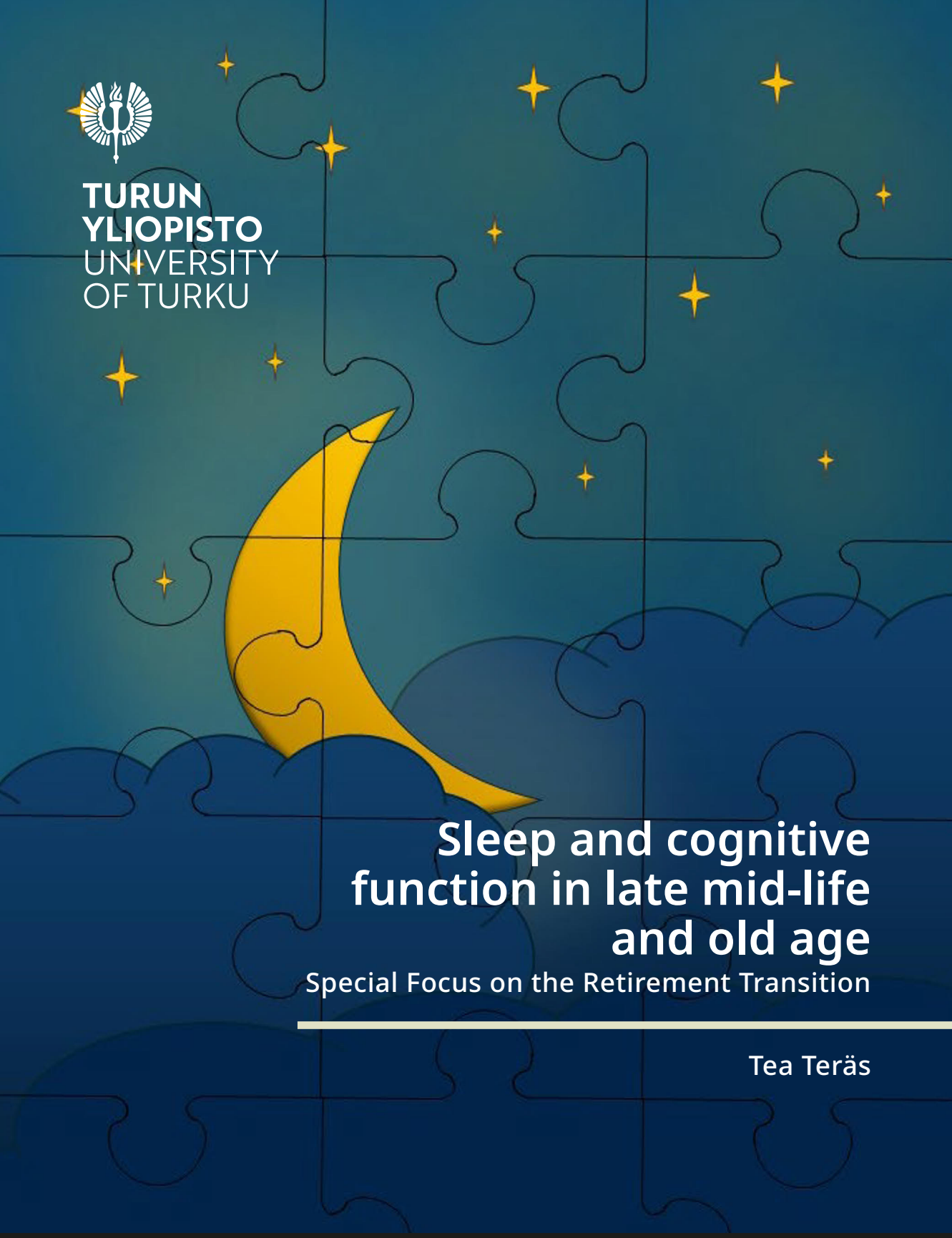

TURUN YLIOPISTO
UNIVERSITY OF TURKU

Sleep and cognitive function in late mid-life and old age

Special Focus on the Retirement Transition

Tea Teräs

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
SARJA – SER. D OSA – TOM. 1950 | MEDICA – ODONTOLOGICA | TURKU 2026

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ABSTRACT

The aim of this PhD thesis is to examine the association between sleep characteristics (duration and difficulties) and cognitive function in late mid-life and old age – especially around the retirement transition. It comprises of four cohort studies: the Finnish Retirement and Aging Study (n=289), the Cardiovascular Risk in Young Finns Study (n=1908), the Turku Senior Health Clinic Study (n=758), and the Whitehall II Study (n=2980). Sleep characteristics were measured through self-reports and accelerometer readings, and cognitive function was measured using paper-and-pencil and computer-based tests across multiple cognitive domains. Sleep characteristics and cognitive function were examined cross-sectionally as well as longitudinally, using repeated measurements before and after retirement.

Long sleep duration in late mid-life and old age was associated with multiple cognitive domains, including poorer learning and memory, complex attention, and executive function. Difficulties staying asleep and nonrestorative sleep were associated with executive function among the participants who were still actively working. Sleeping more than usual the night prior to cognitive testing was associated with poorer information processing. Cognitive function, especially learning and memory, temporarily improved during retirement transition independently from changes in sleep characteristics. In a longer follow up around the retirement transition, increasing and decreasing sleep difficulties were associated with a pronounced decline in cognitive function during and after the retirement transition.

In conclusion, long sleep duration and sleep difficulties were associated with poorer cognitive function before and after retirement. Cognitive function temporarily improved during the retirement transition, and future research should focus on finding the cause behind this improvement in order to promote improved cognitive health in working life.

