Investigating the Influence of Sleep Behaviours on Cognitive Performance and Aging

Mahshid Sadr

A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Interdisciplinary Health Sciences

Interdisciplinary School of Health Sciences
Faculty of Health Sciences
University of Ottawa

ABSTRACT

Background: Cognitive reserve (CR) has been associated with better cognitive performance, yet it remains unclear whether sleep behaviours, a lifestyle factor, can serve as a proxy for cognitive reserve. This study aims to identify whether sleep behaviours influence the relationship between brain structure and cognitive performance in the same way in healthy younger and older groups.

Materials and Methods: This study included 81 participants: 41 in the younger group (18–30 years) and 40 in the older group (60+ years). Sleep behaviours were evaluated using self-reported questionnaires, cognitive performance was measured through a neuro-behavioural battery, and brain volume was obtained using MRI scans. Linear modelling examined the moderating effects of sleep behaviours on brain-cognitive performance relationships across age groups.

Results: This study revealed age-related differences in how average sleep hours influence the relationship between brain structure and cognitive performance. Specifically, the interaction between age, sleep behaviours, and brain regions illustrates that sleep serves as a mechanism of cognitive reserve.

Conclusion: Age-specific sleep behaviours influence the relationship between brain structure and cognitive performance. Personalized interventions related to sleep hygiene can enhance cognitive performance in the younger and older groups, potentially mitigating age-related cognitive decline.

Keywords: Cognitive Reserve, Sleep, Brain Structure, Aging, MRI, Cognitive Performance

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor, Dr. Jason Steffener. Your guidance has been invaluable in helping me understand the intricacies of the materials and collected data and master the techniques needed for effective data analysis. I am especially thankful for your advice on focusing on each step of the research process, which has enhanced my learning and allowed me to truly enjoy and appreciate my studies. The knowledge and skills I gained under your supervision have prepared me for the next stages of my academic and professional journey.

I also sincerely thank my committee members, Dr. Stuart Fogel and Dr. Angeliki Tsapanou, for their constructive feedback and steadfast support, particularly during my thesis proposal defence. Your insights and encouragement have significantly contributed to the success of my research.

To my family and friends, thank you for standing by me through the highs and lows of this journey. Your unwavering support, kind words, and love have been my greatest source of strength. A special note of gratitude goes to my husband, Mohsen, whose encouragement has motivated me through this degree's most challenging moments. Thank you for believing in my dreams and being my anchor whenever I needed it the most.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BIC	Brain Imaging Centre
BM	Brain Maintenance
BR	Brain Reserve
CARP	Canadian Association of Retired Persons
CCHS	Canadian Community Health Survey
CLSA	Canadian Longitudinal Study on Aging
CR	Cognitive Reserve
DF	Degrees of Freedom
GLM	General Linear Model
MEMPRAGE	Multi-echo Magnetization Prepared Rapid Acquisition Gradient Echo
MoCA	Montreal Cognitive Assessment
MRI	Magnetic Resonance Imaging
MR-PET	Magnetic Resonance Positron Emission Tomography
ms	Milliseconds
ROIs	Regions of Interest(s)
ROMHC	Royal Ottawa Mental Health Centre
SD	Standard Deviation
SRT	Selective Reminding Test
SWS	Slow-Wave Sleep
TR	Repetition time

CHAPTER 1: INTRODUCTION

Background

Across the globe, the population of older individuals is significantly increasing (Government of Canada & Canada, 2019). This demographic shift is important because aging is characterized by cumulative damage at the cellular and molecular levels over time (Harman & Martín, 2020). Such damage gradually reduces physical and mental capacities, heightening susceptibility to various diseases (Harman, 2003). It has been emphasized that while life expectancy has increased, the additional years are often characterized by poor health and disability (Vos et al., 2020). Despite advances in medicine and public health measures, there is a scarcity of evidence demonstrating that increasing longevity is accompanied by an extended period of good health (Beard et al., 2016).

Cognitive decline is a common consequence of aging, characterized by diminished performance in tasks requiring quick information processing (Murman, 2015). This decline affects an individual's ability to perform everyday tasks and reduces quality of life and independence, often leading to increased reliance on caregivers (Cheng et al., 2024). Furthermore, cognitive decline is closely linked to the development of neurodegenerative diseases such as Alzheimer's, which have profound personal, social, and economic consequences (Lipnicki et al., 2017). The decline in cognitive abilities with age underscores the importance of better understanding the factors influencing this change and exploring potential interventions to promote cognitive health and improve quality of life in later life.

Although everyone undergoes the aging process, there is considerable variability in cognitive aging trajectories (Cabeza et al., 2018; Salthouse, 1996). Some individuals perform

better than others, contributing to significant differences (Steffener & Stern, 2012). It is important to explore how lifestyle factors impact cognitive performance and why some individuals display greater resilience to the effects of aging or diseases. Understanding these dynamics can inform policies and interventions to improve cognitive health and support aging populations.

Numerous studies have been conducted in cognitive neuroscience to understand the neural mechanisms underlying age-related cognitive decline and optimal aging (Cabeza et al., 2018). Various molecular, cellular, and network mechanisms contribute to age-related changes, offering explanations through genetic, cellular, and systems analyses (Stern et al., 2020). For example, synaptic plasticity at the network level is crucial for memory formation and cognitive performance, and age-related declines in plasticity have been linked to cognitive impairments (Burke & Barnes, 2006). Observations of cognitive resilience, where individuals maintain cognitive performance despite diseases or physical damage, have led researchers to introduce various terms to better understand and investigate these complex processes (Stern et al., 2020).

A key concept that helps explain the differences between an individual's cognition, function, or clinical status relative to age/disease-related changes in brain measures is 'reserve' (Stern et al., 2020). Reserve includes several models: Cognitive Reserve (CR), Brain Reserve (BR), and Brain Maintenance (BM) (Cabeza et al., 2018). Each of these models suggests different mechanisms, such as structural changes in the brain, optimized cognitive functioning, maintenance of brain health, and reorganization of neural pathways, to explain how the brain can maintain cognitive performance despite the influences of aging, dementia, or brain injuries (Cabeza et al., 2018).

Cognitive Reserve

Cognitive reserve (CR) is the brain's capacity to perform cognitively better than expected, considering life-course-related brain changes, injuries, or diseases (Katzman et al., 1988; Stern, 2002; Stern et al., 2020). CR should be viewed as a cumulative enhancement resulting from genetic and/or environmental factors that bolster the use of neural resources, thereby mitigating the impact of neural declines caused by aging or age-related diseases (Stern, 2009). Cognitive reserve (CR) describes the phenomenon where some individuals exhibit partial protection against the negative impacts of age-related neural changes (Stern, 2002, 2009). This protection can be shaped by the interplay of inherent factors, such as in utero or genetically determined individual differences, and exposures throughout one's lifetime (Stern et al., 2020). That is why cognitive reserve (CR) is often referred to as an 'active' model, as its dynamic nature allows the threshold for functional decline to be flexible and influenced by experiences rather than being strictly determined by quantitative brain measures (Barulli & Stern, 2013). Education is a pivotal factor in fostering cognitive reserve, with higher levels linked to improved cognitive performance through enhanced cognitive strategies and efficiency, which may mitigate age-related neural declines (Wilson et al., 2019). Several additional indicators are considered reserve proxies, including occupational attainment, engagement in leisure activities, and social interaction (Harrison et al., 2015). Studies have also investigated the role of sleep on memory, cognitive performance, and overall cognitive health, underscoring the critical importance of evaluating sleep behaviours concerning cognitive performance (Alhola & Polo-Kantola, 2007; Zijlmans et al., 2023; Khan & Al-Jahdali, 2023). Consequently, the current study focuses on sleep behaviours, considering their potential influence in mitigating age-related cognitive changes in later stages of life.

Brain Reserve

Brain reserve (BR) refers to neurobiological capital, encompassing factors such as the number of neurons and synapses (Mortimer, 1997; Neth et al., 2019; Stern et al., 2020). It suggests that variations in the structural characteristics of the brain enable certain individuals to navigate brain aging and pathology more effectively than others, delaying the onset of clinical or cognitive changes (Neth et al., 2019). Brain reserve is considered a fixed construct at any given moment, representing the neurobiological capital available during that specific period (Stern et al., 2020). BR is considered a passive model of the brain, as functional impairment becomes inevitable once a specific ratio of pathological quantity to brain quantity is reached (Barulli & Stern, 2013; Cavedo et al., 2012; Christensen et al., 2007; Stern, 2002).

The difference between Cognitive Reserve (CR) and Brain Reserve (BR) is that BR refers to the brain's structural capacity to withstand damage. In contrast, CR involves the brain's ability to maintain cognitive function through adaptive and efficient use of cognitive processes developed over a lifetime despite the presence of neurological damage (Groot et al., 2018; Harrison et al., 2015).

Furthermore, cognitive reserve (CR) and brain reserve (BR) may contribute to the overall level of reserves, helping the brain's ability to reduce the impacts of pathology (Stern et al., 2019). CR is dynamic and influenced by life experiences, such as education, occupation, and cognitive activities, allowing individuals to adapt and compensate for brain changes (Barulli & Stern, 2013). In contrast, BR is relatively static, providing a stable but limited buffer against neurological damage after its peak development (Barulli & Stern, 2013). Although CR and BR play a role in resilience against cognitive decline, understanding how they interact is still unclear.

Therefore, more research is needed to explore how CR and BR work together to help maintain cognitive health.

Brain Maintenance

Brain maintenance refers to preserving neural resources, including the ongoing repair and replenishment of the brain in response to cellular and molecular damage (Nyberg et al., 2012). BM continues throughout life but becomes more crucial in old age as the brain faces increased pressures from the aging process (Cabeza et al., 2018). Brain maintenance is the process that minimizes the vulnerability of the brain to various aging processes. Various factors contribute to effective brain maintenance, such as genetics, early-life experiences, and diverse life experiences (Cabeza et al., 2018; Stern et al., 2020). These protective factors collectively support the brain's ability to sustain cognitive performance and reduce or prevent age- and disease-related changes in the brain (Yaffe et al., 2009).

The concepts of cognitive reserve and brain maintenance share a connection, but it is essential to highlight their distinctions (Alvares Pereira et al., 2022). While both involve enhancing the brain’s ability to perform better, the reserve concept explains why some individuals have better cognitive performance while facing brain pathology (Nyberg et al., 2012). In contrast, brain maintenance focuses on conditions that promote the preservation of neurochemical, structural, and functional brain integrity in old age (Nyberg et al., 2012). This preservation influences neural mechanisms related to repair and plasticity, helping to maintain brain health and cognitive performance as people age (Burke & Barnes, 2006).

The concepts of cognitive reserve, brain reserve, and brain maintenance are not separate or isolated topics. Instead, they are interconnected and collectively contribute to the maintenance of cognitive performance throughout aging. These three concepts are also related to individual differences. When individual differences, such as years of education, influence the relationships between age, brain, and cognitive performance, they are considered indicators of reserve and resilience.

Identifying factors contributing to enhanced cognitive performance through reserve and resilience in healthy aging is essential (Kondo et al., 2021). Understanding these factors is crucial for developing targeted interventions to mitigate cognitive decline, improve quality of life, and reduce the societal burden of age-related cognitive impairments (Sindi et al., 2017). Numerous lifestyle factors, such as education, physical activity, and social engagement, have been positively associated with reserve and resilience, enhancing overall cognitive performance (Kondo et al., 2021). While some lifestyle factors are well-established as influencing age-related changes in cognitive performance, the specific role of sleep as a lifestyle factor remains somewhat uncertain (Lo et al., 2016).

Sleep

Sleep is a vital physiological process intricately linked to various aspects of health and well-being, including cognitive performance across the lifespan (Hirshkowitz et al., 2015; Medic et al., 2017). As people age, their sleep behaviours typically shift, resulting in shorter total sleep time, more frequent awakenings at night, and less deep sleep (Gulia & Kumar, 2018; Li et al., 2018).

In a recent study, approximately half of the older group reported difficulty sleeping (Qin et al., 2023), with nearly half facing at least one sleep-related problem (Lo et al., 2016). Younger individuals are also not immune to sleep-related cognitive effects, as insufficient sleep, often due to academic, social, or work-related demands, can negatively impact cognitive performance (Carpenter et al., 2023). Research done by Lim and Dinges (2010) suggests that even short-term sleep deprivation in young individuals can impair cognitive performance similar to the effects observed in aging populations (Lim & Dinges, 2010). Evidence strongly supports the connection between non-optimal sleep behaviours and a heightened risk of cognitive impairment (Wang et al., 2021).

Sleep is a biologically essential behaviour that plays a crucial role in neural restoration, synaptic plasticity, and the consolidation of cognitive processes, particularly those associated with memory and attention (Diekelmann & Born, 2010; Rasch & Born, 2013). Sleep behaviours change with age, characterized by reduced total sleep time, increased nighttime awakenings, decreased slow-wave sleep (SWS), and lower sleep efficiency (Gulia & Kumar, 2018). These age-related changes are not merely peripheral disturbances but have been strongly linked to structural brain changes (Spira et al., 2016). Specifically, poor sleep quality and shorter sleep duration have been associated with reduced grey matter volume in regions vital for memory, such as the hippocampus (Sexton et al., 2014; Takeuchi et al., 2018). The hippocampus, in particular, appears to be highly sensitive to sleep-related changes; diminished SWS has been shown to impair hippocampal-dependent memory consolidation and accelerate neural atrophy (Rasch & Born, 2013).

Age-related sleep changes, particularly in adults aged 60 and above, have important implications for cognitive performance compared to younger adults in their 20s (Scullin &

Bliwise, 2015). In older adults, aging is typically associated with reduced total sleep time, lower sleep efficiency, and diminished slow-wave sleep, all of which contribute to declines in cognitive performance, such as memory function (Djonlagic et al., 2021; Gildner et al., 2014). In contrast, while younger adults generally experience more restorative and consolidated sleep, they are still vulnerable to cognitive impairments when exposed to short-term or chronic sleep deprivation (Lo et al., 2016). Sleep deprivation—even for just one night—has been linked to reductions in attention, working memory, and decision-making accuracy in young adults (Killgore, 2010; Lo et al., 2016), suggesting that cognitive functions are susceptible to even temporary sleep loss.

Epidemiological research indicates that maintaining healthy sleep habits can significantly decelerate the cognitive aging processes (Meng et al., 2023). The connection between sleep disturbances and cognitive impairment raises concerns about the potential effects of sleep behaviours on cognitive performance, particularly in later stages of life. This period of heightened vulnerability to cognitive decline underscores the importance of understanding how non-optimal sleep behaviours may accelerate these changes, making it essential to identify modifiable risk factors early on (Spira et al., 2014). Understanding the mechanisms underlying the relationship between sleep and its effect on cognitive performance is important for developing interventions to mitigate cognitive decline. Addressing potential risk factors such as sleep disturbances early in the preclinical stage may delay or reduce the onset of cognitive impairment and its associated burdens on individuals and society (Gebara & Karp, 2020).

While cognitive reserve (CR) has been associated with life-long exposures such as education and occupational complexity, emerging evidence suggests that modifiable lifestyle behaviours—particularly sleep—may also affect brain health and cognitive performance across the lifespan (Alhola & Polo-Kantola, 2007; Zijlmans et al., 2023; Khan & Al-Jahdali, 2023).

Sleep supports synaptic plasticity and memory consolidation (Diekelmann & Born, 2010; Rasch & Born, 2013), and poor sleep quality has been linked to reduced hippocampal volume and impaired cognitive performance (Fjell et al., 2019; Spira et al., 2016). Although sleep is not yet a recognized CR proxy, its effects on both brain structure and cognition parallel those of established CR factors such as education. Given the age-related changes in sleep behaviours and the sensitivity of key brain regions like the hippocampus and amygdala to sleep behaviours, it is plausible that sleep behaviours may act as a reserve proxy by supporting brain-cognition relationships across different age groups. Therefore, this study explores whether average sleep hours can function as a proxy of cognitive reserve by moderating the relationship between brain structure and cognitive performance in younger and older groups.

