney Diseases intramural research programme (Z01 DK071013 and Z01 DK071014). The study was performed at the University of Iceland in Reykjavik, Iceland.

CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

RS and RBJ drafted the manuscript and analysed the data. EJ and KYC designed the research. RS and VR collected and organised the data. EJ, KYC, and VR edited the manuscript. All authors reviewed and have approved the final the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Stefansdottir R, Rognvaldsdottir V, Chen KY, Johannsson E, Brychta RJ. Sleep timing and consistency are associated with the standardised test performance of Icelandic adolescents. *J Sleep Res*. 2021;00:e13422. https://doi.org/10.1111/jsr.13422

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Association between free-living sleep and memory and attention in healthy adolescents

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In laboratory studies, imposed sleep restriction consistently reduces cognitive performance. However, the association between objectively measured, free-living sleep and cognitive function has not been studied in older adolescents. To address this gap, we measured one week of sleep with a wrist-worn GT3X+ actigraph in 160 adolescents (96 girls, 17.7 ± 0.3 years) followed by assessment of working memory with an n-back task and visual attention with a Posner cue-target task. Over the week, participants spent 7.1 ± 0.8 h/night in bed and slept 6.2 ± 0.8 h/night with 88.5 ± 4.8% efficiency and considerable intra-participant night-to-night variation, with a standard deviation in sleep duration of 1.2 ± 0.7 h. Sleep measures the night before cognitive testing were similar to weekly averages. Time in bed the night before cognitive testing was negatively associated with response times during the most challenging memory task (3-back; $p = 0.005$). However, sleep measures the night before did not correlate with performance on the attention task and weekly sleep parameters were not associated with either cognitive task. Our data suggests shorter acute free-living sleep may negatively impact difficult memory tasks, however the relationship between free-living sleep and cognitive task performance in healthy adolescents is less clear than that of laboratory findings, perhaps due to high night-to-night sleep variation.

The National Sleep Foundation recommends that teenagers aged 14 to 17 sleep 8–10 h a night in order to maintain overall health and well-being[1]. Yet, the Centers for Disease Control has shown that less than 30% of US teens report achieving the recommend amount of sleep and over two thirds report sleeping 7 h or less[2]. Short sleep in adolescents has been associated with increased risk of a variety of negative health outcomes, from metabolic complications[3,4] to mental health issues[5]. One of the more consistent findings is a link between shortened sleep and impaired cognitive function[6,7]. Randomised clinical studies of adolescents have demonstrated that even partial sleep deprivation, i.e. shorter than recommended sleep duration without recovery sleep[8], for 1–7 nights can deleteriously effect a wide range of cognitive functions including alertness[9], visual attention[10], cognitive processing speed[11], and memory[12]. In some cases, even two nights of recovery sleep, analogous to the weekend "catch-up sleep" common amongst this age group, is not sufficient to completely restore cognitive performance[10,13]. The results of these clinical studies are also supported by large cross-sectional studies that find sleep quantity and quality can negatively affect academic performance amongst teenagers[14,15]. Poor sleep quality is also associated with lower performance on tasks of working memory[15] and executive functioning[16]. Further, adequate sleep may be important for continued brain development during adolescence[17], especially in frontal and parietal regions that underlie cognitive domains such as attention and memory[18].

Evidence that short and disrupted sleep can deleteriously affect cognitive function is largely derived from controlled studies of sleep restriction. Most previous studies of the relationship between free-living sleep and

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Characteristics	Mean ± standard deviation or N (%)
N (% female)	160 (60.0%)
Age (years)	17.7 ± 0.3
Weight (kg)	68.7 ± 13.4
Height (cm)	173.9 ± 9.1
Body mass index (kg/m^2)	22.7 ± 3.9
Videogame use (h/day)	0.8 ± 1.1
Clinical diagnosis of ADHD (N, %)	7 (4.3%)

Table 1. Characteristics for participants with valid weekly sleep and valid sleep measured the night prior to cognitive testing. *ADHD* attention deficit hyperactivity disorder.

	Sleep the night prior to cognitive testing	Weekly sleep	*p* value
Mid-sleep time (clock time ± h)	04:19 ± 1.2	04:48 ± 1.0	**< 0.001**
Total rest time (h/night)	7.0 ± 1.4	7.1 ± 0.8	0.15
Total sleep time (h/night)	6.1 ± 1.4	6.2 ± 0.8	0.11
WASO (min/night)	51.4 ± 28.5	51.9 ± 20.5	0.71
Sleep efficiency (%)[a]	88.4 ± 7.1	88.5 ± 4.8	0.63
Total rest time variability (h)[a]		1.4 ± 0.8	
Total sleep time variability (h)[a]		1.2 ± 0.7	

Table 2. Sleep measures for participants with valid weekly sleep and valid sleep measured the night prior to cognitive testing. Results presented as mean ± standard deviation, unless otherwise noted. *p* values are the result of paired t-tests comparing sleep the night prior to cognitive testing to weekly sleep. Boldface type indicates significant differences. *WASO* wake after sleep onset. [a]Results presented as median ± interquartile range due to skewed distributions.

cognitive function that did not include sleep interventions have relied on self-reported sleep measures[17,19] or examined younger students[15,20,21] or small (< 20 participants), selective samples[22] using actigraphy. Thus, there is limited information about how free-living sleep patterns associate with cognitive function in non-clinical adolescent populations. After identifying widespread actigraphy-measured sleep curtailment in a longitudinal cohort of older Icelandic adolescents[23], we included a cognitive assessment during a subsequent round of data collection to determine whether associations between sleep restriction and cognition identified in laboratory studies were also present in a free-living setting. Thus, the aim of the current study was to measure one week of free-living sleep using wrist actigraphy followed by testing of short-term working memory and visual attention in older adolescents. We tested whether the cognitive function of healthy adolescents was associated with free-living sleep duration and quality measured acutely, the night prior to testing, or cumulatively over an entire week. We hypothesized that shorter and more disrupted free-living sleep would be negatively associated with performance on tasks of short-term memory and visual attention.

Results

Participants. We conducted an exploratory analysis of the association between sleep and cognitive function, a secondary outcome in a longitudinal study of health and fitness from childhood through adolescence in Iceland[23,24]. The analysis included 160 participants that completed the cognitive tasks and a questionnaire which included self-reported videogame use and presence or absence of a clinical diagnosis for attention-deficit hyperactivity disorder (ADHD), met the criteria for a valid week of wrist actigraphy-measured sleep (≥ 3 weeknights and ≥ 1 weekend nights)[23], and had valid sleep measures the night prior to cognitive testing. Participant characteristics are summarized in Table 1.

Sleep measures. A summary of all sleep parameters measured by wrist actigraphy is shown in Table 2. Average weekly rest duration (the time between bedtime and rise time) and sleep duration (time spent asleep) were 7.1 ± 0.8 h/night and 6.2 ± 0.8 h/night, respectively. This suggests that, on average, most participants did not spend the recommend 8–10 h/night in bed. Intra-individual nightly variation (i.e. standard deviation over all valid nights[23,25]) in sleep (1.2 ± 0.7 h) and rest durations (1.4 ± 0.8 h) over the week was also quite high. Measures of sleep quality included sleep efficiency (i.e. the ratio of sleep duration to rest duration multiplied by 100) which was 88.5 ± 4.8%, and minutes of wakefulness after sleep onset (WASO), which was 51.9 ± 20.5 min/night over the week. The average weekly mid-sleep time, a marker of sleep timing, was 04:48 ± 1.0 h. With the exception of an earlier mid-sleep time (04:19 ± 1.0 h, $p < 0.001$), sleep parameters on the night prior to cognitive testing were not significantly different than the weekly averages. The later average weekly mid-sleep time was likely caused

	Response time (ms)	Response accuracy (proportion correct)
Working memory task[a]		
1-Back	409.1 ± 73.6	0.98 ± 0.02
2-Back	522.8 ± 133.8[b]	0.95 ± 0.06[b]
3-Back	538.0 ± 150.6[b,c]	0.87 ± 0.08[b,c]
Visual attention task[a]		
Valid cue	307.2 ± 31.9	0.94 ± 0.05
Invalid cue	360.2 ± 40.6[d]	0.91 ± 0.09[d]
No cue	387.8 ± 45.6[d,e]	0.96 ± 0.04[d,e]

Table 3. Cognitive measures for participants with valid weekly sleep and valid sleep measured the night prior to cognitive testing. Results presented as median ± interquartile range due to skewed distributions. [a]Differences evaluated using mixed effect regression of transformed variables with Bonferroni post hoc correction for multiple comparisons. [b]Significantly different than 1-back load. [c]Significantly different than 2-back load. [d]Significantly different than valid cue presentation. [e]Significantly different than invalid cue presentation.

by including weekend nights into the average, whereas all cognitive testing occurred after a school night. As we have demonstrated previously, students in this cohort tend shift toward later sleep schedules on the weekend[25].

Cognitive measures. *Short-term memory task.* Short-term working memory was assessed using a numeric version of the n-back task. Positive, single-digit integers (i.e. 1–9) appeared one at a time in the centre of the screen in a fixed sequence. Participants indicated whether the current digit was the same as the one presented n positions back in the sequence, where n varied from 1 to 3, with higher numbers representing greater working memory load.

Performance on the N-back task was quantified using response time, or the time between stimulus appearance and participant response, and response accuracy, defined as the proportion of correct responses (i.e. the sum of correct button presses and correct rejections divided by total stimuli), as shown in Table 3. Response time and accuracy varied predictably across cognitive load: response time gradually increased while accuracy decreased in a dose–response manner from the 1-back to the 2-back and 3-back conditions (all $p < 0.05$).