KEYWORDS: Sleep, Sleep duration, Sleep difficulties, Cognition, Cognitive function, Cognitive performance, Retirement, Aging, Older worker

TURUN YLIOPISTO
Lääketieteellinen tiedekunta
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TIIVISTELMÄ

Tämän väitöskirjan tavoitteena oli tutkia unen pituuden ja univaikeuksien yhteyttä kognitioon myöhäisessä keski-iässä ja vanhuudessa sekä erityisesti eläkkeelle siirtymisen yhteydessä. Tutkimus pohjautuu neljään kohorttitutkimukseen: Finnish Retirement and Aging -tutkimus (n=289), Lasten Sepelvaltimotaudin Riskitekijät -tutkimus (n=1908), Ikäneuvolatutkimus (n=758) ja Whitehall II -tutkimus (n=2980). Unen mittaamiseen käytettiin kyselypohjaisia mittareita sekä Actigraph-liikemittaria. Kognition mittaamiseen usealla eri kognition osa-alueella käytettiin sekä kynä ja paperi- että tietokonepohjaisia testejä. Unen ja kognition välistä yhteyttä tutkittiin niin poikkileikkaus- kuin pitkittäisasetelmassa. Pitkittäisasetelmassa tutkittavia seurattiin työelämästä eläkkeelle mitaten toistetusti unta ja kognitiota.

Pitkäunisuus oli yhteydessä useisiin kognition osa-alueisiin kuten heikompaan oppimiseen ja muistiin, tarkkaavuuteen ja toiminnanohjaukseen myöhäisessä keski-iässä ja vanhuudessa. Vaikeudet pysyä unessa ja virkistämätön uni olivat yhteydessä heikompaan toiminnanohjaukseen työelämässä olevilla tutkittavilla. Kun tarkasteltiin edellisen yön unenpituutta, tavallista pidempään nukkuminen oli yhteydessä heikompaan tiedonkäsittelyyn. Eläkkeelle siirtymisen yhteydessä kognitio – erityisesti oppiminen ja muisti – parani hetkellisesti, eikä tämä paraneminen johtunut muuttuneesta unesta. Pidemmällä 16 vuoden seuranta-ajalla lisääntyvät ja vähenevät univaikeudet olivat yhteydessä nopeampaan kognition heikkenemiseen eläköityessä ja eläköitymisen jälkeen.

Yhteenvetona pitkäunisuus ja univaikeudet olivat yhteydessä heikompaan kognitioon ennen ja jälkeen eläköitymisen. Kognition osoitettiin väliaikaisesti paranevan eläköitymisen yhteydessä. Jatkossa tulisi tutkia, mitkä tekijät ovat osoitetun paranemisen taustalla, minkä myötä työikäisten kognitiivista suoriutumista voisi parantaa.

AVAINSANAT: Uni, unenpituus, univaikeudet, kognitio, eläköityminen, ikääntyminen

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Abbreviations

AH4-I	Alice Heim 4-I
ANOVA	Analysis of Variance
BDI	Beck Depression Inventory
BMI	Body Mass Index
CANTAB®	Cambridge Neuropsychological Test Automated Battery
CERAD	The Consortium to Establish a Registry for Alzheimer's Disease
DISS	Daytime Insomnia Symptom Scale
DSM	Diagnostic and Statistical Manual of Mental Disorders
FIREA	Finnish Retirement and Aging (Study)
GEE	General Estimating Equations
GHQ	General Health Questionnaire
GLM	Generalized Linear Model
ISCO	International Standard Classification of Occupations
JCQ	Job Content Questionnaire
MMSE	Mini-Mental State Examination
MoCA	Montreal Cognitive Assessment
NREM	Non-rapid Eye Movement
PSQI	Pittsburgh Sleep Quality Index
REM	Rapid Eye Movement
SD	Standard Deviation
TICS	Telephone Interview for Cognitive Status
TMT	Trail Making Test
WASO	Wake After Sleep Onset

List of Original Publications

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals:

I Teräs T, Rovio S, Spira AP, Myllyntausta S, Pulakka A, Vahtera J, Stenholm S. Associations of accelerometer-based sleep duration and self-reported sleep difficulties with cognitive function in late mid-life: the Finnish Retirement and Aging Study. Sleep Med. 2020 Apr;68:42-49. https://doi.org/10.1016/j.sleep.2019.08.024

II Teräs T, Myllyntausta S, Salminen M, Viikari L, Pahkala K, Muranen O, Hutri-Kähönen N, Raitakari O, Rovio S, Stenholm S. The association of previous night's sleep duration with cognitive function among older adults: a pooled analysis of three Finnish cohorts. Eur J Ageing. 2023 Aug 3;20(1):32. https://doi.org/10.1007/s10433-023-00779-6

III Teräs T, Myllyntausta S, Pentti J, Pasanen J, Rovio S, Stenholm S. Concurrent changes in sleep and cognitive function during retirement transition: the Finnish Retirement and Aging study. Eur J Ageing. 2025 Aug 7;22(1):40. https://doi.org/10.1007/s10433-025-00876-8

IV Teräs T, Rovio S, Pentti J, Head J, Kivimäki M, Stenholm S. Association of sleep with cognitive function during retirement transition: the Whitehall II study. Sleep. 2023 Jan 11;46(1):zsac237. https://doi.org/10.1093/sleep/zsac237.

1 Introduction

Humans spend approximately one-third of their lives asleep. Although it is not completely understood why we sleep, it is known that sleep is essential for our survival. Both sleep duration and sleep difficulties have shown to affect various health outcomes such as cardiovascular health, diabetes, depression, and cognitive function. Yet, 24% of the working-age population in Finland estimate that they do not sleep enough. (Healthy Finland Survey, 2024)

Cognitive function refers to the mental processes of acquiring knowledge and understanding through thought, experience, and the senses, and it consists of several domains. It is needed in all aspects of life, in work, social interactions, and even the smallest of decision-making tasks. Cognitive function improves in the early years of human life, but later it starts to gradually decrease. The degree of decline varies between the cognitive domains, as some domains typically remain intact well into old age while others start to decline as early as when a person is in their twenties.