Objective

This study aims to investigate whether sleep behaviours influence relationships between brain structure and cognitive performance in the same way in the younger and older groups. The specific aim is to examine whether average sleep hours influence the relationship between hippocampal/amygdala volume and memory, speed/attention, vocabulary, and working memory performance in the same way in healthy younger (18-30) and older (60+) groups. Results have the potential to highlight sleep as a proxy for cognitive reserve.

The conceptual model (Figure 1) underscores the exploratory nature of the current study, illustrating potential interactions among age, brain structure, cognitive reserve—represented by sleep as its proxy—and cognitive performance outcomes. In Figure 1, **Arrow "a"** represents the influence of sleep behaviour on the relationship between brain structure and cognitive

performance, reflecting cognitive reserve. **Arrow "b"** illustrates the influence of age on this moderating relationship.

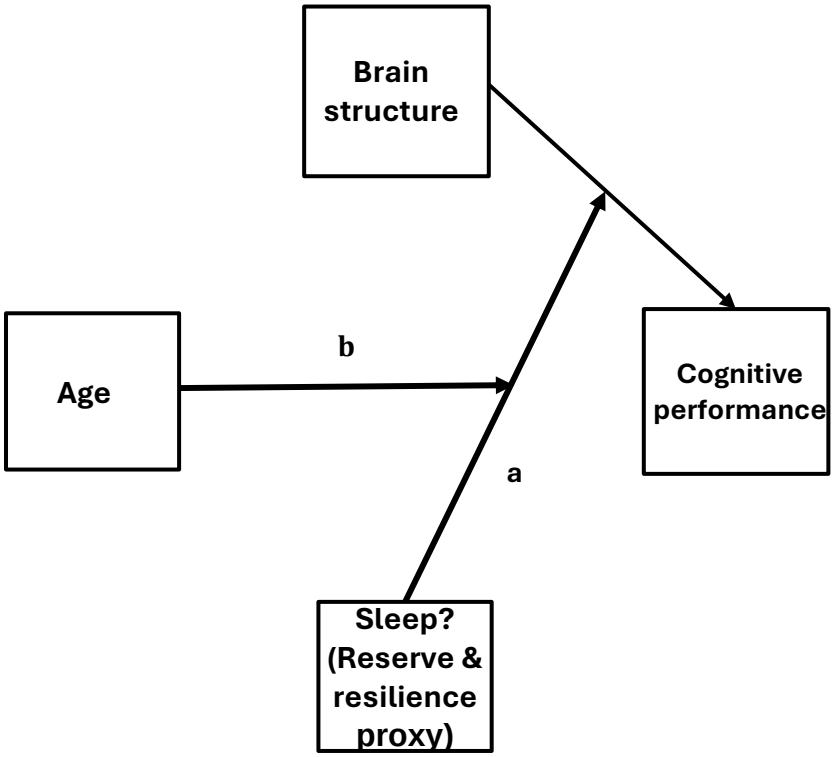

Figure 1. Conceptual Framework of Age, Brain structure, and Cognitive performance, and Sleep as a reserve and resilience proxy. The role of arrow 'a' reflects how the relationship between brain structure and cognitive performance varies across different sleep behaviours. Arrow 'b' reflects whether the potential moderating role of sleep behaviours is the same in the younger and older groups. In statistical terms, this figure represents a three-way interaction between age, brain structure, and sleep behaviours in predicting cognitive outcomes.

Research Question

Does sleep affect the relationship between brain structure and cognitive performance in the same manner in healthy younger and older groups?

Hypothesis

The effect of sleep on brain-cognition relationships differs between age groups. More specifically, Average sleep hours affect the relationship between hippocampal/amygdala volume and memory, speed/attention, vocabulary and working memory performance. This effect differs between healthy younger (18-30) vs. older (60+) groups.

Study Design

This study investigates sleep behaviours as a potential proxy for cognitive reserve by analyzing the relationships among age, brain structure, and sleep behaviours in predicting cognitive performance.

This study analyses five specific brain regions of interest (ROIs): the hippocampus, caudate, amygdala, pallidum, and putamen. These regions were selected based on results from a whole-brain analysis, which identified them as showing statistically significant associations with cognitive reserve (CR) measures (Steffener et al., 2014). In addition to their empirical relationship with CR in the current dataset, these regions are supported by prior literature linking them to key cognitive and neural functions relevant to cognitive aging and reserve (Hilal et al., 2015; Tang et al., 2015). The hippocampus plays a central role in memory and learning (Packard & Teather, 1998; Alahmadi, 2023); the caudate and putamen are involved in motor control and executive function (Packard & Cahill, 2001; Hamann & Mao, 2002); the pallidum contributes to motor regulation (Lissoni et al., 2020); and the amygdala is critically involved in emotional processing and attention (Packard & Cahill, 2001; Lissoni et al., 2020). These regions also undergo structural changes across the lifespan, making them relevant targets for investigating age-related neural differences (Narvacan et al., 2017). Average sleep hours were selected among all sleep behaviours as the primary sleep measure due to their completeness and continuous

scale, which enhances statistical power and interpretability for modelling three-way interactions (age × brain × sleep). Both age and average sleep hours influence hippocampal and amygdala volume, resulting in cognitive performance outcomes (Spira et al., 2016; Lim & Dinges, 2010; Yaffe et al., 2014), suggesting that sleep plays a role in the brain-cognition relationship in the context of healthy younger and older groups. By examining the three-way interactions between age, brain structure, and sleep when predicting cognitive performance, this study tests whether sleep can serve as a proxy of cognitive reserve. Only two regions, the hippocampus and amygdala, are discussed in detail; however, the caudate, pallidum, and putamen analysis is included in the supplementary materials for reference.

CHAPTER 2: METHODS

Quantitative data were collected through questionnaires, cognitive measures, and MRI scans to investigate the influence of sleep behaviours on cognitive performance and aging. This interdisciplinary study, integrating methods and theories from health sciences, psychology, and neuroscience, was conducted under the supervision of Dr. Jason Steffener and his research team.

Participant

Participants for this study were recruited from a younger group aged 18 to 30 years and an older group aged 60 years and above. Recruitment methods for the younger group included posting flyers around the university campus, utilizing social media platforms, presenting the study briefly in classes with the professor's permission, and leaving flyers in classrooms for interested individuals. Recruitment for the older group involved posting flyers at community centers, libraries, and retirement homes. Additionally, contact was made with the Canadian Association of Retired Persons (CARP).

Eligibility criteria

Adults aged 18 to 30 (younger group) and 60 and above (older group) were recruited for this study. All participants had normal or corrected-to-normal vision and no past or current neurological disorders.

Initial Inclusion Screening Questionnaire

A brief 2-minute screening was conducted to determine eligibility based on key inclusion criteria. Participants were asked about their age range. They were required to have either English or French as their maternal or primary language. Additionally, they needed to possess normal or

corrected-to-normal vision and hearing (including using glasses, contact lenses, or corrective surgery) and have no history of neurological disorders, such as lupus.

Inclusion/Exclusion criteria

The exclusion criteria for all participants were the presence of a neurological disorder likely to affect cognitive function, and participants with hearing loss who do not own hearing aids.

Standard MRI exclusion criteria were also applied, including no implantable devices (e.g., pacemaker, defibrillator, cochlear implant, aneurysm clips), no metal in the body, non-pregnant or breastfeeding participants, and no claustrophobia.

No exclusion criteria were applied based on sleep behaviour.

Eligible participants underwent several key steps: First, they provided informed consent and performed cognitive evaluation during their first visit to the lab. Second, they filled out behavioural questionnaires at home. Finally, structural and functional MRI scans were collected during their visit to the imaging center.

Measurements

Cognitive Measures

Participants completed a computerized neuro-behavioural battery, available at the following link: https://github.com/NCMlab/CognitiveTasks. This battery includes the following cognitive domains: **Memory** assessed with the Selective Reminding Task for immediate, delayed recall, and delayed recognition (Buschke & Fuld, 1974); **Speed/Attention** - assessed with a Pattern Comparison task (Salthouse & Babcock, 1991); **Executive Function** - assessed with the Stroop Tasks for colour, word, and colour/word interference; **Fluid Intelligence** - assessed with the

Matrix Reasoning task (Raven, 1962) and the Wisconsin Card Sorting Test (Bowden et al. 1998); **Vocabulary** - assessed with a Synonyms task (Salthouse, 1993) and the National Adult Reading Test (Nelson & O'Connell, 1978); and finally **Working Memory** - assessed with Verbal Delayed Match-to-Sample task (Sternberg, 1966) and Spatial Delayed Match-to-Sample task (Nagel et al., 2009; Park et al., 2002), and Forward and Backward Digit Span tasks (Richardson, 2007).

While the computerized neuro-behavioural battery included various cognitive-related assessments, the following variables were prioritized as key indicators of cognitive performance due to their potential links to CR.

Memory: Memory was assessed using the Selective Reminding Task (SRT), which includes three sub-scores: total recall, delayed recall, and delayed recognition (Buschke & Fuld, 1974). In this task, participants are read a list of 12 words and asked to recall them over six trials. Words not recalled are selectively reminded before subsequent attempts. SRT-total is the cumulative number of recalled words (maximum score: 72), SRT-delayed recall measures correctly recalled words after a 15-minute delay, and SRT-delayed recognition assesses correct identification of words among distractors.

Speed/Attention: Speed and attention were assessed using the Pattern Comparison Task. Participants are presented with pairs of visual patterns and must determine whether they are identical or different (Salthouse & Babcock, 1991).

Vocabulary: The Antonym Task was designed to assess participants' word knowledge by requiring them to identify the opposite of a given word or the word that is most different in meaning. As Salthouse (1991) outlined, this task measures participants' ability to comprehend and recognize relationships between words (Salthouse, 1991). The task was implemented as a

challenging multiple-choice test, with the proportion of correct responses as the primary dependent variable. This test provided insight into higher-level language processing, emphasizing the participants' capability to process and retrieve vocabulary knowledge effectively under standardized conditions.

Working Memory: Working memory was evaluated using two tasks. The first was the Digit Span Forward Capacity assesses short-term memory and working memory by requiring participants to recall sequences of digits in the same order as presented (Wechsler, 1981). The second task was the Verbal Delayed Matching to Sample assessed using a staircase protocol to identify someone’s capacity or span (Sternberg, 1966).

Sleep Measures

A self-reported questionnaire was used to assess the impact of sleep behaviours on cognitive performance. This assessment included the Sleep Self-reported Questionnaire from the Canadian Community Health Survey (CCHS) (Dai et al., 2020) and the Canadian Longitudinal Study on Aging (CLSA) (Nicholson et al., 2020), chosen for their proven reliability and validity. These questionnaires cover various aspects of sleep, such as duration, quality, disturbances, and perceived effects.

While the questionnaire included various sleep-related questions, the following variable (as detailed in Table 1) was seen as key indicator of sleep behaviour used for describing the sample. The complete sleep questionnaire is provided in the supplementary materials for reference.

Table 1. Selected sleep variable and its description

Variable Name	Question Text	Answer Options	Range/Notes
Sleep Average Hours (SlpAvgHours)	During the past month, on average, how many hours of actual sleep did you get at night?	Integer number	0–24 hours

Abreviations: Slp = Sleep; Avg = Average

MRI Data Acquisition

MRI Data Collection Parameters

All neuroimaging used the 3T Siemens Biograph mMR MR-PET scanner at the Brain Imaging Centre (BIC) at the Royal Ottawa Mental Health Centre (ROMHC). Participants wore protective earplugs during the scans and held a squeeze ball they could activate if they felt uncomfortable and wished to terminate the scan.

Structural MRI

A T1-weighted multi-echo magnetization prepared rapid acquisition gradient echo (MEMPRAGE) image was acquired sagittally (TR = 2530ms; TE 1/2/3/4 = 1.69/3.55/5.41/7.27ms; flip angle = 7°; 1mm isotropic resolution; 192 slices; 256mm field of view, ipat (acceleration) = 2, with 32 ref lines and a non-selective inversion time of 1150 ms and 650 Hz/Px BW)—duration: 6:03 minutes (van der Kouwe et al., 2008).

All structural brain imaging data were analyzed using FreeSurfer (version 7.3.2), a software suite widely employed for the analysis and visualization of structural neuroimaging data, particularly MRI (Fischl, 2012). The accuracy of Freesurfer's subcortical segmentation and cortical parcellation (Fischl et al., 2002, 2004) has been reported to be comparable with manual labeling. FreeSurfer provides tools for automated brain segmentation, surface reconstruction, and

cortical thickness measurement, allowing for a detailed examination of the brain's anatomical structure (Fischl, 2012). In this study, the focus was on subcortical grey matter volumes. Analyses targeted the following regions of interest (ROIs): hippocampus, caudate, amygdala, pallidum, and putamen. The regional volumes were calculated by summing the two hemispheres and no correction for total brain volume was made due to the high confounding between total volume and age group, which was included in the model.

Statistical Analysis

Descriptive statistics summarized the sample characteristics, including demographics, sleep measures, cognitive performance, and brain regions. Independent sample T-tests compared mean differences in all variables between the age groups (younger vs. older). Linear regression models examined the moderating role of sleep in the relationship between brain structure and cognitive performance. The analysis predicted cognitive performance and the model included age group, brain region, and average sleep hours as predictors and their interactions. The three-way interaction among age group, brain region, and sleep tested the hypothesis that average sleep hours affect the relationship between the brain and cognitive performance measures differently for younger and older groups. The three-way interaction specifically tests whether the moderating role of sleep on brain-cognition relationships is the same between age groups. In other words, the three-way interaction tests whether sleep acts as a proxy of cognitive reserve and whether its role is the same between age groups.

Effect sizes are included in the results sections. The effect size ‘d’ refers to Cohen’s d which is a measure of the number of standard deviations difference there is between groups. The rules of thumb are that the effect size is considered small (d = 0.2), medium (d = 0.5), or large (d

≥ 0.8). The interaction terms use the partial eta-squared effect size measure (η^2_p). This is a measure of the proportion of variance that a predictor accounts for in the outcome variable after accounting for (partialling out) all other factors in the model. The rules of thumb are that η^2_p = 0.01 indicates a small effect, η^2_p = 0.06 indicates a medium effect, η^2_p = 0.14 indicates a large effect.

The statistical analysis of the data was conducted using the software Jamovi (version 2.3).

Research Ethics

The Royal Mental Health Institute and the University of Ottawa Research Ethics Board have approved this study. All research procedures adhered strictly to these institutions' guidelines.

CHAPTER 3: RESULTS

Participant

The study included 41 younger groups (mean age = 23.4 years, *SD* = 2.81) and 40 older groups (mean age = 73.5 years, *SD* = 6.63), see Table 2. There was no significant difference in the sex distribution between the two age groups, $\chi^2(1) = 0.26$, $p = 0.61$. The younger group consisted of 24 males and 17 females. In comparison, the older group comprised 25 males and 14 females. One participant in the older group did not specify their sex. The two age groups had comparable years of education, $t(77) = 1.30$, $p = 0.20$, $d = 0.29$. The younger groups reported an average of 15.5 years of education (*SD* = 1.38), whereas the older groups reported an average of 16.2 years (*SD* = 2.86). Two participants in the older group did not provide their years of education.

Table 2. Participant characteristics

Variables Name	**Younger Group** Mean(SD)	**Older Group** Mean(SD)	**Statistics** *t*(DF)=*t* value p, effect size (d)
Age	23.4 (2.81)	73.5 (6.63)	*t*(79.0)=44.5 p<.0001, d=9.89
Sex (M/F)	24/17	25/14	χ^2=0.26, p=0.61
Education	15.5 (1.38)	16.2 (2.86)	*t*(77.0)=1.30 p=0.20, d=0.29

Abbreviations: SD = standard deviation; DF = degrees of freedom

Although the focus of this work was on a subset of the sleep, brain, and cognitive measures, descriptives of all variables provide greater characterization of the sample. Table 3

presents the group comparisons for sleep variables between younger and older groups. Significant group differences were found for Sleep Fall Asleep Time, Sleep Leg Discomfort, and Sleep Act Dreams. For Fall Asleep Time, the younger group reported taking longer to fall asleep (M = 3.17, SD = 1.12, n = 41) compared to the older group (M = 2.33, SD = 1.25, n = 40), $t(79)$ = -3.22, p = 0.002, d = -0.72. For Sleep Leg Discomfort, the younger group reported more leg discomfort (M = 1.82, SD = 0.39, n = 40) compared to the older group (M = 1.50, SD = 0.51, n = 40), $t(78)$ = -3.23, p = 0.002, d = -0.72. One younger adult did not provide data for the Sleep Leg Discomfort question. Finally, Sleep Act Dreams were higher in the older group (M = 1.94, SD = 0.23, n = 36) compared to the younger group (M = 1.63, SD = 0.49, n = 38), $t(72)$ = 3.48, p = 0.0008, d = 0.81. Data are missing for three participants in the younger group and four in the older group, as they did not provide any responses to the Sleep Act Dreams question.