Response times for all three memory loads were positively correlated with one another (all $p \leq 0.01$; Table S1 in the Supplementary Information), suggesting those who responded rapidly on lower memory load also did so on higher memory loads. Correlations between response accuracies were less consistent, with a positive correlation only between 2-back and 3-back accuracies ($p \leq 0.05$). We found limited correlation between response time and accuracy for each cognitive load, with the exception of a negative correlations for the 3-back load ($p < 0.05$), suggesting those with faster responses were also more accurate for this load.

Visual attention task. Visual attention was evaluated using a Posner cue-target paradigm task[26–28]. Participants were instructed to focus on a cross centred on the screen between two rectangles and indicate whether the target stimulus (an asterisk) appeared in the left or right rectangle. The task consisted of a pre-determined sequence of three possible cue presentations: "valid cue", "invalid cue", and "no cue". "Valid cue" presentation occurred when a rectangle frame thickened (cue) as the target stimulus appeared at its centre. "Invalid cue" presentation occurred when a rectangle frame thickened as the target stimulus appeared inside the opposite rectangle. "No cue" presentation was the absence of either rectangle frame thickening during target stimulus appearance[28,29].

Response time and accuracy on the visual attention task also varied significantly across conditions (all $p < 0.001$, Table 1). However, trends across cue presentations for response time differed from those of response accuracy. The no cue presentation elicited the slowest but most accurate responses. During the valid cue presentation, responses were fastest, but accuracy was intermediate between no cue and invalid cue presentations. On the other hand, during the invalid cue, responses were least accurate, but response times were intermediate between the valid and no cue presentation.

Response times for each cue presentation in the visual attention task were all highly positively correlated to one another (all $p < 0.001$, Table S2 in the Supplementary Information). Similarly, response accuracies of all cue presentations were also all positively correlated (all $p \leq 0.01$). Taken together, these results suggest that those who responded rapidly and accurately on one cue presentation did so on others. As in the working memory task, correlations between response time and response accuracy were inconsistent by cue presentation. While response time was directly correlated to response accuracy during the invalid cue presentation ($p = 0.03$), it was inversely correlated to accuracy during the no cue presentation ($p < 0.001$) and unrelated to accuracy for the valid cue presentation.

Associations between sleep and cognitive measures. Associations between cognitive measures and free-living sleep parameters were assessed using linear regression models. Presence or absence of a clinical diagnosis of ADHD and weekly videogame usage were determined via self-report and included in all regression models since the presence of ADHD and extensive videogame use have previously been associated with cognitive performance in visuospatial tasks[30,31]. Response times and accuracies on higher cognitive loads of the working memory task (i.e. 2-back and 3-back response times) were adjusted for analogous measures on the 1-back

	2-Back response time (ms)	2-Back response accuracy (proportion correct)	3-Back response time (ms)	3-Back response accuracy (proportion correct)
	β [95% CI] (*p*)	β [95% CI] (*p*)	β [95% CI] (*p*)	β [95% CI] (*p*)
Sleep measures of the night prior to short-term memory task				
Total rest time (h)	−0.03 [−0.18, 0.11] (0.7)	−0.02 [−0.18, 0.15] (0.9)	−0.22 [−0.38, −0.07] (0.005)*	0.04 [−0.12, 0.20] (0.6)
Total sleep time (h)	0.02 [−0.13, 0.16] (0.8)	−0.06 [−0.22, 0.10] (0.5)	−0.19 [−0.34, −0.03] (0.02)	0.07 [−0.09, 0.23] (0.4)
Sleep efficiency (%)	0.15 [0.01, 0.29] (0.04)	−0.15 [−0.31, 0.00] (0.06)	0.03 [−0.13, 0.18] (0.8)	0.09 [−0.07, 0.25] (0.3)
WASO (min)	−0.13 [−0.27, 0.01] (0.06)	0.13 [−0.03, 0.29] (0.1)	−0.12 [−0.28, 0.04] (0.1)	−0.08 [−0.24, 0.08] (0.3)
Weekly sleep measures				
Total rest time (h/night)	−0.01 [−0.15, 0.13] (0.9)	−0.06 [−0.22, 0.10] (0.5)	−0.11 [−0.26, 0.05] (0.2)	0.11 [−0.05, 0.26] (0.2)
Total sleep time (h/night)	0.04 [−0.10, 0.18] (0.6)	−0.04 [−0.20, 0.12] (0.6)	−0.07 [−0.23, 0.09] (0.4)	0.13 [−0.03, 0.28] (0.1)
Sleep efficiency (%)	0.10 [−0.04, 0.24] (0.2)	−0.004 [−0.16, 0.16] (0.96)	0.06 [−0.10, 0.21] (0.5)	0.05 [−0.11, 0.20] (0.6)
WASO (min/night)	−0.10 [−0.24, 0.04] (0.2)	−0.06 [−0.22, 0.10] (0.5)	−0.08 [−0.24, 0.07] (0.3)	−0.05 [−0.20, 0.11] (0.6)
Total rest time variability (h)	0.01 [−0.13, 0.15] (0.9)	−0.04 [−0.20, 0.12] (0.7)	0.15 [−0.01, 0.30] (0.07)	−0.05 [−0.21, 0.11] (0.5)
Total sleep time variability (h)	0.002 [−0.14, 0.14] (0.98)	−0.02 [−0.18, 0.14] (0.8)	0.13 [−0.03, 0.28] (0.1)	−0.07 [−0.22, 0.09] (0.4)

Table 4. Results of linear regression between sleep parameters and response times and accuracies on the short-term working memory task. β, standardized beta value; CI, confidence interval; WASO, wake time after sleep onset. *Significant after Benjamini–Hochberg analysis of all comparisons with 0.25 false discovery rate. All regressions adjusted for clinical diagnosis of attention deficit hyperactivity disorder and reported weekly video game use. 2-back and 3-back response time additionally adjusted for 1-back response times. 2-back and 3-back response accuracy additionally adjusted for 1-back response accuracy. Response times, response accuracies, sleep efficiency, total sleep time variability, and total rest time variability were transformed prior to analysis due to skewed distributions.

task[32,33]. Similarly, response times and accuracies of the invalid and no cue conditions of the visual attention task were adjusted for the analogous measures on the valid cue condition.

We first explored the association between working memory and sleep parameters measured the night prior to cognitive testing and observed p values below 0.05 for the positive association between sleep efficiency and 2-back response time and the negative associations between total rest and sleep times and 3-back response times (Table 4). Next, we examined the association between working memory and weekly averages of sleep parameters and found no associations with p values below 0.05 (Table 4). To control for possible type 1 error, we performed a Benjamini–Hochberg analysis of the 40 comparisons summarized in Table 4 with a false discovery rate (Q) of 0.25, and determined that only the association between rest duration the night before cognitive testing and 3-back response time ($p=0.005$) fell below the critical p value of 0.006. This suggests that less time in bed acutely, the night prior to the working memory task, was significantly associated with longer response times only on the most difficult cognitive load (Fig. 1A), although no such relationship existed for average weekly time in bed (Fig. 1C).

In an additional, exploratory analysis of the relationship between total rest time and working memory, we tested whether participants with a total rest time of 7 h or less performed differently on the task than those with greater than 7 h. The threshold value of 7 h of total rest time was selected since it was the group mean for the participants in this study and previously used as an indicator of short sleep[34]. We found that the 82 students with a rest duration of 7 h or less the night prior to cognitive testing had longer 3-back response times on than the 78 students with a rest duration of greater than 7 h (median ± interquartile range: 551.7 ± 148.1 vs. 514.5 ± 138.2 ms, $p=0.04$; Fig. 1B, Table S3). We also found that the 66 participants who averaged 7 h or less total rest time over the week had longer 3-back response times than the 94 participants who did not (570.3 ± 135.7 vs. 511.3 ± 143.7 ms, $p=0.03$; Fig. 1D, Table S3). Thus, results of the categorical analysis support the finding that short, acute total rest time prior to cognitive testing is associated with longer response times on the most difficult cognitive task. Analyzing the data in a categorical fashion also allowed us to detect a similar difference in 3-back response time between those with shorter and longer weekly rest time.

Surprisingly, we found no associations between response times on the visual attention task and sleep parameters measured the night prior to cognitive testing or over the entire week (Table 5). There were also no differences in the visual attention task performance of participants with 7 h or less total rest time compared to those with greater than 7 h (Table S4).