Several diseases, such as Alzheimer's disease and vascular dementia, are characterized by the decline of cognitive function. As the population ages and cognitive impairment becomes more prevalent, it is important to understand and examine the modifiable risk factors behind cognitive decline and to find ways to prevent or at least postpone any forthcoming impairment. Therefore, this PhD study examined the late middle-age population to identify the changes in cognitive function that take place before clinical cognitive impairments can be detected.

As mentioned, sleep and cognitive function are both integral parts of human life. Accumulating evidence has shown that they are interrelated. As sleep and cognitive function are both vast entities, many questions related to the association between sleep characteristics (sleep duration and difficulties) and cognitive domains remain unanswered.

This PhD thesis focuses also on the retirement transition. Retirement is a major life event that is accompanied by various changes in everyday life and use of time. Consequently, several changes take place in a person's health and social behavior. Thus, the retirement transition is an optimal period for examining changes in sleep characteristics and cognitive function, and how they are associated with each other.

The aim of this PhD thesis is to examine how sleep characteristics are associated with cognitive function, by focusing on aging workers and following them into retirement. The study utilized both self-reported and accelerometer-based sleep measurements and examined several individual cognitive domains. It also examined how changes in usual sleep duration the night prior to cognitive testing may affect test performance. Lastly, this study examined how sleep characteristics and cognitive function change during and after the retirement transition, and how these changes are interconnected.

2 Review of the Literature

2.1 Sleep

Although sleep is essential for survival, many people sleep suboptimal amounts or have sleep difficulties that restrict its benefits. Multiple factors can impair sleep — stress and other psychosocial factors, caffeine and other stimulants, smoking, alcohol consumption, various medications, and many psychological and somatic diseases. (Dynamed, 2025) Personality, sleep-related behavior, daily routine, physical activity, and chronotype can also affect sleep.

The US National Sleep Foundation has published guidelines for optimal sleep duration (e.g., 7–9 hours for 26–64-year-olds and 7–8 hours for ≥65-year-olds), but the amount of sleep that individuals need can vary greatly, depending on genetic factors, age, sex, and chronotype, for example. (Hirshkowitz et al., 2015) However, a U-shaped association between sleep duration and mortality (Da Silva et al., 2016) and morbidity—for example, diabetes, cardiovascular disease, coronary heart disease, and obesity—have been reported (Itani et al., 2017; Jike et al., 2018) meaning that either short or long sleep duration can be detrimental to health.

The US National Sleep Foundation has also issued similar guidelines for sleep difficulties, but as these focus on each individual aspect of sleep difficulties (e.g., sleep efficiency, sleep latency, percentage of rapid eye movement (REM) sleep, percentage of N1 sleep, >5–minute awakenings) they offer more value for research purposes than for individuals. (Ohayon et al., 2017) Sleep difficulties (i.e., insomnia) are defined by the Diagnostic and Statistical Manual of Mental Disorders 5 (DSM-5) as: difficulty initiating sleep, difficulty maintaining sleep, or early-morning awakenings on at least three nights/week for at least three months. Sleep difficulties have shown to be associated with several psychological and somatic diseases, such as hypertension, type 2 diabetes, depression, anxiety, arthrosis, and asthma. (Cappuccio et al., 2010; Jarrin et al., 2018; Sivertsen et al., 2014)

Sleep characteristics can be measured using self-reports such as questionnaires and sleep diaries, or more objectively using accelerometers and polysomnography. Self-reported sleep duration can be easily assessed by asking one question (e.g., “How many hours do you usually sleep per night?”), but evaluating sleep difficulties is commonly based on validated questionnaire instruments, such as the Jenkins Sleep

Problem Scale (Jenkins et al., 1988) and the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989).

Population studies have typically relied on questionnaires, but in recent years, sleep has increasingly been measured using accelerometers because the availability of these wearable monitors has increased and their costs have decreased. An accelerometer is a small device worn on a limb (usually an arm) to measure its movements. It offers a cost-effective, nonobtrusive method for measuring sleep objectively and can easily be worn at home.

The gold standard for measuring sleep is polysomnography, which simultaneously measures eye movement and the electrical activity of the brain and muscles. However, the cost and intricacy of polysomnography restricts its use in population studies, and the method usually requires taking sleep measurements in a laboratory.

Self-reported sleep characteristics have shown to moderately correlate with those obtained using objective methods. (Lauderdale et al., 2008; Zinkhan et al., 2014) Compared to polysomnography, an accelerometer is highly sensitive to detecting sleep, but its moderate specificity limits its detection of periods of wakefulness during the night. (Marino et al., 2013)

2.2 Cognitive function

Cognitive function refers to the mental processes of acquiring knowledge and understanding through thought, experience, and senses. We constantly need cognitive function, be it for the smallest decisions in our personal lives or for decisions in our stimulating, fast-paced working lives.

Cognitive function comprises several distinct domains that reflect different cognitive aspects. DSM-5 categorizes cognitive function into six domains: complex attention, executive function, learning and memory, language, perceptual-motor control, and social cognition. (**Figure 1**) Each of these domains are further divided into several subdomains.

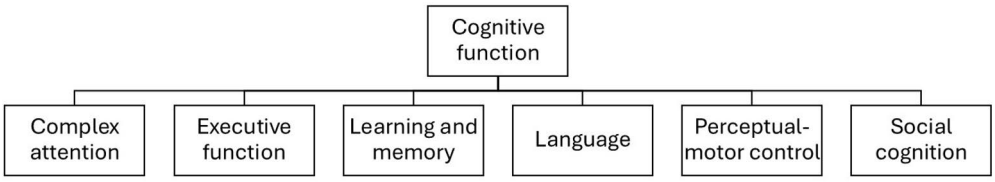

Figure 1. Cognitive function and its six subdomains as defined by DSM-5.