The analysis revealed no significant differences between the younger and the older group regarding Sleep Average Hours, Sleep Satisfaction, and Sleep Wake variables. The younger group reported longer Sleep Duration (M = 7.28, SD = 1.15, n = 40) compared to the older group (M = 6.85, SD = 1.12, n = 40), $t(78)$ = -1.67, p = 0.10, d = -0.37. One younger adult did not provide data for the Sleep Average Hours question. The younger group also reported higher Sleep Satisfaction (M = 2.90, SD = 1.01, n = 40) compared to the older group (M = 2.52, SD = 1.06, n = 40), $t(78)$ = -1.62, p = 0.11, d = -0.36, considering one younger adult did not report the sleep satisfaction question. In terms of Sleep Wake, the younger group reported lower wakefulness (M = 2.37, SD = 1.13, n = 41) compared to the older group (M = 2.77, SD = 1.23, n = 40), $t(79)$ = 1.56, p = 0.12, d = 0.35.

Table 3. Sleep Variables

Variables Name	**the younger group** Mean(SD)	**the older group** Mean(SD)	**Statistics** t(DF)=t value p, effect size (d)
Sleep Average Hours	7.28 (1.15) n=40	6.85 (1.12) n=40	*t*(78.0)=-1.67 p=0.10, d=-0.37
Sleep Satisfaction	2.90 (1.01) n=40	2.52 (1.06) n=40	*t*(78.0)=-1.62 p=0.11, d=-0.36
Sleep Fall Asleep	3.17 (1.12) n=41	2.33 (1.25) n=40	*t*(79.0)=-3.22 p=0.002, d=-0.72
Sleep Wake	2.37 (1.13) n=41	2.77 (1.23) n=40	*t*(79.0)=1.56 p=0.12, d=0.35
Sleep Leg Discomfort	1.82 (0.39) n=40	1.50 (0.51) n=40	*t*(78.0)=-3.23 p=0.002, d=-0.72
Sleep Act Dreams	1.63 (0.49) n=38	1.94 (0.23) n=36	*t*(72.0)=3.48 p=0.0008, d=0.81

Abbreviations: SD = standard deviation; DF = degrees of freedom

Table 4 compares brain volume across five regions between younger and older groups. The older group has smaller brain volumes across all regions compared to the younger group. MRI data for one participant were of poor quality and excluded from the analysis.

Hippocampus: The younger group (M = 8321, SD = 823) had significantly larger hippocampal volumes than the older group (M = 7362, SD = 689), $t(78) = -5.65$, $p < 0.0001$, $d = -1.26$.

Caudate: The younger group (M = 7653, SD = 1013) had significantly larger caudate volumes compared to the older group (M = 6592, SD = 1072), $t(78) = -4.55$, $p < 0.0001$, $d = -1.02$.

Amygdala: The younger group (M = 3585, SD = 466) had significantly larger amygdala volumes than the older group (M = 3211, SD = 475), $t(78) = -3.56$, $p = 0.0006$, $d = -0.80$.

Pallidum: The younger group (M = 4112, SD = 576) had significantly larger pallidum volumes than the older group (M = 3437, SD = 489), $t(78) = -5.66$, $p < 0.0001$, $d = -1.27$.

Putamen: The younger group (M = 10512, SD = 1386) had significantly larger putamen volumes than the older group (M = 8724, SD = 1293), $t(78) = -5.97$, $p < 0.0001$, $d = -1.33$.

Table 4. Brain Variables

Variables Name	**the younger group** Mean(SD, mm^3)	**the older group** Mean(SD, mm^3)	**Statistics** t(DF)=t value p, effect size (d)
Hippocampus volume	8321 (823) n=40	7362 (689) n=40	*t*(78.0)=-5.65 p<0.0001, d=-1.26
Caudate volume	7653 (1013) n=40	6592 (1072) n=40	*t*(78.0)=-4.55 p<0.0001, d=-1.02
Amygdala volume	3585 (466) n=40	3211 (475) n=40	*t*(78.0)=-3.56 p=0.0006, d=-0.80
Pallidum volume	4112 (576) n=40	3437 (489) n=40	*t*(78.0)=-5.66 p<0.0001, d=-1.27
Putamen volume	10,512 (1386) n=40	8724 (1293) n=40	*t*(78.0)=-5.97 p<0.0001, d=-1.33

Abbreviations: SD = standard deviation; mm^3 = cubic millimetres

Table 5 summarizes the results of cognitive performance tests, demonstrating age group differences across several cognitive tasks:

Selective reminding test (Immediate Total Recalled): The younger group had higher performance scores (M = 57.5 words, SD = 12.4, maximum possible score = 72) compared to the

older group (M = 49.5, SD = 10.8; $t(77) = -3.06$, $p = 0.003$, $d = -0.69$). Two participants in the older groups did not provide data for this test.

Selective reminding test (Delayed Recalled): The younger group had higher performance than the older group (M = 10.2 words, SD = 1.56 vs. M = 7.42, SD = 3.04; $t(77) = -5.21$, $p < 0.0001$, $d = -1.17$, maximum possible score = 12). Two participants in the older groups did not provide data for this test.

Pattern comparison accuracy (Load 03): The younger group had higher accuracy than the older group (M = 0.94; proportion of correct responses), SD = 0.06 vs. M = 0.82, SD = 0.13; $t(79) = -5.06$, $p < 0.0001$, $d = -1.12$).

Antonyms Task (Accuracy): The older group performed significantly better (M = 0.75, SD = 0.18) than the younger group (M = 0.43, SD = 0.18; $t(78) = 7.85$, $p < 0.0001$, $d = 1.76$). One older adult did not provide data for this test.

Other cognitive tasks did not reveal significant differences between age groups. These cognitive tasks include digit span forward capacity with (M = 6.94; number list length recalled), SD = 1.15 in the younger group vs. (M = 6.71; number list length recalled), SD = 0.87; $t(79) = -0.99$, $p = 0.32$, $d = -0.22$ in the older group. And delayed matching to sample (behavioural Capacity) with the younger group M = 7.22 (letters), SD = 0.95 vs. M = 7.07, SD = 1.03; $t(79) = -0.69$, $p = 0.49$, $d = -0.15$ in the older group.

Table 5. Cognitive Assessments

Variables Name	**the younger group** Mean(SD)	**the older group** Mean(SD)	**Statistics** t(DF)=t value p, effect size (d)
Selective Reminding Test (Immediate Total Recalled)	57.5 (12.4) n=41	49.5 (10.8) n=38	*t*(77.0)=-3.06 p=0.003, d=-0.69
Selective Reminding Test (Delyed_Recall)	10.2 (1.56) n=41	7.42 (3.04) n=38	*t*(77.0)=-5.21 p<0.0001, d=-1.17
Digit Span Forward Capacity	6.94 (1.15) n=41	6.71 (0.87) n=40	*t*(79.0)=-0.99 p=0.32, d=-0.22
Pattern comparison accuracy (Load 03)	0.94 (0.06) n=41	0.82 (0.13) n=40	*t*(79.0)=-5.06 p<0.0001, d=-1.12
Delayed matching to sample (Capacity)	7.22 (0.95) n=41	7.07 (1.03) n=40	*t*(79.0)=-0.69 p=0.49, d=-0.15
Antonyms Task (Accuracy)	0.43 (0.18) n=41	0.75 (0.18) n=39	*t*(78.0)=7.85 p<0.0001, d=1.76

Abbreviations: SD = standard deviation; DF = degrees of freedom

General Linear Model (GLM) Analyses

The following section highlights the significant three-way interactions (sleep × age × brain) found in the current study, specifically focusing on average sleep hours in two brain regions: the hippocampus and the amygdala.

Hippocampus

In the hippocampus, the Age × Brain × Sleep interaction effects were observed for Digit Span Forward Capacity ($t = -1.84$, $p = 0.07$, $\eta^2_p = 0.05$), Pattern Comparison Accuracy (Load 03) ($t = 1.72$, $p = 0.09$, $\eta^2_p = 0.04$), Selective Reminding Test (Immediate Total Recalled) ($t = 1.65$, $p = 0.10$, $\eta^2_p = 0.04$), and Selective Reminding Test (Delayed_Recall) ($t = 1.84$, $p = 0.07$, $\eta^2_p = 0.05$).

As shown in Figure 2, the three-way interaction between hippocampal volume, average sleep hours, and age group predicting Digit Span Forward Capacity showed that when average sleep hours were low (one standard deviation below the mean), the younger group exhibited a positive association between hippocampal volume and performance. In contrast, the older group displayed a negative association. When average sleep hours were high (one standard deviation above the mean), both age groups showed positive associations between hippocampal volume and cognitive performance. These findings support the study's hypothesis that sleep moderates the relationship between brain structure and working memory differently across age groups when average sleep hours is low.

This finding shows that low/high average sleep hours influence the hippocampus–working memory relationship differently. In older adults, the brain-cognition relationship changes from strongly negative at low average sleep hours to positive at high average sleep

hours. This finding demonstrates that the negative effect of low sleep hours on brain-cognition relationships diminishes with high sleep hours supporting the notion that sleep supports working memory performance by strengthening the brain–cognition relationship and acting as a proxy for cognitive reserve.

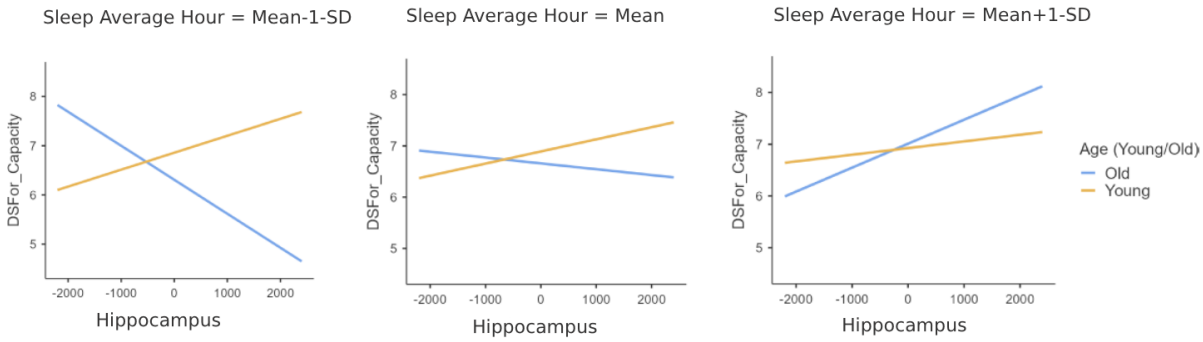

Figure 2. Interaction between Age (Young/Old), Hippocampus Volume, and Average Sleep Hours on Digit Span Forward Capacity (DSFor_Capacity), a measure of working memory

As shown in Figure 3, the three-way interaction between age group, hippocampal volume, and average sleep hours predicted accuracy for the highest level of complexity of the pattern comparison task. In the younger group, no relationship between hippocampal volume and accuracy was observed when average sleep hours were low (one standard deviation below the mean). However, when average sleep hours were high (one standard deviation above the mean), a positive relationship between hippocampal volume and accuracy was observed in the younger group. In the older group, a strong positive relationship was observed between hippocampal volume and accuracy when average sleep hours were low (one standard deviation below the mean). However, no relationship was observed between hippocampus and accuracy when average sleep hours were high (one standard deviation above the mean) in the older group.

This finding shows that sleep hours influence the hippocampus–speed/attention relationship differently. In the younger group, a positive brain–cognition relationship emerged only at high average sleep hours. In the older group, the strong positive brain–cognition relationship under low average sleep hours changed to a weak positive relationship at high average sleep hours. These brain-cognition relationship changes across average hours of sleep demonstrate that sleep acts as a proxy for cognitive reserve for a processing speed task.

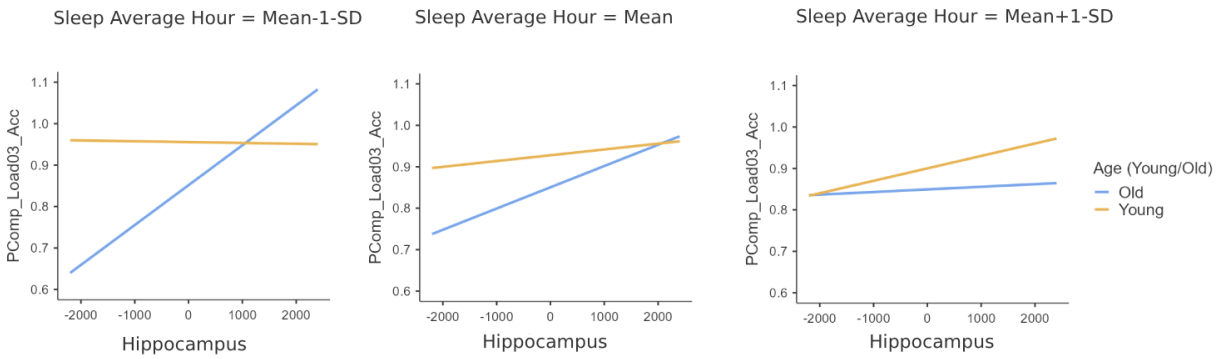

Figure 3. Interaction between Age (Young/Old), Hippocampal Volume, and Sleep Average Hours on Pattern Comparison Accuracy (Load 03) (PComp_Load03_Acc), a measure of speed/attention

As shown in Figure 4, the three-way interaction between age group, hippocampal volume, and average sleep hours predicted immediate recall memory performance (Selective Reminding Test (Immediate Total Recalled)). When average sleep hours were low, (one standard deviation below the mean) hippocampal volume and cognitive performance were positively associated for the older group. However, in high average sleep hours (one standard deviation above the mean), there was a negative relationship between hippocampus volume and performance on the Selective Reminding Test (Immediate Total Recalled). In the younger group,

a negative relationship between the hippocampus and performance on the Selective Reminding Test (Immediate Total Recalled) was observed when average sleep hours were low (one standard deviation below the mean). Conversely, when average sleep hours were high (one standard deviation above the mean), the hippocampus-cognition relationship reversed to a weak positive relationship.

This finding highlights age-specific effects of average sleep hours on brain-cognition relationships. The relationship between the hippocampus and memory is different between younger and older groups, regardless of whether they experience low or high average sleep conditions.

This finding shows that low and high average sleep hours influence the hippocampus–memory relationship differently. In the younger group, the hippocampus–memory relationship changed from negative at low average sleep hours to positive at high average sleep hours. In the older group, the strong positive brain-cognition relationship at low average sleep hours changed to a negative relationship at high average sleep hours. These brain-cognition relationship changes across low and high average sleep hours again support the idea that sleep acts as a proxy for cognitive reserve for an immediate recall memory task.