Discussion

We explored the association between objectively measured free-living sleep and working memory and visual attention tasks in healthy adolescents since prior studies conducted in clinical settings have shown that sleep restriction affects these cognitive functions[35]. We found that shorter time in bed the night prior to the cognitive testing was negatively associated with performance on the most challenging short-term memory load, indicating that acute short sleep can affect short-term working memory, even in a healthy population measured in a free-living setting. We did not observe a similar continuous association between weekly rest duration and short-term working memory, despite short average sleep duration and time in bed over the week. However, we did find that participants with rest durations of 7 h or less, measured either acutely on the night prior to cognitive testing or

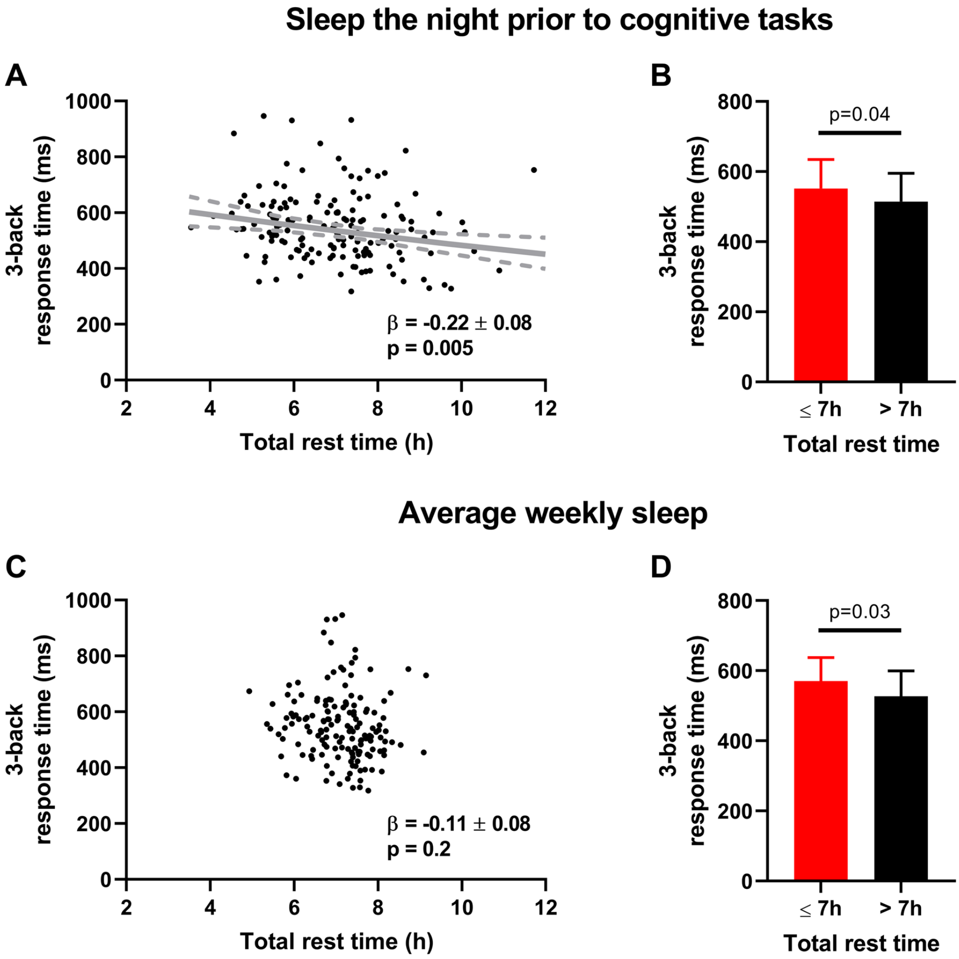

Figure 1. Relationship between response time on the most difficult (3-back) work memory load and total rest time. (**A**) The solid grey line demonstrates the inverse correlation between total rest times the night prior to the cognitive task and 3-back response times. Broken grey lines indicate the 95% confidence intervals. (**B**) Participants with 7 h or less total rest time (in red, N = 82) had longer response times than those with greater than 7 h (in black, N = 78). (**C**) Average weekly total rest time did not correlate with 3-back response times. (**D**) Participants that average 7 h or less daily total rest time over the week (N = 66) had longer response times than those that averaged greater than 7 h (N = 94). All comparisons adjusted for clinical diagnosis of attention deficit hyperactivity disorder, reported weekly video game use, and 1-back response times. Response times were log-transformed prior to analysis due to skewed distributions; inverse transformation was applied for displayed in (**A**); bars and error bars in (**B**) and (**D**) are medians and interquartile ranges. β, standardized beta ± standard error.

averaged over the week, had longer response times during the most difficult short-term memory load than those with greater than 7 h. Taken together with the considerable intra-participant night-to-night variation in sleep and rest duration, this suggests that compensatory bouts of shorter and longer sleep over the week may obscure associations between sleep duration and working memory and may require a larger sample size to detect a correlation based on continuous measures. Despite strong previous evidence to the contrary from clinical studies, we did not observe any association between sleep parameters and performance on the visual attention task. This suggests that the task lacked complexity, the variability of free-living sleep parameters was too high, or both.

Sleep curtailment has been shown to have a deleterious effect on cognitive function both in laboratory studies[9,35] and actigraphy-based sleep assessment[15]. For example, adolescents aged 15–19 years randomly assigned to seven nights of sleep restriction, i.e. 5 h of sleep opportunity, had lower sustained attention, working memory, executive function, and processing speed compared to those assigned to 9 h of sleep opportunity[9]. Similarly, four nights of partial sleep restriction (6–6.5 h/night) significantly reduced information processing speed compared

	Invalid cue response time (ms)	Invalid cue response accuracy (proportion correct)	No cue response time (ms)	No cue response accuracy (proportion correct)
	β [95% CI] (*p*)	**β [95% CI] (*p*)**	**β [95% CI] (*p*)**	**β [95% CI] (*p*)**
Sleep measures of the night prior to short-term memory task				
Total rest time (h)	− 0.05 [− 0.14, 0.04] (0.3)	0.01 [− 0.09, 0.11] (0.8)	0.04 [− 0.05, 0.13] (0.3)	− 0.08 [− 0.24, 0.09] (0.4)
Total sleep time (h)	− 0.06 [− 0.15, 0.03] (0.2)	0.02 [− 0.09, 0.12] (0.8)	0.03 [− 0.06, 0.12] (0.5)	− 0.07 [− 0.23, 0.09] (0.4)
Sleep efficiency (%)	− 0.05 [− 0.14, 0.04] (0.3)	− 0.01 [− 0.11, 0.09] (0.9)	− 0.02 [− − 0.11, 0.07] (0.6)	− 0.02 [− 0.18, 0.14] (0.8)
WASO (min)	0.02 [− 0.07, 0.11] (0.7)	− 0.01 [− 0.11, 0.10] (0.9)	0.04 [− 0.05, 0.13] (0.4)	− 0.02 [− 0.18, 0.14] (0.8)
Weekly sleep measures				
Total rest time (h/night)	0.01 [− 0.08, 0.10] (0.8)	− 0.01 [− 0.11, 0.09] (0.9)	0.02 [− 0.07, 0.10] (0.7)	0.04 [− 0.12, 0.19] (0.7)
Total sleep time (h/night)	− 0.02 [− 0.11, 0.07] (0.7)	0.03 [− 0.07, 0.13] (0.6)	0.01 [− 0.08, 0.10] (0.8)	0.02 [− 0.14, 0.18] (0.8)
Sleep efficiency (%)	− 0.07 [− 0.16, 0.02] (0.1)	0.07 [− 0.03, 0.17] (0.2)	− 0.01 [− 0.1, 0.08] (0.8)	− 0.05 [− 0.21, 0.11] (0.6)
WASO (min/night)	0.07 [− 0.02, 0.16] (0.1)	− 0.07 [− 0.17, 0.03] (0.2)	0.01 [− 0.08, 0.09] (0.9)	0.04 [− 0.12, 0.20] (0.6)
Total rest time variability (h)	− 0.001 [− 0.09, 0.09] (0.98)	0.03 [− 0.07, 0.13] (0.6)	− 0.07 [− 0.16, 0.01] (0.1)	0.03 [− 0.13, 0.18] (0.7)
Total sleep time variability (h)	− 0.01 [− 0.1, 0.08] (0.8)	0.05 [− 0.05, 0.15] (0.3)	− 0.06 [− 0.15, 0.02] (0.2)	− 0.003 [− 0.16, 0.16] (0.97)

Table 5. Results of linear regression between sleep parameters and response times and accuracies on the visual attention task. All regressions adjusted for clinical diagnosis of attention deficit hyperactivity disorder and reported weekly video game use. Invalid cue and no cue response time additionally adjusted for valid cue response times. Invalid cue and no cue response accuracy additionally adjusted for valid cue response accuracy. Response times, response accuracies, sleep efficiency, total sleep time variability, and total rest time variability were transformed prior to analysis due to skewed distributions. β, standardized beta value; CI, confidence interval; WASO, wake time after sleep onset.

to four nights of sleep extension (10–10.5 h/night) for adolescents with a mean age of 16.9 years[36]. Interestingly, a previous study of younger adolescents (aged 6–13 years) found that shorter actigraphy-measured sleep averaged over three nights was associated with reduced performance only on the highest memory load of on an n-back task[15]. Other studies have also reported that reduced sleep duration might be particularly important for more demanding tasks that require enhanced working memory capacity and concentration[17]. It should also be noted that most interventional studies define study arms according greater or lesser sleep opportunity while most self-reported measures rely either on a typical time-in-bed or the difference between bedtime and rise time, and do not take into account nightly awakenings since awakenings are generally difficult to measure by report[37]. Perhaps the closest actigraphy-derived variable to these measures is the total rest time, which, unlike total sleep time, does not subtract minutes of awakenings. Thus, our finding that rest time the night before cognitive testing is negatively associated with performance on the most challenging memory load of the n-back task is in-line with these previous findings and demonstrates that the deleterious effects of short sleep on demanding tasks of memory are also present in the free-living setting for older adolescents.

Although our finding that shorter rest duration the night prior to testing was associated with slower responses at the highest cognitive load of the memory task is in line with that from another actigraphy study of adolescents[15], our results differed in that we did not detect an association between sleep quality and working memory performance. However, the mean age of the participants in that study (9.9 ± 1.9 years) was much younger and the age range (6.9–13.3 years) was much broader than the current study. The authors also noted that age associated positively with sleep duration and negatively with sleep efficiency[15], indicating that younger participants likely slept longer than 8.2 ± 0.6 h/night with an efficiency below 86.5 ± 5.1%, the reported averages for each parameter. A recent study of healthy adults with a mean age closer to that of our participants (approximately 21 years) found no association between subjective sleep quality and working memory[38]. The authors suggest that the lack of association may have been due to a ceiling effect of studying a healthy population with limited prevalence of disorders known to cause sleep disturbances, which is also the case in the present study. These observations suggest that, compared to younger populations, free-living sleep quality may play a lesser role than sleep duration in the working memory task performance of healthy older adolescents and young adults.