Cognitive function is also commonly divided into fluid and crystallized abilities. (**Figure 2**) Fluid abilities, such as memory, processing speed, and spatial ability, typically improve in the early years of human life. They may start to decline as early as when a person is in their twenties, and gradually decline as the life course progresses. (Murman, 2015; Singer et al., 2003; Singh-Manoux et al., 2012; Van Der Willik et al., 2021) What the aforementioned cognitive subdomains have in common is the need to quickly process or transform information. Crystallized abilities, on the other hand, tend to improve and persist throughout the life course, with only a small decline in the last years of a person's life. (Murman, 2015; Singer et al., 2003; Singh-Manoux et al., 2012) The typical subdomains of these abilities are vocabulary, information, and comprehension, i.e., subdomains that mainly require cumulative knowledge. Accordingly, the population-based Healthy Finland Survey has shown a clear incline in self-reported difficulties with memory, learning, and concentration among people aged 70 and older in comparison to younger age groups. Cognitive tests show a similar gradually declining trend in cognitive function with age, the more pronounced decline being among 70- to 79- and ≥80-year olds. (Koponen et al., 2018)

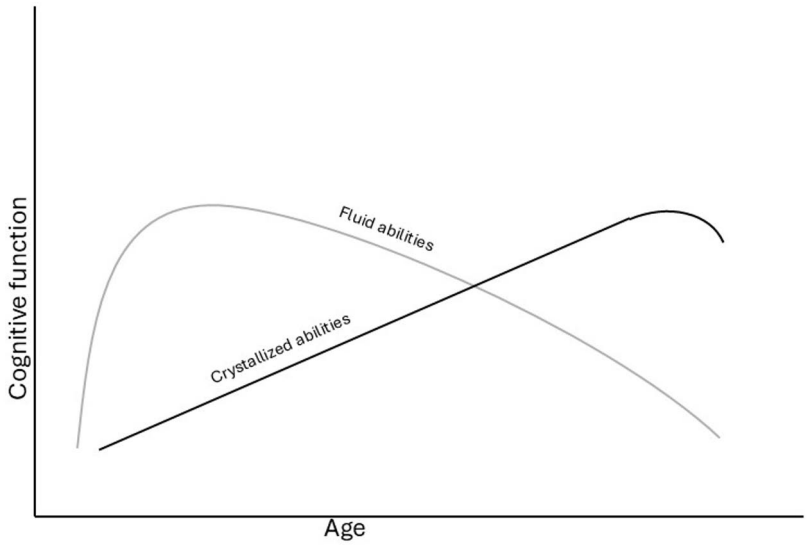

Figure 2. Representation of fluid and crystallized abilities during the life course.

Several other factors are associated with cognitive function. Men and women typically have domain-specific differences in cognitive function, men having the advantage in spatial tasks and women in verbal memory tasks. (Siedlecki et al., 2019) Additionally, higher socioeconomic status (Kremen et al., 2019), physical exercise

(Singh et al., 2025), and social activity (Evans et al., 2019) have shown to be associated with better cognitive function, while many diseases (e.g., diabetes, heart disease, and restless legs syndrome) (Jin et al., 2023; S. Wang et al., 2023; Zhao et al., 2024) and unhealthy lifestyle factors (e.g., smoking, alcohol consumption, and poor diet) (Petersson & Philippou, 2016; Sabia et al., 2014; Zhang et al., 2022) seem to be associated with poorer cognitive function.

As there are multiple cognitive domains and even more cognitive subdomains, cognitive function can be measured in various ways. A common method to assess global cognitive function is the use of screening tools. Examples of such tools are the Mini-Mental State Examination (MMSE) (Folstein et al., 1975), the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005), and the Consortium to Establish a Registry for Alzheimer's Disease (CERAD) (Morris et al., 1989). These are widely used in research as well as in clinical practice. Several other cognitive tests exist that more specifically examine individual cognitive domains, but isolating an individual (sub)domain can be difficult, as the measured (sub)domains typically overlap. For example, the widely used Trail Making Test (TMT) (Reitan, 1958) involves multiple subdomains of executive function (e.g., processing speed, set-shifting) as well as components of complex attention.

Cognitive function tests can also be divided by the style in which they are conducted, i.e., paper-and-pen and computer-based tests. The latter can better detect small errors and delays that might be beneficial when examining a healthy population. When studying younger healthy populations, it is important to detect subtle changes in cognitive function, which may be more difficult using paper-and-pencil tests. Computer-based cognitive tests may also enable the individual domains and subdomains of cognitive function to be studied more precisely. However, similar cognitive tests can be used in both forms, for instance, the aforementioned TMT can easily be conducted in either paper-and-pencil or computer-based format.

2.3 Sleep duration and cognitive function

2.3.1 Cross-sectional associations between sleep duration and cognitive function

Similar to the association between sleep duration and several health outcomes, the association between sleep duration and cognitive function is an inverted U-shape. (**Figure 3**) The association between sleep duration and global cognitive function has been quite thoroughly researched, but research on sleep duration and individual cognitive domains is still quite scarce and inconclusive. (**Table 1**)