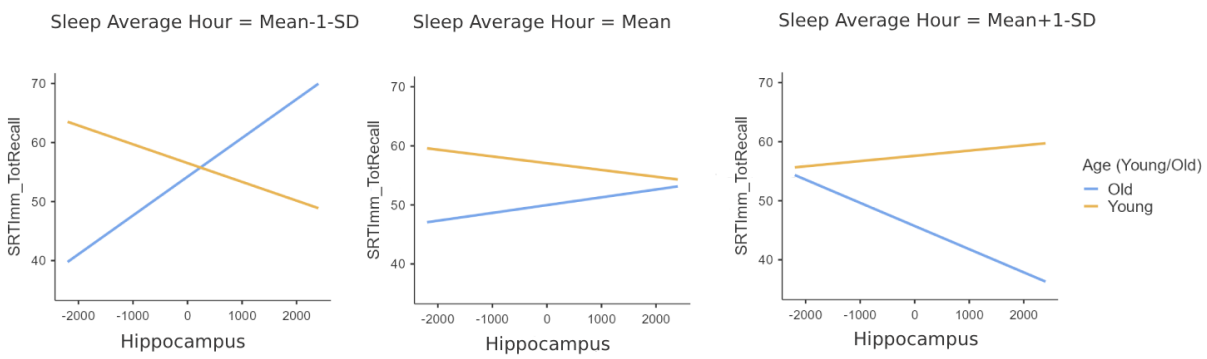

Figure 4. Interaction between Age (Young/Old), Hippocampus Volume, and Sleep Average Hours on Selective Reminding Test (Immediate Total Recalled) (SRTImm_TotRecall), a measure of memory

As shown in Figure 5, the three-way interaction between age group, hippocampal volume, and sleep average hours predicting delayed recall memory performance (Selective Reminding Test (Delayed Recalled)) showed that when sleep average hours were low (one standard deviation below the mean), there was a positive relationship between hippocampal volume and delayed recall performance for the older group. In high average sleep hours (one standard deviation above the mean), however, the hippocampus-cognition relationship was negative in the older group. In the younger group, when average sleep hours were low (one standard deviation below the mean), a negative relationship between hippocampal volume and Selective Reminding Test (Delayed Recalled) was observed. In high average sleep hours (one standard deviation above the mean), however, the hippocampus-cognition relationship was positive in the younger group.

This supports the study's hypothesis by demonstrating that sleep's moderating role varies by age group. The relationship between the hippocampus and memory is different between

younger and older groups, regardless of whether they experience low or high average sleep conditions. This finding highlights the age-specific effects of sleep on the brain-cognition relationship.

This finding shows that average sleep hours influence the hippocampus–memory relationship differently between age groups. In the younger group, the hippocampus–memory relationship varied from negative at low average sleep hours to positive at high average sleep hours. In the older group, the brain–cognition relationship was positive at low average sleep hours and negative at high average sleep hours. These brain-cognition relationship differences between age groups from low to high average sleep hours support the idea that sleep acts as a proxy for cognitive reserve whose effect differs between age groups for delayed memory performance.

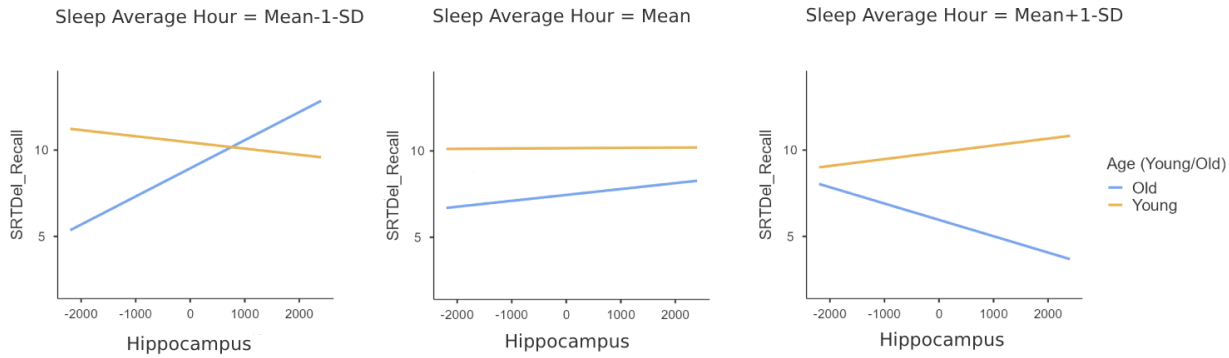

Figure 5. Interaction between Age (Young/Old), Hippocampus Volume, and Sleep Average Hours on Selective Reminding Test (Delyed_Recalled) (SRTDel_Recall), a measure of memory

Amygdala

In the amygdala, an Age × Brain × Sleep interaction was observed for Selective Reminding Test (Immediate Total Recalled) (t=2.53, p=0.01, η^2_p = 0.09), Antonyms Task (Accuracy) (t=2.52, p=0.01, η^2_p = 0.08), and Delayed Matching to Sample (Capacity) (t=1.77, p=0.08, η^2_p = 0.04).

As shown in Figure 6, the three-way interaction between age group, amygdala volume, and average sleep hours revealed that immediate recall memory performance, as measured by the Selective Reminding Test (Immediate Total Recalled), was significant. When average sleep hours were low (one standard deviation below the mean), the younger group exhibited a decrease in performance as amygdala volume increased. In contrast, the older group demonstrated an increase under the same conditions. When average sleep hours were high (one standard deviation above the mean), the younger group demonstrated increased recall performance with increasing amygdala volume. In contrast, the older group's performance decreased as amygdala volume increased.

This finding supports the study's hypothesis by demonstrating that sleep moderates the brain-cognition relationship differently between the age groups. The positive/negative amygdala–memory relationship between younger and older adults across both low and high-average sleep conditions emphasizes that sleep exerts distinct effects on memory-related brain function in each age group.

This finding shows that average sleep hours influence the amygdala–memory relationship differently between age groups. In the younger group, a negative brain-cognition relationship at low average sleep hours was positive at high average sleep hours. In the older group, the positive

amygdala–memory relationship at low sleep was negative at high average sleep hours. These changes in brain-cognition relationships across low and high average sleep hours support the idea that sleep acts as a proxy for cognitive reserve for immediate recall memory.

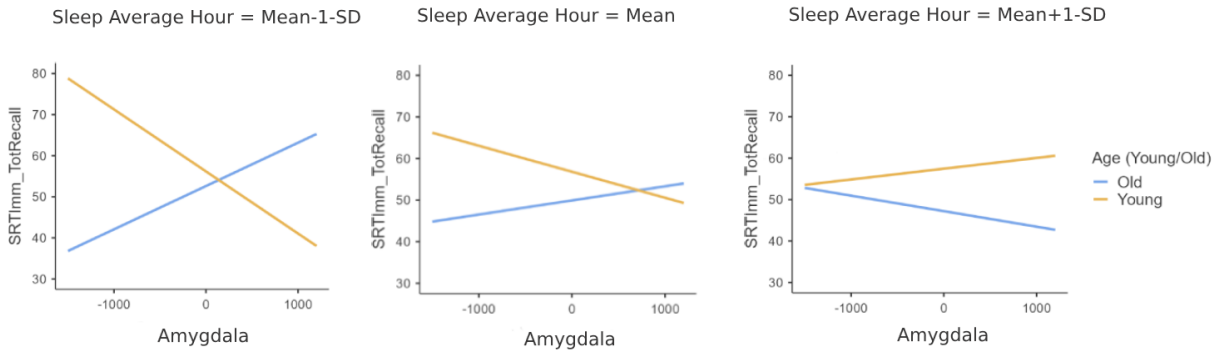

Figure 6. Interaction between Age (Young/Old), Amygdala Volume, and Sleep Average Hours on Selective Reminding Test (Immediate Total Recalled) (SRTImm_TotRecall), a measure of memory

As shown in Figure 7, the three-way interaction between age group, amygdala volume, and average sleep hours revealed that verbal accuracy, as measured by the Antonyms Task, increased for the older group with increasing amygdala volume under low average sleep hours (one standard deviation below the mean). In comparison, the younger group experienced a decrease in performance. When average sleep hours were high (one standard deviation above the mean), the younger group increased verbal accuracy with increasing amygdala volume. In contrast, the older group's performance slightly decreased.

This finding supports the study's hypothesis by illustrating that sleep's moderating effect on brain–cognition relationships differed between age groups. The amygdala–vocabulary relationship varies between younger and older groups depending on average sleep hours. When

average sleep hours were low, the relationship between amygdala-vocabulary accuracy was negative in the younger group but positive in the older group. This relationship supports the study's hypothesis that average hours of sleep affects the relationship between brain structure and cognitive performance, and that this moderating effect differs in age group.

This finding shows that average sleep hours influence the amygdala–vocabulary relationship differently between age groups. In the younger group, the strong negative brain–cognition relationship at low average sleep hours was positive at high average sleep hours. In the older group, the positive amygdala–vocabulary relationship at low sleep was only slightly negative at high average sleep hours. These age group differences in brain–cognition relationships across low and high average sleep hours support the idea that sleep acts as a proxy for cognitive reserve.

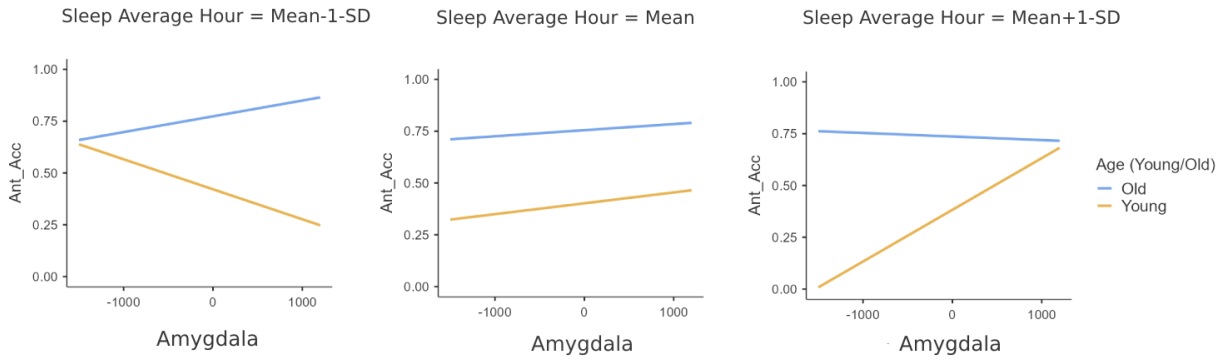

Figure 7. Interaction between Age (Young/Old), Amygdala Volume, and Sleep Average Hours on Antonyms Task (Accuracy) (Ant_Acc), a measure of vocabulary memory

As shown in Figure 8, the three-way interaction between age group, amygdala volume, and average sleep hours showed that working memory capacity, as measured by Delayed Matching to Sample, increased for the older group with increasing amygdala volume under low

average sleep hours (one standard deviation below the mean). In comparison, the younger group showed only a slight increase. When average sleep hours are high (one standard deviation above the mean), the older group exhibited a decrease in working memory capacity with increasing amygdala volume. At the same time, the younger group demonstrated an increase in performance.

This finding supports the study's hypothesis by showing that sleep moderates brain–cognition relationships differently across age groups. The positive/negative amygdala–working memory relationship varies between younger and older groups when average sleep hours is high.

The finding shows that average sleep hours influence the amygdala–working memory relationship differently between age groups. In the older group, the positive amygdala–working memory relationship at low average sleep hours was negative at high average sleep hours. This difference across sleep levels supports the idea that sleep influences brain–working memory relationships and acts as a proxy for cognitive reserve.

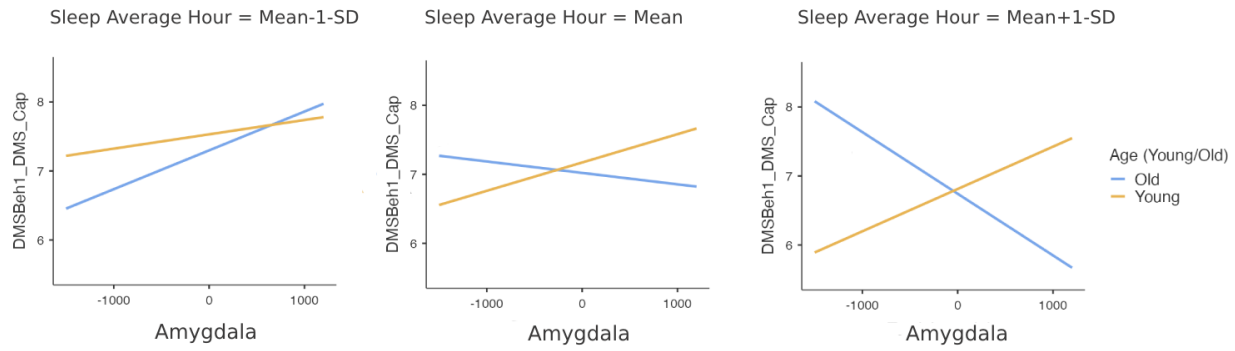

Figure 8. Interaction between Age (Young/Old), Total Amygdala Volume, and Sleep Average Hours on Delayed Matching to Sample (behavioural Capacity) (DMSBeh1_DMS_Cap), a measure of working memory

CHAPTER 4: DISCUSSION

This study revealed age-related differences in how average sleep hours moderated the relationship between brain structure and cognitive performance. In the younger group, high average sleep hours was related to a positive relationship between the hippocampus volume and performance on memory, working memory and speed/attention tasks. In the older group, high average hours of sleep was related to a negative relationship between hippocampus volume and performance on memory tasks. A positive relationship between hippocampus volume and cognitive performance in working memory and speed/attention tasks was observed in the older group when average sleep hours was high.

In the younger group, low average sleep hours was related to a negative relationship between the hippocampus volume and cognitive performance in memory tasks. A positive relationship between the hippocampus volume and cognitive performance in working memory tasks in the younger group was observed when sleep average hours was low. In the older group, low average sleep hours was related to a positive relationship between the hippocampus volume and performance on memory tasks. A negative relationship between the hippocampus volume and performance on working memory tasks in the older group was observed when sleep average hours was low.

In the younger group, a positive amygdala-cognition relationship in memory tasks, working memory tasks, and vocabulary memory tasks was observed in people with high average sleep hours. In the older group, a negative relationship between amygdala and cognitive performance in memory tasks, working memory tasks, and vocabulary memory tasks was observed in people with high average sleep hours. These results demonstrate that the moderating role of sleep on brain-cognition relationships differ between age groups.

In the younger group, low average sleep hours were related to a negative relationship between the amygdala volume and cognitive performance in memory and vocabulary memory tasks. A positive relationship between the amygdala volume and cognitive performance in working memory tasks was observed in the younger group in people with low average sleep hours. In the older group, a positive relationship between amygdala volume and cognitive performance was observed in memory tasks, working memory and vocabulary memory tasks when average sleep hours was low.

The positive and negative relationships of average sleep hours on brain-cognition relationships underscore the potential role of average sleep hours in influencing cognitive well-being. The findings of the current study suggest that average sleep hours serve as a proxy of cognitive reserve by moderating the relationship between brain structure and cognitive performance.

The following sections focus on the detailed influence of average sleep hours on the relationships between brain structures and cognitive performance in the younger and older groups to provide a more comprehensive understanding.

Hippocampus

In **high average sleep hours** (one standard deviation above the mean) a positive relationship between the hippocampus volume and cognitive performance in working memory and speed/attention tasks was observed in both age groups. This positive relationship was also observed for memory tasks in the younger age group. In the older group, a negative relationship was observed between hippocampus volume and cognitive performance in memory tasks.

The observed positive relationship underscores the role of high average sleep hours in supporting cognitive processes. Observing a positive hippocampus-cognition relationship in high

sleep hours condition, may reflect that sleep allows the individuals to take full advantage of their brain to have increased cognitive performance. For instance, high average sleep hours may play a role in enhancing slow-wave sleep (SWS), which supports hippocampal-dependent tasks. During slow-wave sleep (SWS), the hippocampus is involved in a process called neural replay (Diekelmann & Born, 2010; Rasch & Born, 2013). This process reactivates memory traces that were recently formed, helping to integrate these memories into the brain's cortical networks (Diekelmann & Born, 2010; Rasch & Born, 2013). This mechanism is crucial for both immediate recall, which reflects short-term memory encoding, and delayed recall, which relies on long-term memory storage (Diekelmann & Born, 2010; Rasch & Born, 2013). By facilitating these memory processes, high average sleep hours may enable individuals to efficiently utilize their hippocampus, thereby reinforcing a positive relationship between hippocampus and cognitive performance.

An exception is noted in older groups, where a negative relationship between hippocampal volume and memory task performance was observed. This negative relationship might be linked to underlying health issues, such as mood disorders. One of the most prevalent mood disorders, depression, often leads to emotional dysregulation and cognitive impairments (Dong et al., 2021; Sun et al., 2018). Individuals with depression frequently experience extended sleep hours, which often correlate with disrupted sleep quality (Dong et al., 2021; Sun et al., 2018). This dysregulation can impair cognitive performance by interfering with memory consolidation processes. A study by Naismith et al. (2012) has indicated that hypersomnia in individuals with depressive disorders is associated with poorer performance on memory tasks, particularly those that rely on hippocampal activity. Our findings support this claim.