We did not detect any significant continuous associations between working memory and weekly averages of sleep duration or quality. This lack of association was surprising as we expected observations of sleep patterns over a longer duration would have greater associations with cognitive function than acute sleep observations, but we have considered several potential explanations. The pervasive short sleep in our study sample, where over 88% averaged less than the recommended 8 h time-in-bed over the week, may have resulted in a floor effect that made it difficult to detect associations between weekly sleep duration and cognitive function. The absence of cognitive results following a period of recommended sleep opportunity for comparison, as is common in most clinical interventions, also complicates the interpretation of the results, since both sleep needs[39,40] and performance on cognitive tasks[41] are likely to be individualized. However, it should also be noted that due to biological changes during puberty[42], older adolescents may be able to remain awake longer and may be less likely to notice to sleep deficits than younger adolescents and adults since they accumulate homeostatic sleep pressure more slowly[43,44] and are less sensitive to its effects[44,45].

On the other hand, the minimal associations between free-living sleep and cognitive function may have been due to a ceiling effect in the performance on the cognitive tasks related to the peak in the cognitive function that reportedly occurs in young adulthood, close to the age range of our generally healthy, older adolescent population. Working memory has been reported to peak in young adulthood[38,41,46,47]. In support of this, the responses on all cognitive loads of the working memory task in the current study were faster and more accurate than in a previous study of male participants with a slightly older mean age (28 ± 4 years) tested with the same paradigm in our laboratory[48]. In contrast, performance on visual attention tasks may be less related to age[49]. However, in the current study we observed response times and accuracies that were similar to those of a group of male Norwegian participants within the same age range (17.9 + 0.9 years) undergoing the same visual attention task[29], suggesting a similar level of motivation and performance. Thus, we cannot determine whether the cognitive tasks used in our study may have lacked the sensitivity to assess the effects of free-living sleep on working memory and visual attention of our generally healthy, older adolescent population and the topic warrants further study.

Another potential explanation for the limited association between weekly sleep and cognitive function was that the participants were able to compensate for low sleep duration over the week. The high intra-individual variation in sleep duration is indicative of compensatory nights of shorter and longer sleep over the week, which may obscure associations between weekly sleep parameters and cognitive function. However, irregular sleep patterns have also been shown to be associated with poorer academic performance in younger children[50] and college-aged students[51]. Collectively, these observations suggest that any compensatory benefit of a highly varied sleep schedule on cognitive function are likely outweighed by the negative impacts on cognition. The participants may also have compensated for short sleep with caffeine intake, which we did not control for and is reportedly widespread amongst Icelandic adolescents[52]. These potential compensatory behaviours may have led to a more subtle relationship between free-living sleep and cognitive function than those observed during clinical trials with greater control of diet and sleep schedule.

The high night-to-night variability in rest and sleep duration amongst participants in this study also suggests that a larger sample size may be required to detect a correlation based on continuous measures of free-living rest or sleep duration and cognitive function in older adolescents. The standardized beta coefficients of the associations between 3-back response time and total rest times for the night prior to cognitive testing ($\beta = -0.22 \pm 0.08$; standardized $\beta \pm$ standard error) and averaged over the week ($\beta = -0.11 \pm 0.08$) both indicated inverse relationships and did not significantly differ when tested statistically. However, only total rest time measured on the night prior to cognitive testing was significantly correlated with 3-back response times. Dichotomizing a continuous variable can increase the statistical power to detect differences. Employing this strategy, we found that 3-back response times were shorter for participants with total rest time above versus below the 7-h group average, independent of the sleep measurement duration. Taken together, these observations suggest that, although sleep measured over both durations may have similar relationships to working memory task performance, in our sample, sleep measured acutely before testing had a stronger relationship to 3-back response time and more subjects are likely needed to increase statistical power enough to detect a similar continuous association between 3-back response time and weekly rest time.

As with the limited association between free-living sleep and working memory, the absence of a relationship between free-living sleep and visual attention likely stems from a confluence of factors, including many discussed previously, such as the likelihood of compensatory behaviours, limitations in statistical power, and the floor effect of wide-spread short sleep. Prior research on the relationship between sleep and attention has demonstrated that errors increase with continued wakefulness[53]. Despite average short sleep both over the entire week and acutely before the cognitive task, < 8% of participants spent less than 5 h in bed the night before the task, a duration of sleep opportunity previously used in studies of acute sleep restriction in adolescent[9]. Thus, although the limited rest duration may have affected performance of the most complex working memory task, greater deprivation may be required for detectable degradation of attention task performance, particularly when considering the size of our sample relative to the inter-participant variation in time-in-bed (1.4 h). Attention task errors have also been shown to increase with task duration[54], and short sleep has greater impact with increasing task complexity[17]. The duration of our visual attention task (9 min) was short and thus, a longer and/or more complex task may be needed to better demonstrate the relationship between free-living sleep and visual attention.

Most previous studies of the relationship between sleep and cognition have used controlled sleep interventions on a smaller sample in a laboratory setting. Unlike inpatient sleep assessments, free-living sleep measurements benefit from monitoring sleep patterns in a familiar environment and allow subjects to maintain typical daily routines and habits. Our chosen method of measuring free-living sleep, wrist actigraphy, is less sensitive to subjective bias and has greater accuracy to detect sleep duration[55] and awakenings[56] than self-report methods when compared to the gold standard—polysomnography. However, actigraphy is more difficult to administer than questionnaire-based self-report, which limited our sample size, although it is larger than most clinical sleep studies and representative of Reykjavík students in this age group during the study period (1382 17-year-olds in 2017)[57].

Although wrist actigraphy has been shown to have high accuracy and sensitivity compared to polysomnography, its specificity is limited[58]. Further, our analysis focused on the primary nightly sleep period since the parameters of the automated detection algorithm may have been insufficient to detect naps and there is no accepted criterion for scoring actigraphy-assessed naps[59] and the automated sleep detection algorithm may have been inadequate to detect naps. Participants were only explicitly instructed to log primary sleep periods and may not have thought to include naps in the diary. Thus, we were unable to determine whether short periods of inactivity outside of the primary sleep period were naps due to a lack of a validated automated method or confirmatory log. Exclusion of naps could have affected our results, as napping has been shown to be a prominent behaviour among this age group and is associated with both shorter and more disrupted night-time sleep[59].

It was not feasible to control the time of day or day of week for cognitive testing due to the highly varied schedules of the participants in this age group, which is a considerable limitation. However, all tests were conducted on weekdays in the afternoon (starting from 12:30–19:00, with a mean start time of 15:43 ± 1.3 h) and in preliminary analyses, we found no correlation between cognitive response times and time of day or day of the week for testing. Similarly, we found no theoretical basis for a sex-based difference in the relationship between sleep and cognitive responses in previous literature[60] or preliminary analyses. Thus, final regression models were not statistically adjusted for these variables.

Finally, this was an exploratory analysis of a secondary outcome for an ongoing longitudinal study of Icelandic youth. Thus, it was not powered to detect a pre-specified outcome and the homogeneity of the study sample may limit the generalizability of the results. However, the results provide a basis for future study design in broader and more diverse populations. The cross-sectional design of the analysis and the absence of comparable cognitive data following a period of "sufficient" sleep makes it difficult to determine cause and effect.

Conclusions. Our study of the relationship between free-living sleep and cognitive function in generally healthy, older adolescents demonstrated that shorter time in bed the night prior to the cognitive testing was negatively associated with performance on the most challenging short-term memory load. However, despite a short and varied sleep duration over the week, we did not find a clear, continuous association between weekly sleep measures and short-term working memory or visual attention as hypothesized. Taken together, these results suggest that the considerable intra-participant night-to-night variation in sleep duration observed with free-living sleep of older adolescents may result in a relationship between sleep and cognitive task performance that is less stark than those observed with laboratory-imposed sleep restriction. Nevertheless, the negative impact of shorter acute sleep on difficult tasks of working memory appears to persist even in a generally healthy population measured in a free-living setting.

Methods

Participants. We were able to contact 420 participants who had participated in previous waves of the study and 236 (146 girls) agreed to participate (56% participation rate) and 231 (61% girls) had height and weight measured and completed the cognitive tasks and the questionnaire (Fig. 2A). Free-living sleep was measured for one week with wrist actigraphy, and 188 participants (62% girls) also met the requirements for valid sleep measurements over the week (≥ 3 weeknights and ≥ 1 weekend night). However, due to schedule conflicts or non-compliance, 28 participants with valid weekly sleep measures did not have a sleep measurement the night prior to cognitive testing. The remaining 160 participants with valid sleep measures over the week and the night prior to cognitive testing were included in the analysis.

Data collection. We collected the data from early February until early May of 2017. Each participant had two visits separated by 7 ± 1 days on average (min = 6, max = 17, median = 7). The first visit occurred at the Icelandic Heart Association where participants completed a tablet-based questionnaire, weight and height were measured by trained research staff, and participants were provided with a wrist-worn accelerometer. The second visit occurred at the University of Iceland where participant performed cognitive tasks and returned the accelerometer (Fig. 2B).

The study was conducted in agreement with the guidance provided in the Declaration of Helsinki and the National Bioethics Committee and the Icelandic Data Protection Authority approved the study (Study number: VSNb2015020013/13.07). Written informed consent was obtained from participants or guardians of underage participants.