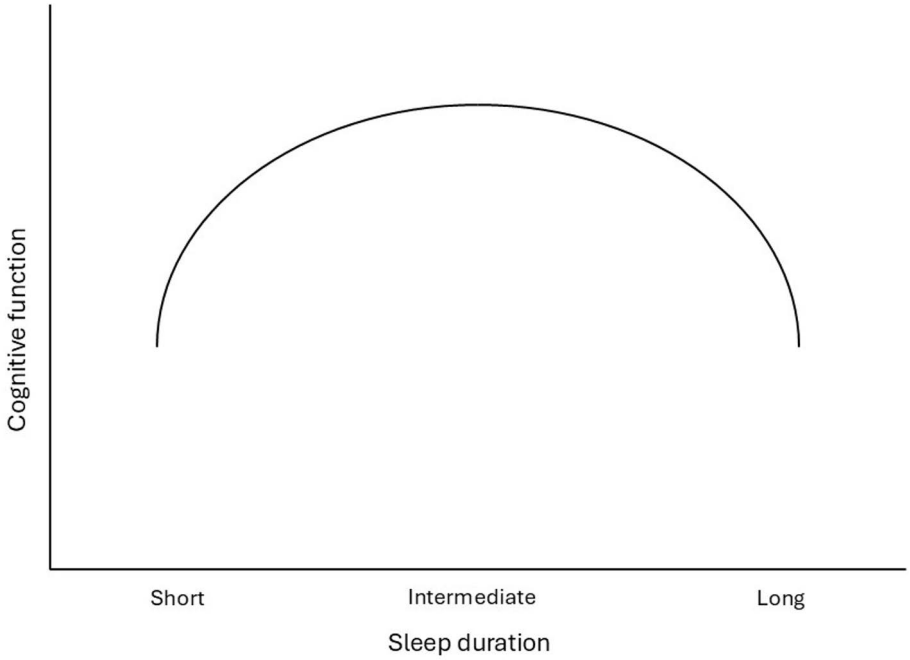

Figure 3. Representation of inverted U-shaped association between sleep duration and cognitive function.

Table 1. Previous studies of cross-sectional associations between sleep duration and specific cognitive domains.

Author	Year	N	Age	Sleep measurement method	Cognitive test	Cognitive domain*	Main findings
Schmutte et al.	2007	375	75–85 years	Self-report	Blessed Information-Memory-Concentration Test, Fuld Object–Memory Evaluation, Selective Reminding Task, Category fluency Test, Raven's Progressive Matrixes Set A, Purdue Pegboard Test, subtests of the Wechsler Adult Intelligence Scale	Verbal and nonverbal	Long sleepers had poorer verbal short-term memory.
Blackwell et al.	2011	3132	≥65 years	Actigraphy and self-report	The Modified Mini-Mental State examination, TMT B, Digit Vigilance Test	Global, Attention, Vigilance	Self-reported intermediate sleepers showed better global cognition, attention, and vigilance than long sleepers. Actigraph-measured intermediate sleepers showed better global cognition than long sleepers.
Xu et al.	2011	28 670	50–85 years	Self-report	Delayed Word Recall Test	Memory	Intermediate sleepers had better memory than short and long sleepers.
Spira et al.	2017	782	≥71 years	Actigraphy	The Modified Mini-Mental State examination, California Verbal Learning Test-II-Short Form, Digit Span, Verbal Fluency Tests, TMT B	Global, Memory, Attention, Working memory, Verbal fluency, Executive function	Intermediate sleepers showed better global cognition and verbal fluency than long sleepers.
Tsapanou et al.	2017	1589	≥65 years	Self-report	Greek Verbal Learning Test, Medical College of Georgia Complex Figure Test	Memory	Short and intermediate sleepers had better memory than long sleepers.

Author	Year	N	Age	Sleep measurement method	Cognitive test	Cognitive domain*	Main findings
Low et al.	2019	1496	≥60 years	Self-report	Immediate and Delayed Recall (CERAD), Animal Fluency, Digital Symbol Substitution Test, Subjective Cognitive Problems	Verbal memory, Semantic fluency, Working memory, Processing speed	Intermediate sleepers showed better cognitive function in all measurements than long sleepers.
Kondo et al.	2021	241	≥65 years	Self-report	National Center for Geriatrics and Gerontology-Functional Assessment Tool	Word memory, Story memory, Attention, Executive function, Processing speed	Intermediate sleepers had better word memory and story memory than long sleepers.
Okuda et al.	2021	63	≥60 years	Actigraphy	TMT B, Wisconsin Card Sorting Test, number of the Back Task	Executive function, Working memory	Intermediate/short sleepers had better working memory than long sleepers.
Scarlett et al.	2021	1520	≥50 years	Actigraphy and self-report	MMSE, MoCA, Verbal Fluency, Immediate and Delayed Verbal Recall, Color Trails, Choice Reaction Test	Global cognition, Memory, Processing speed, Executive function	Self-reported intermediate sleepers showed better global cognition and executive function, and had better memory than long sleepers. Actigraph-measured intermediate sleepers showed better global cognition than short sleepers.
Swanson et al.	2021	1126	Mean 65 years	Actigraphy	Immediate and Delayed Verbal Recall, Symbol Digit Modalities Test, Digit Span Backwards Task	Immediate and delayed verbal memory, Working memory, Information processing speed	Sleep duration was not associated with cognitive function.
Deng et al.	2022	226	≥60 years	Self-report	MMSE, Auditory Verbal Learning Test, Verbal Fluency test, TMT A and B & Symbol Digit Modalities Test, Rey-Osterrieth Complex Figure Test	Global Memory Language Attention and executive function Visuospatial abilities	Short sleep duration was associated with poorer global cognition and visuospatial ability.

Author	Year	N	Age	Sleep measurement method	Cognitive test	Cognitive domain*	Main findings
Ihle-Hansen et al.	2024	3348	62–65 years	Self-report	MoCa, Delayed Recall Trial, TMT A and B	Global, Working memory, Processing speed, Attention and Executive function	Intermediate sleepers showed better global cognition and had better working memory than short and long sleepers.
Rezende et al.	2024	7248	Mean 62.7 years	Self-report	CERAD: Memory, Verbal Fluency, TMT B	Memory, Language processing Executive function, Attention, Concentration, Psychomotor speed	Intermediate sleepers showed better cognitive performance in all domains than short and long sleepers.
Sewell et al.	2025	589	65–80 years	Actigraphy and self-report	MoCa, Letter Comparison Test, Digit Symbol Substitution Test, TMT, N-back Working Memory Task, Spatial Working Memory Task, List Sorting Working Memory task, Matrix Reasoning, Spatial Relations, Brief Visuospatial Memory Test, Picture Sequencing Test, Hopkins Verbal Learning Test, Logical Memory Test, Verbal Paired Associates, Flanker task, Stroop Task (incongruent trial), Dimensional Change Card Sort Task	Episodic memory, Processing speed, Working memory, Visuospatial processing, Executive function/attentional control	Self-reported short sleepers showed poorer cognitive function in all domains. Actigraph-measured short sleepers showed poorer executive function/attentional control and processing speed.