In **low average sleep hours** (one standard deviation below the mean) a negative relationship between the hippocampus volume and cognitive performance in memory tasks in the younger group and a positive relationship in the older group was observed. In low average sleep hours a positive relationship between the hippocampus and working memory task in the younger group and a negative relationship in the older group was also observed.

Low average sleep hours are often linked to poor cognitive performance (Fjell et al., 2019; Elcombe et al., 2015; Chai et al., 2020). While it is generally understood that insufficient sleep can negatively impact cognitive performance, the current study highlighted some exceptions. In the younger group, in low average sleep hours a positive relationship between hippocampal volume and working memory tasks was observed. In the older group a positive association between hippocampal volume and memory tasks was observed.

These findings suggest that both age groups may employ compensatory strategies to sustain cognitive performance. Compensation in this context may involve increased reliance on alternative cognitive pathways or engagement of additional brain regions to combat lower sleep hours. This compensatory mechanism notion is supported by research showing that sleep deprivation leads to increased connectivity between the hippocampus and basic alertness networks of the brainstem and thalamus during memory consolidation tasks (Yoo et al., 2007). The current study also indicated that this potential compensation is not consistent across all tasks. Instead, the effectiveness of these compensatory mechanisms varies depending on the specific cognitive task. The task-specific nature of these potential compensatory mechanisms might indicate that both younger and older groups tailor their approaches to maintain cognitive performance across specific tasks. The potential task-specific nature of these compensatory

mechanisms underscores the need for further research into how these compensatory processes operate to maintain cognitive functioning despite low average sleep hours.

In the older group, another possibility for the positive relationship between hippocampus and cognitive performance in memory tasks could be due to the reason that low average sleep hours may not necessarily lead to poor sleep quality. Even with low average sleep hours, sleep quality in older groups may be adequate to support cognitive processes involved in memory tasks. The self-reported sleep questionnaire used in the current study included a sleep satisfaction question. However, self-assessment of sleep satisfaction does not objectively measure sleep quality (Jackowska et al., 2016). Further research is needed to determine whether low sleep hours necessarily result in low sleep quality.

Amygdala

In **high average sleep hours,** a positive amygdala-cognition relationship was observed in the younger group in memory tasks, working memory tasks, and vocabulary memory tasks, and a negative relationship was observed in the older group in the same cognitive tasks.

In the present study, the positive brain-cognition relationship in the younger group underscores the role of sleep as a mechanism of cognitive reserve. The observed positive amygdala-cognition relationship among the younger group, supports the idea that sleep-as a cognitive reserve mechanism- allows the younger group to take full advantage of their brain to sustain cognitive performance. However, an exception was observed in the older group. The negative relationship between amygdala volume and cognitive performance in the older group when average sleep hours was high may be influenced by other factors, such as mood disorders, similar to the previously discussed findings with the hippocampus, which are common in aging

populations (Dong et al., 2021). Depression, a prevalent mood disorder in older individuals, disrupts circadian rhythms and sleep behaviours, leading to fragmented sleep and reduced sleep quality (Campos Costa et al., 2013). These disruptions impair the brain's ability to restore and strengthen neural networks during sleep (Owusu et al., 2022). As a result, the restorative effects of sleep on cognitive functions like memory, vocabulary, and working memory are diminished, which might contribute to the negative amygdala-cognition relationship in the older group (Naismith et al., 2012).

In **Low average sleep hours** (one standard deviation below the mean) a positive relationship between the amygdala volume and working memory was observed in both age groups. In the older group, a positive relationship was observed between amygdala volume and cognitive performance in memory and vocabulary tasks. In the younger group, a negative relationship between memory and vocabulary tasks was observed.

In the present study, although a negative relationship between amygdala volume and cognitive performance in memory and vocabulary tasks was observed in the younger group, one exception was noted. In the younger group, a positive relationship between amygdala volume and working memory was observed. This positive relationship may be due to the occurrence of a compensatory mechanism. More specifically, the amygdala, like the hippocampus, might use some compensatory mechanisms to maintain cognitive performance.

The idea of compensatory mechanisms highlights the brain's remarkable plasticity and ability to allocate resources dynamically to maintain performance under adverse conditions, such as low average sleep hours. Similar to previous findings related to the hippocampus (Yoo et al., 2007) the current findings suggest compensatory processes related to the amygdala as well.

However, this potential compensatory mechanism warrants further investigation to determine whether the cognitive processes associated with the amygdala engage compensatory strategies during specific tasks and under diverse conditions.

In the older group, the positive relationship between amygdala volume and cognitive performance in the older group might suggest the potential of using compensatory mechanisms to offset the negative impact of reduced sleep on brain-cognition relationship. As detailed in the hippocampus region, another possibility for the positive relationship between the amygdala and cognitive performance could be due to the reason that low average sleep hours may not necessarily lead to poor sleep quality. Even with low average sleep hours, sleep quality in older groups may be adequate to support cognitive processes.

Given that younger individuals reporting less than seven hours of sleep per night may not exhibit healthy sleep behaviours, an additional exploratory analysis was conducted excluding these participants. The seven-hour threshold was selected based on established sleep guidelines recommending 7–9 hours for optimal cognitive functioning in healthy young adults (Hirshkowitz et al., 2015; Lo et al., 2016). This exclusion aimed to assess whether the observed brain–cognition relationships were driven by the presence of short sleepers.

After comparing the results from the full sample with the sample that excluded people whose average sleep was less than seven hours, (n=32 young adults), the overall relationships between brain volume and cognitive performance remained consistent. However, two notable changes emerged. First, the relationship between the hippocampus and working memory resulted in a less pronounced group difference, as reflected by an increase in the p-value and a reduction in effect size. Second, the relationship between the amygdala and vocabulary memory resulted in

a less pronounced group difference, as reflected by an increase in the p-value and a reduction in effect size. Results are provided in Supplementary Material, Tables 11 and 12.

Key Insights from the Discussion/ Integrating the Findings

We have demonstrated support that average sleep hours is a proxy of cognitive reserve. The current results demonstrate that the relationship between brain and cognitive measures differ as a function of sleep hours. This role of sleep fits the definition of cognitive reserve. As an active model, CR leverages various factors, such as sleep, to enhance cognitive strategies and efficiency, thereby maintaining cognitive performance.

The findings also revealed three main points in the relationship between brain and cognitive performance in the amount of sleep a person receives.

A positive relationship between brain and cognitive performance was observed with higher average sleep hours. However, this relationship was not consistently found in older group. Observing a negative brain-cognition relationship in high average sleep hours in the old group suggests that longer sleep duration in this group may result from other factors such as mood disorders. The presence of mood-related factors, such as depression, are known to be associated with prolonged sleep (Dong et al., 2021; Sun et al., 2018). Individuals with depression frequently experience extended sleep hours, which often correlate with disrupted sleep quality (Dong et al., 2021; Sun et al., 2018). Recent research has further demonstrated that prolonged sleep duration linked to depression contributes to cognitive decline (Xu et al., 2021). A study by Naismith et al. (2012) has indicated that hypersomnia in individuals with depressive disorders is associated with poorer performance on memory tasks, particularly those that rely on hippocampal activity (Naismith et al., 2012). Similarly, Wan et al. (2023) found that individuals with prolonged sleep

duration, particularly those with mood disturbances, exhibited increased risks for cognitive impairment, further supporting the connection between depression-induced sleep disturbances and cognitive decline in the older group (Wan et al., 2023). Thus, the observed negative brain-cognition relationship in older adults with prolonged sleep may be explained by underlying mood disturbances, such as depression, which not only contribute to extended sleep duration but also disrupt sleep quality and decreased cognitive performance.

In the present study, while a negative brain-cognition relationship was found with low average sleep hours, some exceptions were observed in both age groups. More specifically, a positive brain-cognition relationship was observed in low average sleep hours in the younger and older groups for specific cognitive tasks. These positive brain-cognition relationships suggest that both age groups may employ compensatory strategies to sustain cognitive performance. The idea of compensatory strategies supports the concept of cognitive reserve (CR), which proposes that individuals with greater neural efficiency or alternative cognitive strategies can better withstand the negative effects of sleep deprivation, maintaining performance despite reduced sleep duration (Ourry et al., 2023; Sullan et al., 2020). In older adults, cognitive reserve has been shown to moderate the impact of sleep disturbances on cognitive decline, allowing individuals with higher CR to preserve cognitive function despite poor sleep quality (Ourry et al., 2023). Similarly, young adults compensate for sleep deprivation by increasing cognitive effort, and engaging compensatory neural mechanisms to sustain performance, particularly in tasks requiring attention and working memory (Sullan et al., 2020).

In the current study, while a negative brain-cognition relationship was found in low average sleep hours, some exceptions were observed in the older group. The positive brain-cognition relationship observed in this group suggests that low average sleep hours does not necessarily equate to poor sleep quality. When average sleep hours is low, older adults with higher sleep efficiency and fewer sleep disturbances tend to maintain cognitive function at levels comparable to those with longer sleep durations (Gildner et al., 2014). This finding suggests that shorter sleep durations might not necessarily be equal to poor sleep quality and impaired cognition in older adults. Thus, the observed positive brain-cognition relationship in low average sleep hours conditions among older adults in the present study may reflect an underlying resilience to shorter sleep durations, where cognitive efficiency is preserved through quality sleep rather than sheer sleep quantity. Further research is needed to explore and understand relationship between sleep hours and sleep quality.

An important consideration when interpreting these results is the use of average sleep hours. This work defines low and high sleep hours as one standard deviation above and below the mean of the current sample. Therefore, the current definitions may differ from other studies based on different low/high designations or those based on larger samples.

CHAPTER 5: CONCLUSION

This study examined how sleep behaviours influence the relationship between brain structure and cognitive performance across younger and older adults. The findings suggest that sleep behaves as a proxy of cognitive reserve by influencing the relationship between brain and cognitive performance, but its effects differ by age group.

In the younger group, a positive relationship between brain structure and cognitive performance was observed in high average sleep hours, while the brain-cognition relationship showed mixed positive and negative relationships depending on the cognitive task in the same group. In the older group, the relationship was more complex. In high sleep hours, generally, a negative brain-cognition relationship was observed, possibly due to factors like mood disorders. However, in low sleep hours, the brain-cognition relationship was positive, suggesting the presence of compensatory mechanisms. These results indicate that sleep acts as a mechanism of cognitive reserve.

In summary, this study highlights the important role of sleep in cognitive aging. While younger adults benefit from more sleep, older adults may utilize different neural strategies depending on their sleep behaviours. These findings support the idea that sleep is a modifiable factor that could be targeted in interventions to promote cognitive health across the lifespan.

Limitations

This study relied on self-reported sleep measures, which introduces potential response biases. Self-reported data may lack accuracy and reliability due to recall errors or subjective interpretations of sleep behaviours. However, this issue was addressed using well-established and validated questionnaires, and the data were closely monitored to identify any inconsistencies

or outliers. This study had a relatively small sample size, which may affect the statistical power and limit the generalizability of the findings. While the cross-sectional design allows for efficient data collection within a shorter time frame, the sample size may not capture the full variability of sleep behaviours, brain structure, and cognitive performance across different populations. Furthermore, this study did not account for potential covariates such as sex, education, intracranial volume, and sleep disturbances, which may affect the brain-cognition relationships.

Future Directions

This exploratory study demonstrated the value of sleep in understanding cognitive aging. Despite p-values that were not smaller than 0.05, the effect sizes were medium to large, suggesting that the study may have been underpowered. To enhance the reliability of future results, researchers should consider increasing the sample size, which could provide greater statistical power to detect significant effects.

Future studies could also benefit from integrating advanced methods of sleep data collection to reduce potential biases and enhance accuracy. Electroencephalography (EEG), a gold-standard technique for measuring brain activity during sleep, provides detailed insights into sleep stages and quality (Forbes et al., 2022). Additionally, wearable devices, such as Muse headbands, offer a more practical and accessible solution for long-term, real-world sleep tracking (Krigolson et al., 2021). These devices enable continuous monitoring of sleep duration, quality, and stages in naturalistic settings, offering objective data reflective of everyday sleep behaviours (Krigolson et al., 2021). These measurements of sleep can provide deeper insights into how the relationship between brain and cognitive performance varies across different sleep behaviors, highlighting the specific aspects of sleep that act as a mechanism for cognitive reserve. By

incorporating these technologies, future research can further explore the brain-cognition interactions under more detailed sleep assessment, ultimately informing personalized interventions aimed at preserving cognitive performance across the lifespan.

While a negative brain-cognition relationship in low average sleep hours was observed, some exceptions were found in the older group. The current study's results highlight that, in the older group, a positive brain-cognition relationship was observed in low average sleep hours, suggesting that low sleep duration does not necessarily equate to poor sleep quality. This positive relationship underscores the need to distinguish between sleep quality and sleep quantity, as shorter sleep durations might not inherently lead to poor cognitive outcomes if sleep quality is maintained. Future research should further investigate whether there is a difference between sleep quality and low average sleep hours in older adults, determining whether sleep quality serves as a protective factor against cognitive decline.

In the present study, a positive brain-cognition relationship was observed with high average sleep hours. Observing the positive relationship in high average sleep hours may reflect that sleep allows individuals to take full advantage of their brain to have increased cognitive performance. Nonetheless, the negative brain-cognition relationship observed in older adults with high average sleep hours suggests that other factors, such as underlying health conditions or psychological factors, may contribute to this association. Future studies could explore whether interventions like mood issues or other psychological conditions influence the brain-cognition relationship by affecting sleep quality influence.

Interdisciplinary of Study

The study takes an interdisciplinary approach by integrating neuroscience, psychology, and health sciences. It examines how sleep behaviours affect the relationship between brain structure and cognitive performance, combining insights from cognitive theories and brain imaging techniques like MRI. Studying the younger and the older groups addresses differences in cognition and brain health across the lifespan. This approach enhances understanding of aging and provides practical insights for developing interventions and policies to improve cognitive performance through better sleep behaviour management.

References

Alahmadi, A. (2023). Functional connectivity of sub-cortical brain regions: Disparities and similarities. *NeuroReport, 34*(2), 214–219.

Alhola, P., & Polo-Kantola, P. (2007). Sleep deprivation: Impact on cognitive performance. *Neuropsychiatric Disease and Treatment*, *3*(5), 553–567.

Alvares Pereira, G., Silva Nunes, M. V., Alzola, P., & Contador, I. (2022). Cognitive reserve and brain maintenance in aging and dementia: An integrative review. *Applied Neuropsychology. Adult*, *29*(6), 1615–1625.

Balsamo, F., Berretta, E., Meneo, D., Baglioni, C., & Gelfo, F. (2024). The complex relationship between sleep and cognitive reserve: A narrative review based on human studies. *Brain Sciences*, *14*(7), 654. https://doi.org/10.3390/brainsci14070654.

Barulli, D., & Stern, Y. (2013). Efficiency, capacity, compensation, maintenance, plasticity: emerging concepts in cognitive reserve. *Trends in Cognitive Sciences*, *17*(10), 502–509.

Beard, J. R., Officer, A., de Carvalho, I. A., Sadana, R., Pot, A. M., Michel, J.-P., Lloyd-Sherlock, P., Epping-Jordan, J. E., Peeters, G. M. E. E. G., Mahanani, W. R., Thiyagarajan, J. A., & Chatterji, S. (2016). The world report on ageing and health: a policy framework for healthy ageing. *The Lancet*, *387*(10033), 2145–2154.

Bowden, S. C., Fowler, K. S., Bell, R. C., Whelan, G., Clifford, C. C., Ritter, A. J., & Long, C. M. (1998). The reliability and internal validity of the Wisconsin Card Sorting Test. *Neuropsychological Rehabilitation*, *8*(3), 243–254. https://doi.org/10.1080/713755573.

Burke, S. N., & Barnes, C. A. (2006). Neural plasticity in the ageing brain. *Nature Reviews. Neuroscience*, *7*(1), 30–40.