Sleep measures. Participants were asked to wear a small (3.8 cm × 3.7 cm × 1.8 cm), lightweight (27 g) accelerometer (model GT3X+, Actigraph Inc., Pensacola FL) on their non-dominant wrist for one entire week. Tri-axial accelerometer data recorded at 80 samples/second was subsequently filtered and aggregated into one-minute activity counts with Actilife software version 6.13.0 (Actigraph Inc., Pensacola, FL, USA). Periods of sixty or more consecutive minutes of zero counts on all axes were identified as non-wear by customized programs in Matlab version R2016B (Mathworks Inc., Natick, MA). Each night was considered valid if the device was worn for ≥ 14 h from 12 to 12 noon the next day and the longest detected sleep period beginning within that interval was analysed. As detailed previously[23], to make full use of software-based editing functions, nightly sleep periods and awakenings were first detected in the Actilife software with the Sadeh algorithm validated for adolescents[61]. Each software-detected rise- and bedtime was then visually confirmed or adjusted by two trained scorers, using participant daily sleep diaries only when necessary and available. The total rest time, total sleep time, sleep efficiency, and WASO were computed for each night of sleep. Weekly averages of all sleep parameters and the weekly variability of rest and sleep duration were computed and used in regression analyses for participants with valid data on ≥ 3 weeknights (Sunday-Thursday) and ≥ 1 weekend night (Friday, Saturday, and nights prior to school holidays), based on guidelines presented in a recent systematic review of standards for accelerometer data collection[62] and in concordance with the criteria used in our previous analyses[23,25,63].

Cognitive measures. Short-term working memory and visual attention were assessed with previously validated software-based tasks in E-prime 2.0 (standard version, Psychology Software Tools, Inc., Pittsburgh, PA). Tasks were administered on a 13.3″ laptop computer in a quiet corner while wearing noise-cancelling headphones. Before each task, participants were given verbal instructions and provided with a short practice session to make sure they understood the instructions. Response time and response accuracy, the proportion of correct responses were the outcome measure for each stimulus category[28,29,64]. Erroneous responses consisted of commission errors (i.e. wrong button pushed) and omission errors (incorrect rejections and responses provided ≤ 149 ms after target appearance)[29].

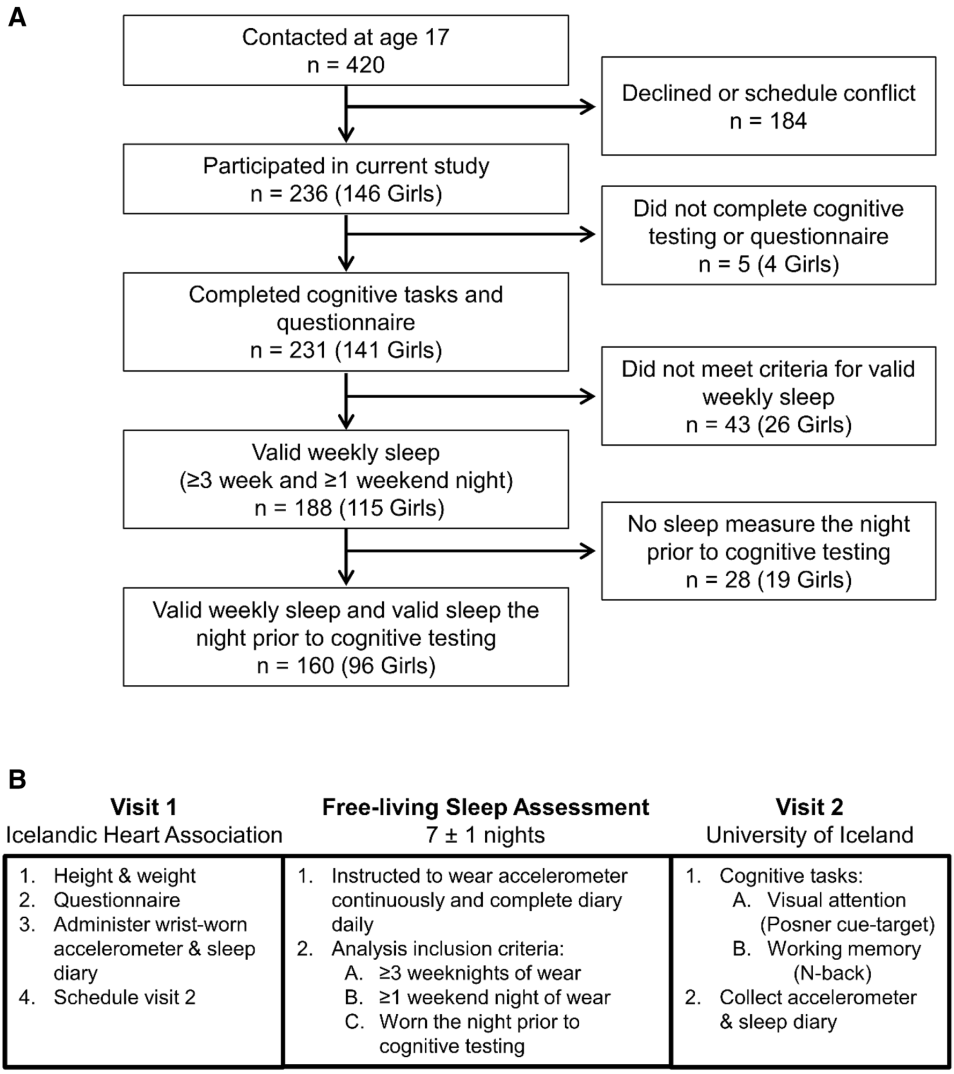

Figure 2. (**A**) Participant flowchart. (**B**) Schematic representation of the study procedure.

Short-term memory task. A numeric-based version of the n-back task was used to assess short-term working memory (Fig. 3A). Participants were instructed to quickly and accurately press the spacebar if the current digit was the same as the one presented n positions back in the sequence, where n varied from 1–3, with higher numbers representing greater working memory load. Each digit was presented for 500 ms with an interstimuli-interval of 1000 ms. The task was comprised of three sessions with the working memory load condition increasing from 1-back to 3-back[65]. Sixty-three digits were presented for each session with ten correct answers.

Visual attention task. Visual attention was evaluated using a Posner cue-target paradigm task[26–28] with a predetermined sequence of three possible cue presentations: "valid cue", "invalid cue", and "no cue" (Fig. 3B). Each stimulus was presented for 500 ms with interstimuli-intervals between 600 and 1400 ms. A total of 336 target stimuli were presented, 224 (67%) with a valid cue, 56 (17%) with an invalid cue, and 56 (17%) with no cue[29]. The sequence and timing of cue and target stimulus presentations were the same for all participants.

Covariates. Participants self-reported videogame use and presence or absence of a clinical diagnosis of ADHD on the questionnaire during the initial visit. Videogame use was reported using a seven-point scale with the following response options presented separately for weekdays and weekends: 1 = "none", 2 = "about ½ h", 3 = "1 up to 2 h", 4 = "2 up to 3 h", 5 = "3 up to 4 h", 6 = "4 to 5 h" and 7 = "more than 5 h". A weighted average was

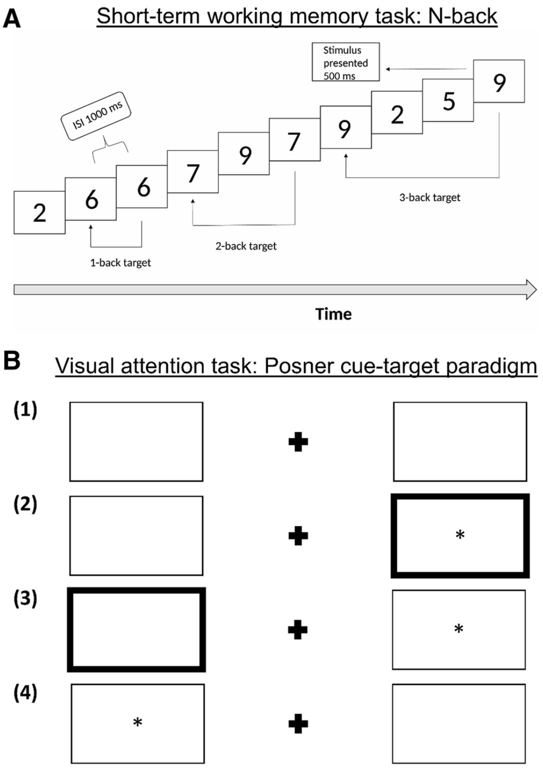

Figure 3. Schematic representation of the cognitive tasks. (**A**) The N-back task for working short-term memory. Sixty-three digits were presented one at a time for each session of one working memory load condition, which varied from 1-back (least difficult) to 3-back (most difficult). Each stimulus was presented for 500 ms with an inter-stimulus-interval of 1000 ms. (**B**) The Posner cue target task for visual attention. (1) Screen appearance prior to cue presentation and stimulus appearance—central cross with rectangles to the right and left. (2) Valid cue presentation—borders thicken (cue) prior to target stimulus appearance inside the rectangle. (3) Invalid cue presentation—target stimulus appears opposite to cue rectangle. (4) No cue presentation prior to target stimulus appearance.

computed from the weekday and weekend responses using the midpoints of each response category or 0.5 h/day for the "about half an hour" response option and 5.5 h/day for the "more than 5 h" response option (only four participants selected this response). Participants reported clinical diagnosis of ADHD by answering yes or no to the question "Have you been clinically diagnosed with ADHD?".