*Cognitive domain or subdomain as characterized by the authors or by general practice. Abbreviations: CERAD= Consortium to Establish a Registry for Alzheimer's Disease, MMSE=Mini-Mental State Examination, MoCa=Montreal Cognitive Assessment, TMT=Trail Making Test

Global cognitive function. The association between sleep duration and global cognitive function is an inverted U-shape, and both short and long sleepers have poorer global cognitive function than intermediate sleepers. (Cao et al., 2022; Gildner et al., 2014; Ihle-Hansen et al., 2024; M. Li et al., 2022; Wu et al., 2025) However, some studies have found that only short sleepers (Deng et al., 2022) and others have found that only long sleepers (Blackwell et al., 2011; Faubel et al., 2009; Ramos et al., 2013; Scarlett et al., 2021; Spira et al., 2017; West et al., 2024) have poorer global cognitive function than intermediate sleepers.

Complex attention. Short and long sleep duration have been associated with poorer attention, measured by vigilance and processing speed, than intermediate sleep duration, (Blackwell et al., 2011; Low et al., 2019; Sewell et al., 2025) although a few studies have found no such association. (Deng et al., 2022; Scarlett et al., 2021; Spira et al., 2017; Swanson et al., 2021)

Executive function. Examinations of executive function have found that both short and long sleepers have poorer executive function than intermediate sleepers. (Blackwell et al., 2011; Rezende et al., 2024; Scarlett et al., 2021; Sewell et al., 2025) However, some studies have found no associations between sleep duration and executive function. (Okuda et al., 2021; Spira et al., 2014) Working memory—a subdomain of executive function—has similarly shown to be poorer among short and long sleepers than among intermediate sleepers. (Ihle-Hansen et al., 2024; Low et al., 2019; Okuda et al., 2021; Sewell et al., 2025) However, again, some studies have found no association between sleep duration and working memory. (Deng et al., 2022; Swanson et al., 2021)

Learning and memory. An inverted U-shaped association has also been found between sleep duration and memory. (Rezende et al., 2024; Xu et al., 2011) However, some studies have only found short sleepers (Sewell et al., 2025) and some only long sleepers (Kondo et al., 2021; Low et al., 2019; Scarlett et al., 2021; Schmutte et al., 2007; Tsapanou et al., 2017) to have poorer memory function than intermediate sleepers. One study additionally showed that long sleepers had poorer memory function than short sleepers. (Tsapanou et al., 2017) However, some studies have found no associations between sleep duration and memory function. (Deng et al., 2022; Spira et al., 2014; Swanson et al., 2021)

Language. One study found short sleepers to have poorer language than intermediate sleepers (Rezende et al., 2024), a few found long sleepers to have poorer language than intermediate sleepers (Low et al., 2019; Rezende et al., 2024; Spira et al., 2017), and one study found no association between sleep duration and language. (Deng et al., 2022)

Perceptual-motor control. Two studies examined perceptual-motor control via visuospatial ability, and found short sleepers to have poorer visuospatial ability than intermediate sleepers. (Deng et al., 2022; Sewell et al., 2025)

In the reviewed cross-sectional studies, most studies relied on self-reported measurements, and only six out of 21 studies used accelerometers. (Blackwell et al., 2011; Okuda et al., 2021; Scarlett et al., 2021; Sewell et al., 2025; Spira et al., 2017; Swanson et al., 2021) Similarly, many studies have examined global cognitive function without studying specific cognitive domains. (Cao et al., 2022; Faubel et al., 2009; Gildner et al., 2014; M. Li et al., 2022; Ramos et al., 2013; West et al., 2024; Wu et al., 2025)

2.3.2 Short-term effect of sleep duration on cognitive function

Research on the association between the duration of the previous night's sleep and cognitive function is far more limited, and has mainly focused on sleep deprivation. Previous studies have shown that a night of total sleep deprivation can alter brain connectivity (Pesoli et al., 2022), and that the effect on cognitive function is equivalent to alcohol intoxication. (Dawson & Reid, 1997) A meta-analysis showed an association between 24–48 hours of sleep deprivation and poorer cognitive function in several cognitive domains, such as complex attention and working memory (i.e., executive function). (Lim & Dinges, 2010) Sleep deprivation studies have typically been carried out in laboratory settings with a small number of participants, which has reduced the generalizability of their results. Among free-living adults, an association has been found between the previous night's short sleep duration and poorer executive function (sustained attention, concentration, working memory) (O'Brien et al., 2012) and vigilance (Neylan et al., 2010). Some studies have found no association between the previous night's sleep duration and cognitive function. (Kalanadhabhatta et al., 2021; Seelye et al., 2015) However, only Seelye et al. have examined older people—the participants in other studies have been of working age. It also remains unknown how a change in usual sleep duration the night prior to cognitive testing affects performance in cognitive tests, as no previous studies have examined this.

2.3.3 Longitudinal associations between sleep duration and cognitive function

At the beginning of this PhD project, only a few longitudinal studies had examined the association between sleep characteristics and cognitive function. However, research on the subject has increased in recent years. **Table 2** presents the previous longitudinal studies on sleep duration and cognitive function.