Buschke, H., & Fuld, P. A. (1974). Evaluating storage, retention, and retrieval in disordered

memory and learning. *Neurology, 24*(11), 1019–1025. https://doi.org/10.1212/WNL.24.11.1019.

Cabeza, R., Albert, M., Belleville, S., Craik, F. I. M., Duarte, A., Grady, C. L., Lindenberger, U., Nyberg, L., Park, D. C., Reuter-Lorenz, P. A., Rugg, M. D., Steffener, J., & Rajah, M. N. (2018). Maintenance, reserve and compensation: the cognitive neuroscience of healthy ageing. *Nature Reviews. Neuroscience, 19*(11), 701–710.

Campos Costa, I., Carvalho, H. N., & Fernandes, L. (2013). Aging, circadian rhythms and depressive disorders: a review. *American Journal of Neurodegenerative Disease, 2*(4), 228-246.

Carpenter, J. S., Robillard, R., Lee, R. S. C., Hermens, D. F., Naismith, S. L., White, D., Whitwell, B., Scott, E. M., & Hickie, I. B. (2015). The relationship between sleep-wake cycle and cognitive functioning in young people with affective disorders. *PLOS ONE, 10*(4), e0124710. https://doi.org/10.1371/journal.pone.0124710.

Cavedo, E., Galluzzi, S., Pievani, M., Boccardi, M., & Frisoni, G. B. (2012). Norms for imaging markers of brain reserve. *Journal of Alzheimer's Disease: JAD, 31*(3), 623–633.

Chai, Y., Fang, Z., Yang, F., Xu, S., Deng, Y., Raine, A., ... & Rao, H. (2020). Two nights of recovery sleep restores hippocampal connectivity but not episodic memory after total sleep deprivation. *Scientific Reports*, 10. https://doi.org/10.1038/s41598-020-65086-x.

Chai, Y., Gehrman, P., Yu, M., Mao, T., Deng, Y., Rao, J., Shi, H., Quan, P., Xu, J., Zhang, X., Lei, H., Fang, Z., Xu, S., Boland, E. M., Goldschmied, J. R., Barilla, H., Goel, N., Basner, M., Thase, M., Sheline, Y., Detre, J., Zhang, X., & Rao, H. (2023). Enhanced amygdala–cingulate connectivity associates with better mood in both healthy and depressive individuals after sleep deprivation. *Proceedings of the National Academy of Sciences of the*

United States of America, *120*. DOI: 10.1073/pnas.2214505120.

Cheng, Q., Wang, H., Cui, M., Wang, Q., & Li, L. (2024). Efficacy of wooden toy training in alleviating cognitive decline in elderly individuals with cognitive impairment: A cluster randomized controlled study. *PLOS ONE, 19*.https://doi.org/10.1371/journal.pone.0309685.

Christensen, H., Anstey, K. J., Parslow, R. A., Maller, J., Mackinnon, A., & Sachdev, P. (2007). The brain reserve hypothesis, brain atrophy and aging. *Gerontology*, *53*(2), 82–95.

Ciro della Monica, S., Johnsen, S., Atzori, G., Groeger, J., & Dijk, D. J. (2018). Rapid eye movement sleep, sleep continuity and slow wave sleep as predictors of cognition, mood, and subjective sleep quality in healthy men and women, aged 20–84 years. *Frontiers in Psychiatry, 9*, 255. https://doi.org/10.3389/fpsyt.2018.00255.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. https://doi.org/10.4324/9780203771587.

Dai, H., Mei, Z., An, A., Lu, Y., & Wu, J. (2020). Associations of sleep problems with health-risk behaviours and psychological well-being among Canadian adults. *Sleep Health, 6*(5), 657–661.

de Almeida Valverde Zanini, G., Tufik, S., Andersen, M. L., da Silva, R. C. M., Bueno, O. F. A., Rodrigues, C. C., & Pompéia, S. (2012). Free recall of word lists under total sleep deprivation and after recovery sleep. *Sleep*, *35*(2), 223–230.

Diekelmann, S., & Born, J. (2010). The memory function of sleep. *Nature Reviews Neuroscience, 11*(2), 114–126. https://doi.org/10.1038/nrn2762.

Djonlagic, I., Mariani, S., Fitzpatrick, A., Van Der Klei, V. M. G. T. H., Johnson, D. A., Wood, A., Seeman, T., Nguyen, H. T., Prerau, M., Luchsinger, J., Dzierzewski, J., Rapp, S., Tranah, G., Yaffe, K., Burdick, K., Stone, K., Redline, S., & Purcell, S. (2021). Macro and

micro sleep architecture and cognitive performance in older adults. *Nature Human Behaviour, 5*, 123–145. https://doi.org/10.1038/s41562-020-00964-y.

Dong, L., Xu, G., Zhang, Q., & Keenan, K. (2021)**.** Sleep quality and cognitive impairment in older adults: Insights from a population-based study. *Journal of Sleep Research, 30*(2), e13156. https://doi.org/10.1111/jsr.13156.

Elcombe, E., Lagopoulos, J., Duffy, S., Lewis, S., Norrie, L., Hickie, I., & Naismith, S. (2015). Hippocampal volume in older adults at risk of cognitive decline: The role of sleep, vascular risk, and depression. *Journal of Alzheimer's Disease*, 44(4), 1279–1290. https://doi.org/10.3233/JAD-142016.

Fischl, B. (2012). FreeSurfer. *NeuroImage, 62*(2), 774–781. https://doi.org/10.1016/j.neuroimage.2012.01.021.

Fjell, A. M., Sneve, M. H., Grydeland, H., Storsve, A. B., & Walhovd, K. B. (2017). The disconnected brain and executive function decline in aging. *Cerebral Cortex, 27*(3), 2303–2317. https://doi.org/10.1093/cercor/bhw082.

Fjell, A., Sørensen, Ø., Amlien, I., Bartrés-Faz, D., Bros, D. M., Demuth, I., ... & Walhovd, K. (2019). Self-reported sleep relates to hippocampal atrophy across the adult lifespan. *Sleep*, 43. https://doi.org/10.1093/SLEEP/ZSZ280.

Forbes, O., Schwenn, P. E., Wu, P. P., Santos-Fernandez, E., Xie, H.-B., Lagopoulos, J., McLoughlin, L. T., Sacks, D. D., Mengersen, K., & Hermens, D. F. (2022). EEG-based clusters differentiate psychological distress, sleep quality and cognitive function in adolescents. *School of Mathematical Sciences, Queensland University of Technology*.

Gebara, M. A., & Karp, J. F. (2020). Sleep disturbances are among the risk factors associated with cognitive impairment. *International Psychogeriatrics, 32*(7), 791–792.

https://doi.org/10.1017/S1041610219001868.

Gildner, T. E., Liebert, M. A., Kowal, P., Chatterji, S., & Snodgrass, J. J. (2014). Associations between sleep duration, sleep quality, and cognitive test performance among older adults from six middle-income countries: Results from the Study on Global Ageing and Adult Health (SAGE). *Journal of Clinical Sleep Medicine, 10*(6), 613–621. https://doi.org/10.5664/jcsm.3782.

Gildner, T. E., Liebert, M. A., Kowal, P., Chatterji, S., & Snodgrass, J. J. (2014). Associations between sleep duration, sleep quality, and cognitive test performance among older adults from six middle income countries: Results from the Study on Global Ageing and Adult Health (SAGE). *Journal of Clinical Sleep Medicine, 10*(6), 613–621. https://doi.org/10.5664/jcsm.3782.

Goel, N., Rao, H., Durmer, J. S., & Dinges, D. F. (2009). Neurocognitive consequences of sleep deprivation. *Seminars in Neurology*, *29*(4), 320–339.

Government of Canada, & Canada, S. (2019, February 8). *the older group and population aging statistics*. https://www.statcan.gc.ca/en/subjects-start/older_adults_and_population_aging

Groot, C., van Loenhoud, A. C., Barkhof, F., van Berckel, B. N. M., Koene, T., Teunissen, C. C., Scheltens, P., van der Flier, W. M., & Ossenkoppele, R. (2018). Differential effects of cognitive reserve and brain reserve on cognition in Alzheimer disease. *Neurology*, *90*(2), e149–e156.

Gruber, R., Cassoff, J., & Frenette, S. (2013). Sleep efficiency modulates the association between brain structure and cognitive performance. *Journal of Cognitive Neuroscience, 25*(3), 365–378.

Gulia, K. K., & Kumar, V. M. (2018). Sleep disorders in the elderly: a growing challenge.

Psychogeriatrics: The Official Journal of the Japanese Psychogeriatric Society, *18*(3), 155–165.

Hamann, S., & Mao, H. (2002). Positive and negative emotional verbal stimuli elicit activity in the left amygdala. *NeuroReport*, *13*(1), 15–19.

Harman, D. (2003). The free radical theory of aging. *Antioxidants & Redox Signaling*, *5*(5), 557–561.

Harman, M. F., & Martín, M. G. (2020). Epigenetic mechanisms related to cognitive decline during aging. *Journal of Neuroscience Research*, *98*(2), 234–246. https://doi.org/10.1002/jnr.24436.

Harrison, S. L., Sajjad, A., Bramer, W. M., Ikram, M. A., Tiemeier, H., & Stephan, B. C. M. (2015). Exploring strategies to operationalize cognitive reserve: A systematic review of reviews. *Journal of Clinical and Experimental Neuropsychology*, *37*(3), 253–264.

Hilal, S., Amin, S. M., Venketasubramanian, N., Niessen, W. J., Vrooman, H. A., Wong, T. Y., Chen, C. L. H., & Ikram, M. K. (2015). Subcortical atrophy in cognitive impairment and dementia. *Journal of Alzheimer's Disease*, 48(3), 813–823.

Hirshkowitz, M., Whiton, K., Albert, S. M., Alessi, C., Bruni, O., DonCarlos, L., Hazen, N., Herman, J., Adams Hillard, P. J., Katz, E. S., Kheirandish-Gozal, L., Neubauer, D. N., O'Donnell, A. E., Ohayon, M., Peever, J., Rawding, R., Sachdeva, R. C., Setters, B., Vitiello, M. V., & Ware, J. C. (2015). National Sleep Foundation's updated sleep duration recommendations: Final report. *Sleep Health*, *1*(4), 233–243. https://doi.org/10.1016/j.sleh.2015.10.004

Jackowska, M., Ronaldson, A., Brown, J., & Steptoe, A. (2016). Biological and psychological correlates of self-reported and objective sleep measures. *Journal of Psychosomatic*

Research, 84, 52–55. https://doi.org/10.1016/j.jpsychores.2016.03.017.

Jeun, Y.-J., Nam, Y., Lee, S.-A., & Park, J.-H. (2022). Effects of personalized cognitive training with the machine learning algorithm on neural efficiency in healthy younger adults. *International Journal of Environmental Research and Public Health, 19*(20), Article 13044.

Katzman, R., Terry, R., DeTeresa, R., Brown, T., Davies, P., Fuld, P., Renbing, X., & Peck, A. (1988). Clinical, pathological, and neurochemical changes in dementia: a subgroup with preserved mental status and numerous neocortical plaques. *Annals of Neurology*, *23*(2), 138–144.

Khan, M. A., & Al-Jahdali, H. (2023). The consequences of sleep deprivation on cognitive performance. *Neurosciences* , *28*(2), 91–99.

Killgore, W. D. S. (2010). Effects of sleep deprivation on cognition. *Progress in Brain Research, 185*, 105–129. https://doi.org/10.1016/B978-0-444-53702-7.00007-5.

Kondo, R., Miyano, I., Lee, S., Shimada, H., & Kitaoka, H. (2021). Association between self-reported night sleep duration and cognitive function among the older group with intact global cognition. *International Journal of Geriatric Psychiatry, 36*(5), 766–774.

Krigolson, O. E., Hammerstrom, M. R., Abimbola, W., Trska, R., Wright, B. W., Hecker, K. G., & Binsted, G. (2021). Using Muse: Rapid mobile assessment of brain performance. *Frontiers in Neuroscience*, 15, 1-10. https://doi.org/10.3389/fnins.2021.635672 (PMCID: PMC7876403; PMID: 33584194).

Li, J., Vitiello, M. V., & Gooneratne, N. S. (2018). Sleep in Normal Aging. *Sleep Medicine Clinics, 13*(1), 1–11.

Lim, J., & Dinges, D. F. (2010). A meta-analysis of the impact of short-term sleep deprivation on cognitive variables. *Psychological Bulletin, 136*(3), 375–389.

https://doi.org/10.1037/a0018883.

Lipnicki, D. M., Crawford, J. D., Dutta, R., Thalamuthu, A., Kochan, N. A., Andrews, G., ... & Sachdev, P. S. (2017). Age-related cognitive decline and associations with sex, education, and apolipoprotein E genotype across ethnocultural groups and geographic regions: A collaborative cohort study. *PLoS Medicine, 14*(3), e1002261. https://doi.org/10.1371/journal.pmed.1002261

Lissoni, P., Messina, G., Porro, G., Gavazzeni, C., Trampetti, R., Tartarelli, O., Tartarelli, R., Caddeo, A., & Di Fede, G. (2020). A review on the cognitive functions of basal ganglia, amygdala, and hippocampus. *Mental Health and Addiction Research*.

Lo, J. C., Ong, J. L., Leong, R. L., Gooley, J. J., & Chee, M. W. (2016). Cognitive performance, sleepiness, and mood in partially sleep-deprived adolescents: The need for sleep study. *Sleep*, *39*(3), 687–698. https://doi.org/10.5665/sleep.5552.

Lo, J. C., Groeger, J. A., Cheng, G. H., Dijk, D.-J., & Chee, M. W. L. (2016). Self-reported sleep duration and cognitive performance in the older group: a systematic review and meta-analysis. *Sleep Medicine*, *17*, 87–98.

Iordan, A. D., Cooke, K. A., Moored, K. D., Katz, B., Buschkuehl, M., Jaeggi, S. M., Polk, T. A., Peltier, S. J., Jonides, J., & Reuter-Lorenz, P. A. (2019). Neural correlates of working memory training: Evidence for plasticity in older adults. *NeuroImage, 217*, Article 116887.

Mander, B. A., Winer, J. R., Jagust, W. J., & Walker, M. P. (2016). Sleep: A novel mechanistic pathway, biomarker, and treatment target in the pathology of Alzheimer's disease? *Trends in Neurosciences, 39*(8), 552–566. https://doi.org/10.1016/j.tins.2016.05.002.

Medic, G., Wille, M., & Hemels, M. E. (2017). Short- and long-term health consequences of sleep disruption. *Nature and Science of Sleep, 9*, 151–161.

Meng, W., Gao, T., Zhong, Y., & Ge, L. (2023). Association Between Sleep and Cognition of the older group in Rural Areas: A Cross-Sectional Study. *Inquiry: A Journal of Medical Care Organization, Provision and Financing*, *60*, 469580231171820.

Mortimer, J. A. (1997). Brain reserve and the clinical expression of Alzheimer's disease. Geriatrics, 52(Suppl 2), S50–S53

Murman, D. L. (2015). The Impact of Age on Cognition. *Seminars in Hearing*, *36*(3), 111–121.

Nagel, I. E., Preuschhof, C., Li, S.-C., Nyberg, L., Bäckman, L., Lindenberger, U., & Heekeren, H. R. (2009). Performance level modulates adult age differences in brain activation during spatial working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(52), 22552–22557. https://doi.org/10.1073/pnas.0908238106.

Naismith, S. L., Norrie, L. M., & Hickie, I. B. (2012)**.** Sleep disturbance, hippocampal volume, and memory in depression: Insights from imaging and cognitive studies. *Journal of Affective Disorders*, *140*(3), 256–262. https://doi.org/10.1016/j.jad.2012.02.024.

Narvacan, K., Treit, S., Camicioli, R., Martin, W., & Beaulieu, C. (2017). Evolution of deep gray matter volume across the human lifespan. *Human Brain Mapping*, *38*(7), 3771–3790. https://doi.org/10.1002/hbm.23604.

Nelson, H. E., & O'Connell, A. (1978). Dementia: The estimation of premorbid intelligence levels using the New Adult Reading Test. *Cortex*, *14*(2), 234–244. https://doi.org/10.1016/S0010-9452(78)80049-5.