Statistical analyses. The distributions of all variables were examined for normality to determine whether transformations were needed prior to the use of parametric statistics. Response times, response accuracies, sleep efficiency, and the weekly variability in rest and sleep duration all had asymmetric, non-normal distributions and are reported as median ± interquartile range. All other variables are reported as mean ± standard deviation. Correlations between response times and response accuracies were assessed using the non-parametric Spearman method. Prior to outlier detection and regression analyses, log-transformation was applied to response time variables and the variability in rest and sleep duration and arcsine transformation (i.e. arc-sine of the square root of the proportion variable) was applied to response accuracies and sleep efficiencies. Values that exceeded 3 standard deviations above or below the mean were considered outliers and excluded. Mixed-effect models with post hoc tests with Bonferroni correction for multiple comparisons were performed to evaluate differences in transformed response times and response accuracy across stimuli on the visual attention task and across cognitive load on the working memory task. Linear regression models adjusted for baseline cognitive responses (i.e. 1-back or valid cue response time or accuracy), clinical diagnosis of ADHD, and time spent playing video games were used to assess associations between sleep parameters and cognitive task performance, with results reported as standardized β with 95% confidence intervals. Two sets of regression analyses were performed, the first with sleep parameters from the night prior to cognitive testing as predictor variables and the second with average weekly sleep parameters and sleep variability parameters as predictor variables. Categorical analyses were adjusted for baseline cognitive responses, clinical diagnosis of ADHD, and reported weekly video game use. *p* values less than 0.05 were considered significant unless otherwise stated. Analyses were conducted using R (v3.4.2, https://www.r-project.org/) and GraphPad Prism (v7, La Jolla, CA).

Data availability

Datasets for the current study are available from the corresponding author upon reasonable request.

Received: 25 June 2020; Accepted: 15 September 2020

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Acknowledgements

We would like to thank Randi Stebbins of the University of the Iceland Writing Centre for manuscript editing assistance and Hans Haraldsson for statistical assistance, the participants and staff at participating schools, and the master's students and researchers involved in the data collection. The Icelandic Centre for Research (RANNIS) (Grant No. 152509-051) and the University of Iceland Research Fund provided primary financial support for this project. KYC and RJB were funded by the National Institute of Diabetes and Digestive and Kidney Diseases intramural research program (Z01 DK071013 and Z01 DK071014). The study was performed at the University of Iceland in Reykjavik, Iceland.

Author contributions

R.S. and R.J.B. drafted the manuscript. H.G., S.L.G., K.Y.C., and E.J. designed the research. R.S., H.G., V.R., and S.G. acquired the data. R.S., A.S.L., and R.J.B. analysed the data. K.Y.C. and E.J. edited the manuscript. All authors reviewed and have approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41598-020-73774-x.

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Appendix A: Supplementary tables from paper 1

Table A1. Comparison of baseline (age 15) measurements of included participants and participants who refused or had incomplete follow-up (age 17) data.

Valid repeated measurements at age 17	No	Yes	p-value
Demographics			
Number of participants, N (% Female)	151 (54.3%)	145 (63.4%)	0.14
Age, years	15.9 ± 0.4	15.9 ± 0.3	0.78
Parent with university degree, N (%)	110 (72.8%)	102 (70.3%)	0.73
Organized sports participation, N (%)	104 (68.9%)	101 (69.7%)	0.98
National English exam[a,b]	31.8 ± 10.1	34.2 ± 8.8	**0.04**
National Icelandic exam[a,c]	32.6 ± 10.6	34.8 ± 8.7	0.06
National mathematics exam[a,d]	30.5 ± 10.3	34.5 ± 8.8	**0.001**
Body Composition			
Height, cm	171.8 ± 8.1	171.5 ± 8.1	0.76
Weight, kg	64.8 ± 10.7	64.7 ± 11.7	0.93
Body mass index, kg/m2	21.9 ± 2.8	22.0 ± 3.5	0.82
Body mass index, z-score	0.6 ± 0.8	0.5 ± 0.9	0.68
Body fat, %	25.1 ± 8.3	25.5 ± 9.3	0.63
School night sleep and activity[e]			
Time in bed, h/day	6.99 ± 0.83	7.06 ± 0.76	0.50
Total sleep time, h/day	7.35 ± 0.93	7.33 ± 1.25	0.84
Bed time, clock time ± min	00:26 ± 59.45	00:20 ± 47.46	0.34
Mid-sleep time, clock time ± min	03:58 ± 45.73	03:52 ± 36.13	0.25
Rise time, clock time ± min	07:30 ± 44.48	07:25 ± 37.40	0.28
WASO, min/night	51.48 ± 20.46	48.50 ± 21.52	0.25
Awakenings, number/night	18.80 ± 5.55	18.19 ± 5.35	0.36
Sleep efficiency, %	87.54 ± 4.38	88.37 ± 4.36	0.12
Time in Bed Variability, min	62.86 ± 53.49	51.61 ± 34.80	**0.046**
Sleep time Variability, min	58.24 ± 47.46	47.34 ± 28.65	**0.03**
Bed time Variability, min	47.21 ± 34.08	44.97 ± 33.26	0.59
Rise time Variability, min	41.45 ± 49.24	38.76 ± 40.82	0.63
Activity, counts/wear min/day	2191 ± 480	2207 ± 529	0.79
Wear time, h/day	23.69 ± 0.50	23.79 ± 0.31	0.07
Valid Nights, N	4.57 ± 0.64	4.61 ± 0.60	0.65
Non-school night sleep and activity[e]			
Time in bed, h/day	8.46 ± 1.07	8.33 ± 1.36	0.37
Total sleep time, h/day	6.12 ± 0.75	6.23 ± 0.66	0.21
Bed time, clock time ± min	01:49 ± 77.85	01:36 ± 70.65	0.15
Mid-sleep time, clock time ± min	06:04 ± 75.44	05:49 ± 64.02	0.09
Rise time, clock time ± min	10:20 ± 84.16	10:04 ± 76.74	0.11
WASO, min/night	65.25 ± 25.49	59.56 ± 28.01	0.08
Awakenings, number/night	23.99 ± 7.29	21.94 ± 8.07	**0.03**
Sleep Efficiency, %	86.99 ± 4.43	88.01 ± 4.99	0.08
Activity, counts/wear min/day	1768 ± 502	1796 ± 556	0.66
Wear time, h/day	23.86 ± 0.69	23.84 ± 0.74	0.81
Valid Nights, N	2.45 ± 0.70	2.50 ± 0.60	0.58

Results in mean ± standard deviation; WASO = minutes of wakening after sleep onset; [a]Nationally normalized (mean = 30, standard deviation = 10, maximum score = 60); National test score available for: [b]131 (55.7% Female) No, 129 (62.0% Female) Yes; [c]128 (54.7% Female) No, 129 (63.6% Female) Yes; [d]128 (55.5% Female) No, 126 (61.1% Female) Yes; [e]Participants with valid sleep and activity data: 124 (54.8% Female) No, 145 (63.4 % Female) Yes

Table A2. Characteristics and sleep on school days and non-school days at age 15 and 17 of students attending traditional and college-style schedule schools at age 17.

	Traditional Schedule (N=61, 77% Female)			College-Style Schedule (N=84, 53.6% Female)			Traditional Vs College-style	
	15y old	17y old	p (15 vs 17)	15y old	17y old	p (15 vs 17)	p (15y)	p (17y)
Characteristics								
Parent with university degree, N (%)		47 (77%)			56 (67%)			0.24
Organized sports participation, N (%)	48 (79%)	31 (51%)	**<0.001**	53 (63%)	37 (44%)	**0.005**	0.1	1.0
National English exam^{a,b,c}	35.76 ± 8.09			33.09 ± 9.19			0.14	
National Icelandic exam^{a,b,d}	38.69 ± 7.85			31.97 ± 8.22			**<0.001**	
National mathematics exam^{a,b,e}	38.25 ± 7.67			31.63 ± 8.56			**<0.001**	
School Nights								
Time in bed, h/day	7.2 ± 0.7	6.7 ± 0.8	**<0.001**	7.0 ± 0.8	6.9 ± 0.9	1.0	0.3	0.9
Mid-sleep time, clock time ± min	03:42 ± 31.8	03:54 ± 40.4	0.2	03:59 ± 37.6	04:38 ± 60.4	**<0.001**	0.1	**<0.001**
WASO, min/night	47.7 ± 18.7	45.0 ± 17.4	1.0	49.1 ± 23.4	50.3 ± 23.4	1.0	1.0	0.5
Awakenings, number/night	18.5 ± 4.7	17.2 ± 4.5	0.2	18.0 ± 5.8	18.4 ± 6.2	1.0	1.0	0.8
Sleep efficiency, %	88.7 ± 3.8	88.6 ± 4.3	1.0	88.1 ± 4.7	87.5 ± 5.2	0.8	1.0	0.6
Time in bed variability, min	47.4 ± 36.0	65.8 ± 48.9	**0.04**	54.7 ± 33.8	84.7 ± 45.1	**<0.001**	0.9	**0.02**
Sleep time variability, min	44.8 ± 31.4	57.5 ± 42.4	0.2	49.2 ± 26.5	77.2 ± 42.7	**<0.001**	1.0	**0.002**
Bed time variability, min	40.6 ± 32.5	41.8 ± 26.1	1.00	48.2 ± 33.6	53.8 ± 26.2	0.7	0.7	0.11
Rise time variability, min	27.7 ± 21.6	42.3 ± 37.5	0.2	46.8 ± 49.0	67.3 ± 44.6	**0.003**	**0.02**	**0.001**
Recorded nights, N	4.7 ± 0.6	5.3 ± 0.7	**<0.001**	4.7 ± 0.6	5.3 ± 0.7	**<0.001**	1.0	1.0
Valid nights, N	4.7 ± 0.6	5.2 ± 0.8	**<0.001**	4.6 ± 0.6	5.2 ± 0.8	**<0.001**	1.0	1.0
Invalid nights, N	0.03 ± 0.26	0.02 ± 0.15	0.6	0.08 ± 0.38	0.07 ± 0.26	0.5	1.0	1.0
Non-school Nights								
Time in bed, h/day	8.4 ± 1.2	7.8 ± 1.2	0.053	8.3 ± 1.5	7.8 ± 1.4	**0.01**	1.0	1.0
Mid-sleep time, clock time ± min	05:31 ± 59.1	06:08 ± 70.6	**0.003**	06:03 ± 64.4	06:27 ± 83.3	**0.04**	**0.04**	0.6
WASO, min	58.87 ± 25.7	50.0 ± 20.1	0.1	60.1 ± 29.7	54.8 ± 27.5	0.5	1.0	1.0
Awakenings, number/night	22.2 ± 7.6	19.6 ± 6.4	0.1	21.8 ± 8.5	20.8 ± 8.0	1.0	1.0	1.0
Sleep efficiency, %	88.2 ± 4.7	88.8 ± 4.6	1.0	87.9 ± 5.2	88.2 ± 5.1	1.0	1.0	1.0
Recorded nights, N	2.6 ± 0.6	2.0 ± 0.3	**<0.001**	2.5 ± 0.6	2.0 ± 0.3	**<0.001**	0.4	1.0
Valid nights, N	2.6 ± 0.7	2.0 ± 0.3	**<0.001**	2.5 ± 0.6	2.0 ± 0.4	**<0.001**	0.9	1.0
Invalid nights, N	0.02 ± 0.13	0.02 ± 0.13	1.0	0.02 ± 0.15	0.04 ± 0.19	1.0	0.9	1.0