When examining *sleep duration at baseline and cognitive function later in life*, some studies have found that intermediate sleep duration in mid-life predicts better

global cognitive function in old age than short or long sleep duration. (Devore et al., 2014; Virta et al., 2013)

Studies of *the change in cognitive function in relation to sleep duration at baseline* have shown that short sleep duration is associated with a greater decline in global cognition in two- to eight-year follow ups (C. Li et al., 2022; Lo et al., 2014; Ma et al., 2020) but that long sleep duration is associated with a greater decline in attention and executive function, learning and memory, and global cognition in four- to ten-year follow ups. (Gildner et al., 2019; Ramos et al., 2020; Zhang et al., 2021) Some studies have found that both short and long sleep duration at baseline are associated with a decline in memory and perceptual speed, and with an overall cognitive decline in four-year follow ups. (Nakakubo et al., 2018; Overton et al., 2024; Xu et al., 2014) A 25-year follow-up study found that short sleepers showed a more pronounced decline in processing speed and immediate recall, and that both short and long sleepers showed a more pronounced decline in global cognition. (Sarsembayeva et al., 2025) However, some studies have found no associations between sleep duration at baseline and change in cognitive function in two- to- ten-year follow ups. (Blackwell et al., 2014; Devore et al., 2014; Tworoger et al., 2006; van Oostrom et al., 2018)

Fewer studies have examined *the change in sleep duration and its association with cognitive function later in life.* Short sleepers whose sleep duration decreased showed poorer reasoning, vocabulary, semantic fluency, and global cognition than those whose sleep duration stayed the same in a five-year follow up. (Ferrie et al., 2011) On the other hand, intermediate and long sleepers whose sleep duration increased had poorer episodic memory, inductive reasoning, vocabulary, verbal fluency, and global cognition than those whose sleep duration did not change in a four- to five-year follow up. (Ferrie et al., 2011; Gildner et al., 2019; X. Wang et al., 2024) Similarly, a two-hour increase or decrease from intermediate sleep duration was associated with poorer global cognition in 4- and 14-year follow ups. (Devore et al., 2014; Hua et al., 2020) Hua et al. also showed that a change from short to long sleep duration, or vice versa, was associated with poorer global cognitive function. On the other hand, a change from short to intermediate sleep duration was associated with better global cognitive function in a four- to seven-year follow up. (Hua et al., 2020; C. Li et al., 2022) Two studies have found no associations between changes in sleep duration and cognitive function in 5- and 28-year follow ups. (Troxel et al., 2022; Zitser et al., 2020)

The association between *the change in sleep duration and the change in cognitive function* has scarcely been studied. One study found that intermediate sleepers whose sleep duration increased in a four-year follow up showed a greater decline in global cognitive function. (Gildner et al., 2019)

Table 2. Previous longitudinal studies of sleep duration and specific cognitive domains.

Author	Year	follow up	N	Age (at baseline)	Sleep measurement method	Cognitive test*	Cognitive domain*	Main findings
Tworoger et al.	2006	2 years	1844	70–81 years	Self-report	TICS, MMSE, Immediate and Delayed Recall, Verbal Fluency, Digit Span Backwards	Word memory, Story memory, Attention, Executive function, Processing speed	Intermediate sleepers showed better cognitive function than short sleepers (cross-sectionally). No longitudinal associations.
Ferrie et al.	2011	Mean 5.4 years	5431	45–69 years	Self-report	Verbal Memory, Alice Heim 4-I, Mill Hill, Phonemic and Semantic Fluency, MMSE	Memory, Reasoning, Vocabulary, Verbal fluency, Global	Short sleepers whose sleep decreased in duration showed poorer inductive reasoning, vocabulary, semantic fluency, and global cognition. Long sleepers whose sleep increased in duration showed poorer inductive reasoning, vocabulary, verbal fluency, and global cognition.
Blackwell et al.	2014	3.4 years	2822	>67 years	Actigraphy, self-report	Modified Mini-Mental State Examination, TMT B	Global, Executive function	Sleep duration was not associated with cognitive function.
Devore et al.	2014	14 years	15 385	≥70 years (at the time of cognitive testing)	Self-report	TICS, MMSE, East Boston Memory Test, Immediate and Delayed Recall, Category Fluency, Digit Span Backwards	Global cognition, Memory	Short and long sleep duration in mid-life and old age were associated with poorer cognitive function in old age. Those whose sleep duration changed by two hours showed poorer cognitive function than those whose sleep duration did not change. Sleep duration was not associated with trajectories of cognitive function during a 6-year follow up.

Author	Year	follow up	N	Age (at baseline)	Sleep measurement method	Cognitive test*	Cognitive domain*	Main findings
Lo et al.	2014	2 years	66	≥55 years	Self-report	Symbol Digit Modalities Test, Symbol Search Task in the Wechsler Memory Scale–Third Edition, TMT A, Categorical Verbal Fluency Test, Design Fluency Test of Delis-Kaplan Executive Function System, TMT B, Digit Span Test, Spatial Span Test (Wechsler Memory Scale), Verbal Paired Associates Test (Wechsler Memory Scale), Rey Auditory Verbal Learning Test, Visual Reproduction Test (Wechsler Memory Scale), Visual Paired Associates Test	Processing speed, Executive function, Attention, Verbal memory, Visuospatial memory	The shorter the sleep duration at baseline, the greater the decline in global cognitive performance.
Xu et al.	2014	Mean 4.1 years	13 888	≥50 years	Self-report	Delayed Word Recall Test, MMSE	Memory	Both short and long sleep duration was associated with memory decline.
Oostrom et al.	2018	10 years	2970	41–75 years	Self-report	15-word Verbal Learning Test, Stroop, Word Fluency, Letter Digit Substitution Test	Global, Memory, Processing speed, Cognitive flexibility	Intermediate sleepers had better global cognitive function, memory, and cognitive flexibility than long sleepers (cross-sectionally). Sleep duration was not associated with changes in cognitive function.