Neth, B. J., Graff-Radford, J., Mielke, M. M., Przybelski, S. A., Lesnick, T. G., Schwarz, C. G., Reid, R. I., Senjem, M. L., Lowe, V. J., Machulda, M. M., Petersen, R. C., Jack, C. R., Jr, Knopman, D. S., & Vemuri, P. (2019). Relationship Between Risk Factors and Brain Reserve in Late Middle Age: Implications for Cognitive Aging. *Frontiers in Aging*

Neuroscience, *11*, 355.

Neu, D., Mairesse, O., Newell, J., Verbanck, P., Peigneux, P., & Deliens, G. (2015). Does more sleep matter? Differential effects of NREM- and REM-dominant sleep on sleepiness and vigilance. *Neurophysiologie Clinique/Clinical Neurophysiology*, *45*, 167–175. https://doi.org/10.1016/j.neucli.2014.10.004.

Nicholson, K., Rodrigues, R., Anderson, K. K., Wilk, P., Guaiana, G., & Stranges, S. (2020). Sleep behaviours and multimorbidity occurrence in middle-aged and the older group: findings from the Canadian Longitudinal Study on Aging (CLSA). *Sleep Medicine*, *75*, 156–162.

Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U., & Bäckman, L. (2012). Memory aging and brain maintenance. *Trends in Cognitive Sciences*, *16*(5), 292–305.

Ourry, V., Rehel, S., André, C., Mary, A., Paly, L., Delarue, M., Requier, F., Hendy, A., Collette, F., Marchant, N. L., Felisatti, F., Palix, C., Vivien, D., de la Sayette, V., Chételat, G., Gonneaud, J., & Rauchs, G. (2023). Effect of cognitive reserve on the association between slow wave sleep and cognition in community-dwelling older adults. *Aging (Albany NY)*, *15*, 9275–9292. https://doi.org/10.18632/aging.204943.

Owusu, J., Rabinowitz, J. A., Tzuang, M., An, Y., Kitner-Triolo, M., Zipunnikov, V., Wu, M. N., Wanigatunga, A. A., Schrack, J. A., Thorpe, R. J., Simonsick, E. M., Ferrucci, L., Resnick, S. M., & Spira, A. P. (2022). Associations between objectively measured sleep and cognition: Main effects and interactions with race in adults aged ≥50 years. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences.*

Packard, M., & Cahill, L. (2001). Affective modulation of multiple memory systems. *Current Opinion in Neurobiology*, *11*(6), 752–756.

Packard, M., & Teather, L. (1998). Amygdala modulation of multiple memory systems: Hippocampus and caudate-putamen. *Neurobiology of Learning and Memory, 69*(2), 163–203.

Park, D. C., Lautenschlager, G., Hedden, T., Davidson, N. S., Smith, A. D., & Smith, P. K. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging, 17*(2), 299–320.

Peng, Z., Wang, Y., Dai, C., Wang, L., Xie, S., Li, J., Zeng, L., Shao, Y., & Fu, W.-W. (2020). Recovery sleep attenuates impairments in working memory following total sleep deprivation. *Unpublished manuscript.*

Qin, S., Leong, R. L. F., Ong, J. L., & Chee, M. W. L. (2023). Associations between objectively measured sleep parameters and cognition in healthy the older group: A meta-analysis. *Sleep Medicine Reviews, 67*, 101734.

Rasch, B., & Born, J. (2013). About sleep's role in memory. *Physiological Reviews, 93*(2), 681–766. https://doi.org/10.1152/physrev.00032.2012.

Raven, J. (1962). *Advanced Progressive Matrices, Set II*. H.K. Lewis.

Richardson, J. T. E. (2007). Measures of short-term memory: A historical review. *Cortex, 43*(5), 635–650. https://doi.org/10.1016/S0010-9452(08)70493-3.

Salthouse, T. A., & Babcock, R. L. (1991). Decomposing adult age differences in working memory. *Developmental Psychology, 27*(5), 763–776. https://doi.org/10.1037/0012-1649.27.5.763.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*(3), 403–428.

Scullin, M. K. (2013). Sleep, memory, and aging: the link between slow-wave sleep and episodic

memory changes from younger to the older group. *Psychology and Aging, 28*(1), 105–114.

Scullin, M. K., & Bliwise, D. L. (2015). Sleep, cognition, and normal aging: Integrating a half-century of multidisciplinary research. *Perspectives on Psychological Science, 10*(1), 97–137. https://doi.org/10.1177/1745691614556680.

Sexton, C. E., Storsve, A. B., Walhovd, K. B., Johansen-Berg, H., & Fjell, A. M. (2014). Poor sleep quality is associated with increased cortical atrophy in community-dwelling adults. *Neurology, 83*(11), 967–973. https://doi.org/10.1212/WNL.0000000000000762.

Sindi, S., Johansson, L., & Kulmala, J. (2017). Sleep disturbances and cognitive function in older adults: Findings from the population-based Gothenburg H70 birth cohort study. *Journal of Sleep Research, 26*(6), 699-707. https://doi.org/10.1111/jsr.12555.

Spira, A. P., Chen-Edinboro, L. P., Wu, M. N., & Yaffe, K. (2014). Impact of sleep on the risk of cognitive decline and dementia. *Current Opinion in Psychiatry, 27*(6), 478–483. https://doi.org/10.1097/YCO.0000000000000106.

Spira, A. P., Gonzalez, C. E., Venkatraman, V. K., Wu, M. N., Pacheco, J., Simonsick, E. M., ... & Resnick, S. M. (2016). Sleep duration and subsequent cortical thinning in cognitively normal older adults. *Sleep, 39*(5), 1121–1128. https://doi.org/10.5665/sleep.5770.

Steffener, J., Barulli, D., Habeck, C., O'Shea, D., Razlighi, Q., & Stern, Y. (2014). The role of education and verbal abilities in altering the effect of age-related gray matter differences on cognition. *PLOS ONE, 9*(3), e91196. https://doi.org/10.1371/journal.pone.0091196.

Steffener, J., & Stern, Y. (2012). Exploring the neural basis of cognitive reserve in aging. *Biochimica et Biophysica Acta, 1822*(3), 467–473.

Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *Journal of the International Neuropsychological Society: JINS, 8*(3), 448–460.

Stern, Y. (2009). Cognitive reserve. *Neuropsychologia*, *47*(10), 2015–2028.

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., Ewers, M., Franzmeier, N., Kempermann, G., Kremen, W. S., Okonkwo, O., Scarmeas, N., Soldan, A., Udeh-Momoh, C., Valenzuela, M., Vemuri, P., Vuoksimaa, E., & the Reserve, Resilience and Protective Factors PIA Empirical Definitions and Conceptual Frameworks Workgroup. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's & Dementia: The Journal of the Alzheimer's Association*, *16*(9), 1305–1311.

Stern, Y., Barnes, C. A., Grady, C., Jones, R. N., & Raz, N. (2019). Brain reserve, cognitive reserve, compensation, and maintenance: operationalization, validity, and mechanisms of cognitive resilience. *Neurobiology of Aging*, *83*, 124–129.

Sternberg, S. (1966). High-speed scanning in human memory. *Science*, *153*(3736), 652–654. https://doi.org/10.1126/science.153.3736.652.

Sullan, M. J., Drummond, S., & Granholm, E. (2020). Sleep deprivation and compensatory cognitive effort on a visual information processing task. *Sleep.* https://doi.org/10.1093/sleep/zsaa177.

Sun, Y., Liu, J., Wang, J., & Qi, W. (2018). The impact of poor sleep quality on cognitive decline: A study of older adults. *Sleep Medicine*, *50*, 113–120. https://doi.org/10.1016/j.sleep.2018.08.003.

Takeuchi, H., Taki, Y., Nouchi, R., Yokoyama, R., Kotozaki, Y., Nakagawa, S., ... & Kawashima, R. (2018). Shorter sleep duration and better sleep quality are associated with greater tissue density in the brain. *Scientific Reports*, *8*, 5833. https://doi.org/10.1038/s41598-018-24226-0.

Tang, X., Holland, D., Dale, A. M., Younes, L., & Miller, M. I. (2015). Baseline shape diffeomorphometry patterns of subcortical and ventricular structures in predicting conversion of mild cognitive impairment to Alzheimer's disease. *Journal of Alzheimer's Disease*, 44(2), 599–611.

Van der Kouwe AJW, Benner T, Salat DH, Fischl B. (2008). Brain morphometry with multiecho MPRAGE. *NeuroImage.* 2008;40(2):559-569. doi: 10.1016/j.neuroimage.2007.12.025. PMID: 18242102; PMCID: PMC2408694.

Van Dongen, H. P. A., Maislin, G., Mullington, J. M., & Dinges, D. F. (2003). The cumulative cost of additional wakefulness: dose-response effects on neurobehavioural functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep*, *26*(2), 117–126.

Vos, T., Lim, S. S., Abbafati, C., Abbas, K. M., Abbasi, M., Abbasifard, M., ... & Murray, C. J. L. (2020). Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, *396*(10258), 1204–1222. https://doi.org/10.1016/S0140-6736(20)30925-9.

Wan, Q., Huang, X., Zhang, S., Fang, Y., Zhao, X., Cao, T., & Sun, Y. (2023). Sleep characteristics in older adults with different levels of risk for dementia: A cross-sectional study. *Current Alzheimer Research.* https://doi.org/10.2174/1567205020666230303110244

Wang, X., Chen, Y., Yue, B., Li, S., Liu, Q., Li, Q., Li, L., & Sun, J. (2021). Association of changes in self-reported sleep duration with mild cognitive impairment in the elderly: a longitudinal study. *Aging*, *13*(11), 14816–14828.

Wassing, R., Lakbila-Kamal, O., Ramautar, J., Stoffers, D., Schalkwijk, F., & Van Someren, E. V. (2019). Restless REM sleep impedes overnight amygdala adaptation. *Current Biology*,

29(14), 2351-2358.e4. DOI: 10.1016/j.cub.2019.06.034.

Wechsler, D. (1981). *WAIS-R Manual: Wechsler Adult Intelligence Scale - Revised.* New York: Psychological Corporation.

Wilckens, K. A., Tudorascu, D., Snitz, B., Price, J., Aizenstein, H., Lopez, O., Erickson, K., Lopresti, B., Laymon, C., Minhas, D., Mathis, C., Buysse, D. J., Klunk, W., & Cohen, A. (2018). Sleep moderates the relationship between amyloid-beta and memory recall. *Neurobiology of Aging, 71,* 142–148. DOI: 10.1016/j.neurobiolaging.2018.07.011.

Wilson, R. S., Yu, L., Lamar, M., Schneider, J. A., Boyle, P. A., & Bennett, D. A. (2019). Education and cognitive reserve in old age. *Neurology*, *92*(10), e1041–e1050.

Xu, W.-Q., Lin, L.-H., Ding, K., Ke, Y.-F., Huang, J.-H., Hou, C., Jia, F., & Wang, S.-B. (2021). The role of depression and anxiety in the relationship between poor sleep quality and subjective cognitive decline in Chinese elderly: Exploring parallel, serial, and moderated mediation. *Journal of Affective Disorders, 294,* 464–471. https://doi.org/10.1016/j.jad.2021.07.063.

Yaffe, K., Fiocco, A. J., Lindquist, K., Vittinghoff, E., Simonsick, E. M., Newman, A. B., Satterfield, S., Rosano, C., Rubin, S. M., Ayonayon, H. N., Harris, T. B., & Health ABC Study. (2009). Predictors of maintaining cognitive function in the older group: the Health ABC study. *Neurology*, *72*(23), 2029–2035.

Yoo, S. S., Hu, P. T., Gujar, N., Jolesz, F. A., & Walker, M. P. (2007). A deficit in the ability to form new human memories without sleep. *Nature Neuroscience, 10*(3), 385–392. https://doi.org/10.1038/nn1851.

Zijlmans, J. L., Riemens, M. S., Vernooij, M. W., Ikram, M. A., & Luik, A. I. (2023). Sleep, 24-hour activity rhythms, and cognitive reserve: A population-based study. *Journal of*

Alzheimer's Disease, 91, 663-672. https://doi.org/10.3233/JAD-220714.

Appendix

Appendix A: Neuropsychological Battery

This list presents the cognitive domains, the tasks within each domain, and the specific scores calculated form the tasks.

- Memory
    - Buschke Selective Reminding Test
        - Immediate Recall Score
        - Delayed Recall Score
        - Recognition Score
- Executive Function
    - Progressive Matrices
        - Accuracy score
    - Stroop - Colour, Word, Colour/Word
        - Interference score using response times
    - Wisconsin Card Sorting Test
        - Number of errors
- Working Memory
    - Verbal delayed match-to-sample Task
        - Capacity score
    - Visual-spatial Working Memory Task
        - Capacity score
    - Digit Span
        - Forward Capacity
        - Backward Capacity
- Vocabulary
    - Antonyms
        - Accuracy
    - AMNART
        - Number of errors
- Speed/Attention
    - Pattern Comparison Speed Task
        - Accuracy
        - Response time

Appendix B: Sleep Questionnaire

1. Variable Name: **SlpSatis**
Question Text: How satisfied or dissatisfied are you with your current sleep pattern?

Answer options:
1. Very Satisfied
2. Satisfied
3. Neutral
4. Dissatisfied
5. Very Dissatisfied
6. I don't know
7. Prefer not to answer

2. Variable Name: **SlpAvgHours**
Question Text: During the past month, on average, how many hours of actual sleep did you get at night? (This may be different than the number of hours you spend in bed.)
Answer options:
Integer number

3. Variable Name: **SlpFallAslp**
Question Text: Over the last month, how often did it take you more than 30 minutes to fall asleep?
Answer options:
1. Never
2. <1/week
3. Once or twice/week
4. 3-5 times/week
5. 6-7 times/week
6. I don't know
7. Prefer not to answer

4. Variable Name: **SlpFallDurTrbl**
Question Text: For how many months have you had this trouble going to sleep?
Answer options:
Integer number

5. Variable Name: **SlpFallProbDay**
Question Text: To what extent do you consider your problem falling asleep to interfere with your daily functioning (for example, from daytime fatigue, ability to function at work/daily chores, concentration, memory, mood, etc.).
Answer options:
1. Not at all

2. A little
3. Somewhat
4. Much
5. Very much
6. I don't know
7. Prefer not to answer

6. Variable Name: **SlpWake**
Question Text: Over the last month, how often did you wake in the middle of the night or too early in the morning and found it difficult to fall asleep again?
Answer options:
1. Never
2. <1/week
3. Once or twice/week
4. 3-5 times/week
5. 6-7 times/week
6. I don't know
7. Prefer not to answer

7. Variable Name: **SlpWakeDurTrbl**
Question Text: For how many months have you had this trouble staying asleep?
Answer options:

Integer value

8. Variable Name: **SlpWakeProbDay**
Question Text: To what extent do you consider your problem staying asleep to interfere with your daily functioning (for example, from daytime fatigue, ability to function at work/daily chores, concentration, memory, mood, etc.)?
Answer options:
1. Not at all
2. A little
3. Somewhat
4. Much
5. Very much
6. I don't know
7. Prefer not to answer

9. Variable Name: **SlpDayTired**
Question Text: Over the last month, how often do you find it difficult to stay awake during your normal waking hours when you want to?