Results are means ± standard deviation; All comparisons corrected for sex, parental education, and multiple comparisons; WASO = minutes of wakening after sleep onset; [a]Nationally normalized (mean = 30, standard deviation = 10, maximum score = 60); National test scores available for: [b]55 traditional schedule students (13 boys, 42 girls), [c]74 college-style schedule students (36 boys, 38 girls), [d]74 college-style schedule students (34 boys, 40 girls), [e]71 college-style schedule students (36 boys, 35 girls).

Appendix B: Supplementary tables from paper 2

Table B1. Participant characteristics and national exam scores by sex.

	All (n=253)	**Boys (n=103)**	**Girls (n=150)**	***P*-value**
Age (years)	15.9 ± 0.3	15.8 ± 0.3	15.9 ± 0.3	0.2
Height (cm)	171.5 ± 8.1	178.3 ± 6.2	166.8 ± 5.6	**<0.001**
Weight (kg)	64.8 ± 11.2	68.9 ± 11.5	62.0 ± 10.2	**<0.001**
Body mass index (kg/m^2)	22.0 ± 3.2	21.6 ± 3.2	22.2 ± 3.1	0.1
Parent with university degree, N (%)	178 (70.4)	74 (71.8)	104 (69.3)	0.8
English exam score[a]	32.9 ± 9.4	32.2 ± 9.8	33.4 ± 9.2	0.3
Icelandic exam score[b]	33.6 ± 9.5	31.7 ± 9.2	34.9 ± 9.6	**0.01**
Mathematics exam score[c]	32.6 ± 9.9	32.7 ± 9.3	32.5 ± 10.4	0.9
Average exam score[d]	33.1 ± 8.6	32.3 ± 8.3	33.7 ± 8.8	0.2

Results presented as mean ± standard deviation. *P*-values are the result of t-tests comparing boys and girls. Boldface type indicates significant differences. [a]N=243 (100 boys,143 girls); [b]N=248 (101 boys, 147 girls); [c]N=247 (99 boys, 148 girls); [d]N=236 (97 boys, 139 girls).

Table B2. Comparison of participants with and without complete data

	Complete data (n=253)	**Incomplete data (n=62)**	***P*-value**
Female, N (%)	150 (59.3)	33 (53.2)	0.5
Age (years)	15.9 ± 0.3	15.8 ± 0.4	0.4
Height (cm)	171.5 ± 8.1	172.2 ± 7.7	0.5
Weight (kg)	64.8 ± 11.2	65.2 ± 10.9	0.8
Body mass index (kg/m^2)	22.0 ± 3.2	22.0 ± 3.2	0.98
Parent with university degree, N (%)	178 (70.4)	37 (59.7)	0.1
Participants with exam scores but invalid sleep data, N (% Female)		20 (55)	
English exam score[a]	32.9 ± 9.4	33.4 ± 10.1	0.8
Icelandic exam score[b]	32.6 ± 9.9	31.2 ± 7.2	0.4
Mathematics exam score[c]	33.6 ± 9.5	33.6 ± 11.9	0.99
Average exam score[d]	33.1 ± 8.6	33.1 ± 8.8	0.99
Participants with valid sleep data but no exam scores, N (% Female)		25 (68)	
Rise time (clock time ± min)[e]	08:20 ± 57.6	08:14 ± 49.0	0.5
Mid-sleep time (clock time ± min)[e]	04:31 ± 56.2	04:34 ± 73.4	0.8
Bedtime (clock time ± min)	00:49 ± 51.8	00:48 ± 61.9	0.9
Time in bed (h/night)	7.5 ± 0.7	7.4 ± 0.8	0.4
Total sleep time (h/night)	6.6 ± 0.7	6.4 ± 0.6	0.2
Sleep efficiency (%)[e]	88.1 ± 5.3	88.3 ± 4.9	0.7
Wakening after sleep onset (min)[e]	52.4 ± 25.0	51.4 ± 27.2	0.8
Total sleep time variability (h)[e]	1.2 ± 0.7	1.1 ± 0.8	0.6

Results presented as mean ± standard deviation unless otherwise noted; . [a]N=243 complete vs. 20 incomplete; [b]N=248 complete vs. 19 incomplete; [c]N=247 complete vs 20 incomplete; [d]N=236 complete vs. 19 incomplete. [e]Results presented as median ± interquartile range due to skewed distribution; *P*-values are the result of comparisons between participants with and without complete data with t-tests for normally distributed variables and Mann-Whitney tests for skewed variables.

Table B3. Results of multiple linear regression analyses between sleep parameters and national standardized exam scores in three topics for all participants and separately for boys and girls.

	All* β [95% CI] (*p*)	**Boys** β [95% CI] (*p*)	**Girls** β [95% CI] (*p*)
Bedtime			
English score	-0.03 [-0.15, 0.09] (0.6)	-0.14 [-0.34, 0.06] (0.2)	0.02 [-0.13, 0.18] (0.8)
Icelandic score	-0.16 [-0.28, -0.05] (**0.01**)	-0.21 [-0.40, -0.02] (**0.03**)	-0.14 [-0.29, 0.01] (0.1)
Mathematics score	-0.20 [-0.32, -0.08] (**0.001**)	-0.35 [-0.54, -0.16] (**<0.001**)	-0.11 [-0.27, 0.05] (0.2)
Total sleep time			
English score	0.05 [-0.08, 0.17] (0.4)	0.06 [-0.15, 0.27] (0.6)	0.03 [-0.13, 0.19] (0.7)
Icelandic score	0.14 [0.03, 0.26] (**0.02**)	0.19 [-0.01, 0.39] (0.06)	0.11 [-0.05, 0.26] (0.2)
Mathematics score	0.03 [-0.10, 0.15] (0.7)	0.10 [-0.11, 0.31] (0.4)	-0.02 [-0.18, 0.15] (0.8)
Wakening after sleep onset			
English score	0.02 [-0.10, 0.14] (0.7)	0.12 [-0.07, 0.31] (0.2)	-0.06 [-0.21, 0.10] (0.5)
Icelandic score	0.01 [-0.11, 0.12] (0.9)	0.01 [-0.18, 0.19] (0.96)	0.01 [-0.15, 0.16] (0.9)
Mathematics score	0.03 [-0.09, 0.15] (0.6)	0.11 [-0.09, 0.30] (0.3)	-0.02 [-0.18, 0.15] (0.8)
Sleep efficiency			
English score	-0.001 [-0.12, 0.12] (0.99)	-0.11 [-0.31, 0.08] (0.2)	0.07 [-0.09, 0.23] (0.4)
Icelandic score	0.02 [-0.09, 0.13] (0.7)	-0.01 [-0.19, 0.18] (0.95)	0.03 [-0.12, 0.19] (0.7)
Mathematics score	-0.01 [-0.13, 0.11] (0.9)	-0.07 [-0.26, 0.13] (0.5)	0.02 [-0.15, 0.18] (0.8)
Total sleep time variability			
English score	-0.05 [-0.17, 0.07] (0.4)	-0.05 [-0.25, 0.14] (0.6)	-0.05 [-0.21, 0.10] (0.5)
Icelandic score	-0.19 [-0.30, -0.07] (**0.001**)	-0.19 [-0.37, -0.001] (**0.049**)	-0.19 [-0.34, -0.04] (**0.01**)
Mathematics score	-0.22 [-0.34, -0.10] (**<0.001**)	-0.23 [-0.42, -0.03] (**0.024**)	-0.23 [-0.38, -0.07] (**0.01**)
Social jetlag			
English score	0.06 [-0.06, 0.18] (0.3)	0.14 [-0.06, 0.33] (0.2)	-0.03 [-0.19, 0.12] (0.7)
Icelandic score	0.10 [-0.01, 0.21] (0.1)	0.24 [0.06, 0.43] (**0.01**)	-0.10 [-0.25, 0.05] (0.2)
Mathematics score	-0.003 [-0.12, 0.12] (0.97)	0.10 [-0.10, 0.30] (0.3)	-0.14 [-0.30, 0.02] (0.1)

β, standardized beta value; CI, confidence interval; All regressions adjusted for school and parental education. *Additionally adjusted for sex. Wakening after sleep onset, sleep efficiency, and total sleep time variability were transformed prior to analysis due to skewed distributions. Boldface type indicates a significant relationship based on the Benjamini–Hochberg critical value of $p \leq 0.049$.

Table B4. Results of multiple linear regression analyses between national standardized exam scores averaged over all topics and sleep parameters measured on school nights and non-school nights.

	All Participants* β [95% CI] (*p*)	**Boys** β [95% CI] (*p*)	**Girls** β [95% CI] (*p*)
School Nights			
Bedtime	-0.20 [-0.32, -0.08] (**0.005**)	-0.32 [-0.51, -0.14] (**0.004**)	-0.13 [-0.29, 0.03] (0.5)
Total sleep time	0.15 [0.03, 0.27] (0.06)	0.12 [-0.08, 0.31] (0.99)	0.19 [0.03, 0.34] (0.1)
Wakening after sleep onset	0.05 [-0.07, 0.17] (0.99)	0.12 [-0.07, 0.31] (0.99)	0.13 [-0.15, 0.18] (0.99)
Sleep efficiency	-0.005 [-0.12, 0.11] (0.99)	-0.08 [-0.28, 0.11] (0.99)	0.05 [-0.11, 0.21] (0.99)
Total sleep time variability	-0.05 [-0.17, 0.07] (0.99)	-0.10 [-0.30, 0.10] (0.99)	-0.02 [-0.18, 0.15] (0.99)
Non-school Nights			
Bedtime	-0.08 [-0.20, 0.04] (0.8)	-0.14 [-0.34, 0.07] (0.7)	-0.05 [-0.20, 0.11] (0.99)
Total sleep time	-0.04 [-0.16, 0.09] (0.99)	0.10 [-0.11, 0.32] (0.99)	-0.16 [-0.32, -0.001] (0.2)
Wakening after sleep onset	-0.04 [-0.16, 0.09] (0.99)	-0.04 [-0.24, 0.16] (0.99)	-0.02 [-0.18, 0.14] (0.99)
Sleep efficiency	-0.0003 [-0.12, 0.12] (0.99)	0.01 [-0.19, 0.20] (0.99)	-0.02 [-0.18, 0.14] (0.99)

β, standardized beta value; CI, confidence interval; All regressions adjusted for school and parental education. *Additionally adjusted for sex. Wakening after sleep onset, sleep efficiency, and total sleep time variability were transformed prior to analysis due to skewed distributions. P-values adjusted for multiple comparisons. Boldface type indicates a significant relationship.

Appendix C: Supplementary tables from paper 3

Table C1. Characteristics for participants with valid weekly sleep and valid sleep measured the night prior to cognitive testing.

Characteristics	Mean ± standard deviation or N (%)
N (% Female)	160 (60.0%)
Age (y)	17.7 ± 0.3
Weight (kg)	68.7 ± 13.4
Height (cm)	173.9 ± 9.1
Body mass index (kg/m^2)	22.7 ± 3.9
Videogame use (h/day)	0.8 ± 1.1
Clinical diagnosis of ADHD (N, %)	7 (4.3%)

ADHD, attention deficit hyperactivity disorder

Table C2. Correlation matrix for response times and accuracies on the short-term working memory task.

	1-Back Response Time rho (*p*)	**2-Back Response Time** rho (*p*)	**3-Back Response Time** rho (*p*)	**1-Back Response Accuracy** rho (*p*)	**2-Back Response Accuracy** rho (*p*)	**3-Back Response Accuracy** rho (*p*)
1-Back Response Time	1.0 (1.0)	**0.44 (< 0.001)**	**0.21 (0.01)**	-0.09 (0.3)	-0.15 (0.06)	-0.11 (0.2)
2-Back Response Time	**0.44 (< 0.001)**	1.0 (1.0)	**0.37 (< 0.001**)	-0.02 (0.8)	-0.09 (0.3)	-0.08 (0.3)
3-Back Response Time	**0.21 (0.01)**	**0.37 (< 0.001)**	1.0 (1.0)	-0.08 (0.3)	-0.08 (0.3)	**-0.16 (0.049)**
1-Back Response Accuracy	-0.09 (0.3)	-0.02 (0.8)	-0.08 (0.3)	1.0 (1.0)	0.15 (0.07)	0.10 (0.2)
2-Back Response Accuracy	-0.15 (0.06)	-0.09 (0.3)	-0.08 (0.3)	0.15 (0.07)	1.0 (1.0)	**0.19 (0.02)**
3-Back Response Accuracy	-0.11 (0.2)	-0.08 (0.3)	**-0.16 (0.049)**	0.10 (0.2)	**0.19 (0.02)**	1.0 (1.0)

Correlations were assessed using the non-parametric Spearman method. Boldface type indicates significant correlation.

Table C3. Correlation matrix for response times and accuracies on the visual attention task.

	Valid Cue Response Time rho (*p*)	**Invalid Cue Response Time** rho (*p*)	**No Cue Response Time** rho (*p*)	**Valid Cue Response Accuracy** rho (*p*)	**Invalid Cue Response Accuracy** rho (*p*)	**No Cue Response Accuracy** rho (*p*)
Valid Cue Response Time	1.0 (1.0)	**0.81 (< 0.001)**	**0.81 (< 0.001)**	0.12 (0.1)	**0.18 (0.03)**	**-0.53 (< 0.001)**
Invalid Cue Response Time	**0.81 (< 0.001)**	1.0 (1.0)	**0.75 (< 0.001)**	-0.02 (0.8)	-0.01 (0.9)	**-0.56 (< 0.001)**
No Cue Response Time	**0.81 (< 0.001)**	**0.75 (< 0.001)**	1.0 (1.0)	0.06 (0.5)	0.06 (0.5)	**-0.59 (< 0.001)**
Valid Cue Response Accuracy	0.12 (0.1)	-0.02 (0.8)	0.06 (0.5)	1.0 (1.0)	**0.74 (< 0.001)**	**0.25 (0.002)**
Invalid Cue Response Accuracy	**0.18 (0.03)**	-0.01 (0.9)	0.06 (0.5)	**0.74 (< 0.001)**	1.0 (1.0)	**0.21 (0.01)**
No Cue Response Accuracy	**-0.53 (< 0.001)**	**-0.56 (< 0.001)**	**-0.59 (< 0.001)**	**0.25 (0.002)**	**0.21 (0.01)**	1.0 (1.0)

Correlations were assessed using the non-parametric Spearman method. Boldface type indicates significant correlation.

Table C4. Working memory task performance for participants with less than seven hours of total rest time compared those with more than seven hours total rest time.

	Total rest time ≤ 7h Median ± IQR	**Total rest time > 7h Median ± IQR**	***p*-value**
Sleep measures of the night prior to short-term memory task			
n	82	78	
2-Back response time (ms)	505.80 ± 130.33	523.44 ± 117.90	0.7
2-Back response accuracy (proportion correct)	0.94 ± 0.06	0.95 ± 0.06	0.7
3-Back response time (ms)	**551.67 ± 148.06**	**514.46 ± 138.21**	**0.04**
3-Back response accuracy (proportion correct)	0.87 ± 0.08	0.86 ± 0.08	0.9
Weekly sleep measures			
n	66	94	
2-Back response time (ms)	517.00 ± 114.45	523.44 ± 131.28	0.8
2-Back response accuracy (proportion correct)	0.95 ± 0.06	0.95 ± 0.06	0.6
3-Back response time (ms)	**570.32 ± 135.72**	**511.29 ± 143.71**	**0.03**
3-Back response accuracy (proportion correct)	0.86 ± 0.08	0.87 ± 0.06	0.2

All comparisons adjusted for clinical diagnosis of attention deficit hyperactivity disorder and reported weekly video game use. 2-back and 3-back response time additionally adjusted for 1-back response times. 2-back and 3-back response accuracy additionally adjusted for 1-back response accuracy. Response times and accuracies were transformed prior to analysis due to skewed distributions. IQR, inter-quartile range.

Table C5. Visual attention task performance for participants with less than seven hours of total rest time compared those with more than seven hours total rest time.

	Total rest time ≤ 7h Median ± IQR	**Total rest time > 7h Median ± IQR**	***p*-value**
Sleep measures of the night prior to short-term memory task			
n	78	82	
Invalid cue response time (ms)	356.82 ± 37.16	363.48 ± 44.96	0.3
Invalid cue accuracy (proportion correct)	0.91 ± 0.11	0.91 ± 0.09	0.8
No cue response time (ms)	383.87 ± 38.87	391.66 ± 45.44	0.7
No cue response accuracy (proportion correct)		0.96 ± 0.04 0.96 ± 0.04	0.5
Weekly sleep measures			
n	66	94	
Invalid cue response time (ms)	358.62 ± 41.60	361.37 ± 39.12	0.99
Invalid cue accuracy (proportion correct)	0.89 ± 0.11	0.91 ± 0.07	0.7
No cue response time (ms)	387.68 ± 44.17	385.71 ± 48.87	0.8
No cue response accuracy (proportion correct)	0.96 ± 0.04	0.96 ± 0.04	0.4

All comparisons adjusted for clinical diagnosis of attention deficit hyperactivity disorder and reported weekly video game use. Invalid cue and no cue response time additionally adjusted for valid cue response times. Invalid cue and no cue response accuracy additionally adjusted for valid cue response accuracy. Response times and accuracies were transformed prior to analysis due to skewed distributions. IQR, inter-quartile range.