Answer options:
1. Never
2. <1/week
3. Once or twice/week
4. 3-5 times/week
5. 6-7 times/week
6. I don't know
7. Prefer not to answer

10. Variable Name: **SlpDayTiredDurTrbl**
Question Text: For how many months have you had trouble staying awake?
Answer options:

Integer value

11. Variable Name: **SlpDayTiredProbDay**
Question Text: To what extent do you consider your problem staying awake to interfere with your daily functioning?
Answer options:
1. Not at all
2. A little
3. Somewhat
4. Much
5. Very much
6. I don't know
7. Prefer not to answer

12. Variable Name: **SlpActDreams**
Question Text: Have you ever been told, or suspected yourself, that you seem to acted out your dreams" while asleep (for example, punching, flailing your arms in the air, making running movements, etc.)?
Answer options:
1. Yes
2. No
3. I don’t know
4. Prefer not to answer

13. Variable Name: **SlpActDreamsDurTrbl**
Question Text: For how many months have you had this "acting out" of your dreams?
Answer options:

Integer value

14. Variable Name: **SlpLegDiscomfort**
Question Text: Do you have, or have you sometimes experienced, recurrent, uncomfortable feelings or sensations in your legs while sitting or lying down?
Answer options:
1. Yes
2. No
3. I don’t know
4. Prefer not to answer

15. Variable Name: **SlpLegRest**
Question Text: Do you have, or have you sometimes experienced, a recurrent need or urge to move your legs while sitting or lying down?
Answer options:
1. Yes
2. No
3. I don’t know
4. Prefer not to answer

16. Variable Name: **SlpLegRestDurTrbl**
Question Text: For how many months have you had these uncomfortable feelings or urge to move?
Answer options:

Integer value

17. Variable Name: **SlpLegProbCount**
Question Text: Over the last month, how many times (per week, on average) have you experienced these uncomfortable feelings or urge to move?
Answer options:
1. Less than once
2. Once or twice
3. Three or four times
4. More than four times
5. I don’t know
6. Prefer not to answer

18. Variable Name: **SlpLegDisappear**

Question Text: Do these uncomfortable feelings or sensations in your legs, or the urge to move, disappear/improve when you are active or moving around?
Answer options:
1. Yes
2. No
3. I don’t know
4. Prefer not to answer

19. Variable Name: **SlpLegNight**
Question Text: Are these uncomfortable feelings, or this urge to move, worse in the evening or at night compared with the morning?
Answer options:
1. Yes
2. No
3. I don’t know
4. Prefer not to answer

Appendix C. Supplementary Materials

Supplementary Table 6. Statistical results for all cognitive measures using hippocampal volume and average sleep hours.

		Age	Sleep	Brain	Age*Sleep	Age*Brain	Sleep*Brain	Age*Brain*Sleep
Cognitive domain	Cognitive measure	t	t	t	t	t	t	t
Exec	STRP-Inter	-1.21	-1.25	-0.39	1.17	0.44	-0.45	0.13
Exec	WCST N err	-2.6***	0.07	0.19	-0.52	-0.76	-0.03	-0.29
Exec	WCST N pErr	-2.61***	-0.2	0.43	1.08	-0.23	-0.92	0.91
Vocab	Ant Acc	-6.05****	-0.13	-0.72	-0.17	-0.54	1.19	1.12
Vocab	NART_NErrors	2.65***	-0.47	0.17	0.56	-0.1	-0.83	0.39
Verbal Short-Term Memory	Digit Span FC	0.82	1.12	0.38	-0.93	1.095	1.26	-1.84*
Working Memory	Digit Span BC	-0.02	-0.41	2**	0.14	2.2**	0.01	-0.39
Processing Speed	Pattern Comparison 1 ACC	0.22	-1.74*	1.51	0.24	-0.62	-1.68*	3***
Processing Speed	Pattern Comparison 1 RT	-8.64****	0.49	-0.69	-0.77	2.12**	1.3	-0.59
Processing Speed	PComp 3 Acc	2.86***	-0.88	2.14**	-0.81	-1.22	-0.81	1.72*
Processing Speed	PComp 3 RT	-9.09****	-0.15	-0.58	-0.79	1.1	1.53	0.54
Fluid Ability	Matrix Acc	4.8****	-1.15	-0.09	2.51***	-0.008	-1.4	1.54
Verbal Short Memory	DMSBeh1 DMS Cap	0.8	-0.66	0.02	-0.88	1.05	-0.11	-0.42
Spatial Memory	VSTMBeh1 VSTM Cap	2.46**	0.15	1.6	-0.41	0.8	-0.11	-0.56
Memory	Selective Reminding Test Imm_TotRecall	2.12**	-0.9	0.05	1.16	-0.65	-0.73	1.65*
Memory	Selective Reminding TestDel_Recall	4****	-2.14**	0.46	1.46	-0.41	-1	1.84*
Memory	Selective Reminding TestRecog_Hits	2.01**	-0.57	-0.42	-0.73	0.4	0.48	0.49

Notes: N err: number of errors; N Perr: number of persistent errors, Ant Acc: Antonym Accuracy, FC: Forward capacity, BC: Backward capacity, ACC: Accuracy,

RT: Response time Note: *p<0.1, **p<0.05; ***p<0.01; ****p<0.001

Supplementary Table 7. Statistical results for all cognitive measures using caudate volume and average sleep hours.

		Age	Sleep	Brain	Age*Sleep	Age*Brain	Sleep*Brain	Age*Brain*Sleep
Cognitive domain	Cognitive assessment	t	t	t	t	t	t	t
Exec	STRP-Inter	-1.5	-1.4	-0.26	1.16	0.21	-0.31	0.16
Exec	WCST N err	-3.01***	-0.41	0.47	-0.34	-1.17	-0.02	0.3
Exec	WCST N pErr	-2.94***	-0.29	0.39	1.37	-0.36	-1.25	1.15
Vocab	Ant Acc	-6.84****	0.38	0.02	0.3	-1.12	1.19	0.81
Vocab	NART_NErrors	3.7****	0.22	-1.74*	-0.33	1.4	0.14	0.14
Verbal Short-Term Memory	Digit Span FC	0.24	0.11	2.04**	-0.34	0.54	0.98	-0.82
Working Memory	Digit Span BC	-0.2	-1.18	2.75***	1	1.02	-0.72	0.36
Processing Speed	Pattern Comparison 1 ACC	0.53	-0.53	0.76	-0.29	-0.83	0.97	1.93*
Processing Speed	Pattern Comparison 1 RT	-9.09****	1.3	-1.4	-0.92	1.77*	1.42	-1.33
Processing Speed	PComp 3 Acc	3.64****	-0.33	0.97	-1.06	-0.14	-0.63	1.3
Processing Speed	PComp 3 RT	-9.36****	0.61	-1.58*	-0.33	0.67	1.44	0.44
Fluid Ability	Matrix Acc	4.93****	-0.03	-0.24	1.46	0.72	0.31	0.75
Verbal Short Memory	DMSBeh1 DMS Cap	0.2	-1.51	1.26	-0.56	-0.05	-0.51	0.32
Spatial Memory	VSTMBeh1 VSTM Cap	3.3****	0.08	0.34	-0.16	-0.18	-0.27	-0.39
Memory	Selective Reminding Test Imm_TotRecall	1.93*	-0.65	0.7	1.24	-0.41	-0.87	1.32
Memory	Selective Reminding TestDel_Recall	4.5****	-1.39	-0.18	0.99	0.46	-0.59	0.95
Memory	Selective Reminding TestRecog_Hits	2.74***	-0.42	-1.65*	-0.37	0.26	-0.08	0.57

Notes: N err: number of errors; N Perr: number of persistent errors, Ant Acc: Antonym Accuracy, FC: Forward capacity, BC: Backward capacity, ACC: Accuracy, RT: Response time

Note: Note: *p<0.1, **p<0.05; ***p<0.01; ****p<0.001

Supplementary Table 8. Statistical results for all cognitive measures using amygdala volume and average sleep hours.

		Age	Sleep	Brain	Age*Sleep	Age*Brain	Sleep*Brain	Age*Brain*Sleep
Cognitive domain	Cognitive assessment	t	t	t	t	t	t	t
Exec	STRP-Inter	-1.09	-1.07	-1.4	1.34	-0.18	-0.26	-0.26
Exec	WCST N err	-2.9***	-0.31	0.33	-0.35	-0.99	-0.42	0.15
Exec	WCST N pErr	-2.73***	0.41	-0.02	0.72	-0.64	-0.21	0.69
Vocab	Ant Acc	-7.89****	-0.78	0.92	-0.02	0.26	1.55	2.52**
Vocab	NART_NErrors	3.04***	0.24	-0.59	-0.53	0.27	0.85	-0.15
Verbal Short-Term Memory	Digit Span FC	0.91	-0.3	1	0.27	1.49	-0.41	-0.66
Working Memory	Digit Span BC	0.31	-0.87	1.94*	0.49	0.84	0.07	0.43
Processing Speed	Pattern Comparison 1 ACC	0.32	-0.07	1.6	-1.6	-0.71	0.47	1.66*
Processing Speed	Pattern Comparison 1 RT	-9.92****	0.55	-0.97	-0.71	2.48**	1.57	-0.72
Processing Speed	PComp 3 Acc	3.97****	-0.48	1.96**	-0.97	-1.18	-1.58	1.37
Processing Speed	PComp 3 RT	-10.65****	-0.04	-0.93	-0.91	1.29	2.57**	1.06
Fluid Ability	Matrix Acc	5.14****	-0.56	-0.43	1.67*	0.86	0.29	1.43
Verbal Short Memory	DMSBeh1 DMS Cap	0.62	-2.43**	0.51	-0.31	1.19	-1	1.77*
Spatial Memory	VSTMBeh1 VSTM Cap	2.8***	-0.74	3.43****	-0.26	1.55	-1.14	-0.12
Memory	Selective Reminding Test Imm_TotRecall	2.35**	-0.64	-0.49	1.05	-1.65*	0.27	2.53**
Memory	Selective Reminding TestDel_Recall	4.57****	-1.37	-0.04	0.88	-0.48	-0.11	1.08
Memory	Selective Reminding TestRecog_Hits	2.26**	-0.61	-0.51	-0.59	0.64	0.05	0.38

Notes: N err: number of errors; N Perr: number of persistent errors, Ant Acc: Antonym Accuracy, FC: Forward capacity, BC: Backward capacity, ACC: Accuracy, RT: Response time

Note: Note: *p<0.1, **p<0.05; ***p<0.01; ****p<0.001

Supplementary Table 9. Statistical results for all cognitive measures using pallidum volume and average sleep hours.

Cognitive domain	Cognitive assessment	Age	Sleep	Brain	Age*Sleep	Age*Brain	Sleep*Brain	Age*Brain*Sleep
		t	t	t	t	t	t	t
Exec	STRP-Inter	-1.76*	-2.67***	0.59	2.56**	-0.07	-2.24**	1.11
Exec	WCST N err	-2.72***	-0.56	0.23	-0.14	-1.44	-0.36	0.45
Exec	WCST N pErr	-2.93***	0.42	0.94	0.58	-1.2	-0.49	-0.07
Vocab	Ant Acc	-6.54****	1.04	0.23	-0.68	-0.46	1.9*	0.07
Vocab	NART_NErrors	3.48****	-0.42	-1.37	0.28	0.89	-0.3	0.51
Verbal Short-Term Memory	Digit Span FC	0.45	1.32	1.08	-1.05	0.92	1.12	-2.02**
Working Memory	Digit Span BC	-0.75	0.31	3.26****	0.008	1.72*	0.53	-0.8
Processing Speed	Pattern Comparison 1 ACC	0.51	-1.46	1.12	0.66	-1.07	-1.55	2.76***
Processing Speed	Pattern Comparison 1 RT	-8.27****	0.52	-1.18	-0.22	0.97	0.83	-0.29
Processing Speed	PComp 3 Acc	3.61****	-0.29	0.63	-0.85	-0.29	0.3	1.27
Processing Speed	PComp 3 RT	-8.57****	0.87	-1.98**	-0.86	0.58	1.95*	-0.04
Fluid Ability	Matrix Acc	4.81****	-0.03	-0.36	1.2	0.14	0.88	0.99
Verbal Short Memory	DMSBeh1 DMS Cap	0.57	-0.6	0.34	-0.96	0.45	9.69e_4	-0.44
Spatial Memory	VSTMBeh1 VSTM Cap	2.87***	0.34	0.66	-0.4	0.42	-0.02	-0.59
Memory	Selective Reminding Test Imm_TotRecall	2.2**	-0.14	-0.11	0.55	-1.08	0.38	1.12
Memory	Selective Reminding TestDel_Recall	4.49****	-0.88	-0.49	0.56	0.08	0.07	0.48
Memory	Selective Reminding TestRecog_Hits	2.99***	-1.19	-1.77*	0.24	1.83*	-0.53	1.18

Notes: N err: number of errors; N Perr: number of persistent errors, Ant Acc: Antonym Accuracy, FC: Forward capacity, BC: Backward capacity, ACC: Accuracy, RT: Response time

Note: Note: *p<0.1, **p<0.05; ***p<0.01; ****p<0.001

Supplementary Table 10. Statistical results for all cognitive measures using putamen volume and average sleep hours.

Cognitive domain	Cognitive assessment	Age	Sleep	Brain	Age*Sleep	Age*Brain	Sleep*Brain	Age*Brain*Sleep
		t	t	t	t	t	t	t
Exec	STRP-Inter	-1.08	-0.92	-0.7	0.62	1.36	-1.19	-1.51
Exec	WCST N err	-2.38**	-0.07	-0.16	-0.73	-0.61	-0.05	-0.35
Exec	WCST N pErr	-2.7***	0.27	0.57	0.61	-0.1	-1.07	-0.49
Vocab	Ant Acc	-6.63****	0.43	0.87	0.27	-0.88	1.38	1.03
Vocab	NART_NErrors	3.78****	0.03	-1.84*	-0.19	1.38	-0.19	-0.1
Verbal Short-Term Memory	Digit Span FC	-0.35	0.02	2.33**	0.38	1.56	-0.68	-1.04
Working Memory	Digit Span BC	-1.43	-0.55	4.03****	1.37	1.42	0.49	1.18
Processing Speed	Pattern Comparison 1 ACC	0.65	-0.1	0.61	-0.49	-0.63	-0.32	1.14
Processing Speed	Pattern Comparison 1 RT	-8.15****	1.59	-1.95*	-1.18	1.66*	1.69*	-1.15
Processing Speed	PComp 3 Acc	3.52****	-0.53	0.56	-0.44	0.16	-0.93	1.24
Processing Speed	PComp 3 RT	-8.17****	-78	-2.16**	-0.54	0.77	1.8*	0.52
Fluid Ability	Matrix Acc	4.4****	0.13	0.31	1.45	0.38	1.21	1.37
Verbal Short Memory	DMSBeh1 DMS Cap	0.35	-1.98**	0.62	0.29	-0.07	-1.75*	0.37
Spatial Memory	VSTMBeh1 VSTM Cap	2.34**	-0.37	1.35	0.48	0.46	0.08	1.02
Memory	Selective Reminding Test Imm_TotRecall	2.39**	-0.51	-0.34	1.06	-1.6	0.01	1.49
Memory	Selective Reminding TestDel_Recall	3.96****	-0.83	0.35	0.53	-0.79	-0.003	0.17
Memory	Selective Reminding TestRecog_Hits	2.76***	-0.92	-1.44	-0.03	0.46	-1.01	0.19

Notes: N err: number of errors; N Perr: number of persistent errors, Ant Acc: Antonym Accuracy, FC: Forward capacity, BC: Backward capacity, ACC: Accuracy, RT: Response time

Note: Note: *p<0.1, **p<0.05; ***p<0.01; ****p<0.001

Supplementary Table 11. Interaction Effects of Age, Hippocampus Volume, and Sleep: Full Sample vs. >7 Hours Sleep Subsample

Cognitive Assessment	t (All Hours)	p (All Hours)	η^2_p (All)	t (>7 Hours)	p (>7 Hours)	η^2_p (>7)
Digit Span Forward Capacity	−1.84	0.07	0.05	-0.62	0.54	0.006
Pattern comparison accuracy (Load 03)	1.72	0.09	0.04	1.78	0.08	0.05
Selective Reminding Test (Immediate Total Recalled)	1.65	0.1	0.04	1.68	0.1	0.04
Selective Reminding Test (Delayed Recall)	1.84	0.07	0.05	1.72	0.09	0.05

Supplementary Table 12. Interaction Effects of Age, Amygdala Volume, and Sleep: Full Sample vs. >7 Hours Sleep Subsample

Cognitive Assessment	t (All Hours)	p (All Hours)	η^2_p (All)	t (>7 Hours)	p (>7 Hours)	η^2_p (>7)
Antonyms Task (Accuracy)	2.52	0.01	0.08	0.91	0.37	0.01
Delayed matching to sample (Capacity)	1.77	0.08	0.04	2.38	0.02	0.08
Selective Reminding Test (Immediate Total Recalled)	2.53	0.01	0.09	1.9	0.06	0.06