Author	Year	follow up	N	Age (at baseline)	Sleep measurement method	Cognitive test*	Cognitive domain*	Main findings
Nakakubo et al.	2019	4 years	3151	≥65 years	Self-report	National Center for Geriatrics and Gerontology-Functional Assessment Tool: Word List Memory, TMT A, TMT B, Symbol Digit Substitution Test	Memory, Attention, Executive function, Processing speed	Intermediate sleepers showed less decline in cognitive function than short or long sleepers.
Gildner et al.	2019	Mean 4.7 years	1595	≥50 years	Self-report	Immediate & Delayed Verbal Recall, Digit Span, Verbal Fluency	Verbal learning and recall Attention/Working memory Executive function Global	Intermediate sleepers at baseline whose sleep increased in duration showed a greater decline in cognitive function. Long sleepers at baseline showed a greater decline in attention/working memory and executive function.
Ramos et al.	2020	7 years	5247	45–75 years	Self-report	Spanish-English Verbal Learning Test, Word Fluency, Digit Symbol Substitution, Six-item Screener	Episodic learning and memory, Language, Processing Speed	Long sleep duration was associated with a decline in episodic learning and memory.
Zitser et al.	2020	28 years	613	Mean 42.3 years	Self-report	MoCA, Digit Span, Fluency, TMT, Hopkins Verbal Learning Test-Revised, Rey-Osterrieth Complex Figure, Reaction time (CANTAB)	Global cognition, Executive function, Memory, Processing speed	No differences were observed between the cognitive function of sleep duration trajectory groups.

Author	Year	follow up	N	Age (at baseline)	Sleep measurement method	Cognitive test*	Cognitive domain*	Main findings
Troxel et al.	2022	5 years	168	Mean 67.7 years	Actigraphy	Pittsburgh Hill/Homewood Research on Neighborhood Change and Sleep Study Cognitive Assessment Battery	Attention, Visuospatial ability, Language, Delayed recall, Immediate recall, Executive function	Neither the level of or changes in sleep duration affected cognitive function.
Overton	2024	4 years	5631	Mean 77.7	Self-report	Varied between study cohorts	Episodic memory, Verbal Fluency, Perceptual speed, Executive functioning, Global cognition	Short and long sleepers showed a steeper decline in perceptual speed than intermediate sleepers.
Wang et al.	2024	4 years	5051	≥45 years	Self-report	Word Recall, TICS	Episodic memory, Mental intactness	Long sleepers whose sleep increased in duration had poorer episodic memory and mental intactness than intermediate stable sleepers.
Sarsembayeva et al.	2025	25 years	5132	≥55 years	Self-report	MMSE, 15-word Test, Coding Task	Global cognition, Memory, Processing speed	Short sleepers showed a more pronounced decline in processing speed and immediate recall. Both short and long showed a more pronounced decline in global cognition.

*Cognitive domain as characterized by the authors or general practice. Abbreviations: CANTAB= Cambridge Neuropsychological Test Automated Battery, MMSE=Mini-Mental State Examination, TICS= Telephone Interview for Cognitive Status, TMT=Trail Making Test

2.4 Sleep difficulties and cognitive function

2.4.1 Cross-sectional associations between sleep difficulties and cognitive function

Sleep difficulties have quite consistently shown to be associated with poorer cognitive function, but which specific sleep difficulties are associated with overall and specific domains of cognitive function remains inconclusive. **Table 3** summarizes the previous cross-sectional studies of sleep difficulties and cognitive domains. Most of these studies have focused on overall sleep difficulties, and those that have focused on individual sleep difficulties have usually examined only a selected few. It also remains unclear which cognitive domains are affected by sleep difficulties.

Global cognitive function. Sleep difficulties have been linked to poorer global cognition. (Amer et al., 2013; Gildner et al., 2014; Tang et al., 2025; Tsapanou et al., 2017) Actigraph-measured wake after sleep onset (WASO) has also shown to be associated with poorer global cognitive function, (Blackwell et al., 2011; McSorley et al., 2019; Wu et al., 2025) although one study found no such association. (Spira et al., 2017) Another study found specifically difficulties falling asleep or staying asleep, (Tworoger et al., 2006) and another found sleep fragmentation, percentage of sleep, and wake bouts (McSorley et al., 2019) to be associated with poorer cognitive function.

Complex attention. One study found actigraph-measured WASO—but not self-reported sleep difficulties—to be associated with attention, (Blackwell et al., 2011) whereas another found both poorer sleep efficiency and greater WASO to be associated with poorer attention. (Troxel et al., 2022) Some studies have found overall sleep difficulties to be associated with processing speed—a subdomain of complex attention—, (Saint Martin et al., 2012; Scarlett et al., 2021) but others have found that specifically greater WASO, daytime somnolence, and sleep fragmentation are associated with slower processing speed. (Sewell et al., 2025; Swanson et al., 2021; Tsapanou et al., 2016) However, a few studies found no association between sleep difficulties and complex attention. (Ling et al., 2016; Nebes et al., 2009; Spira et al., 2017)

Executive function. Overall sleep difficulties have been associated with poorer executive function (i.e., working memory, set-shifting, and abstract reasoning). (Nebes et al., 2009; Tang et al., 2025) More specifically, early-morning awakening—but not difficulties initiating or maintaining sleep—(Ling et al., 2016), greater WASO (Sewell et al., 2025; Troxel et al., 2022), sleep efficiency (Troxel et al., 2022), and insomnia (Rezende et al., 2024) have been associated with poorer executive function. However, some studies have found no associations between

sleep difficulties and executive function. (Scarlett et al., 2021; Spira et al., 2017; Suemoto et al., 2023; Swanson et al., 2021)

Learning and memory. Poor overall sleep quality (Tang et al., 2025), longer sleep onset latency (Schmutte et al., 2007), insomnia (Overton et al., 2024; Xu et al., 2011), and greater WASO (Sewell et al., 2025; Spira et al., 2017) have been associated with poorer memory function. Some studies, however, have found no association between sleep difficulties and memory function. (Ling et al., 2016; Rezende et al., 2024; Scarlett et al., 2021; Suemoto et al., 2023)

Language. One study has found greater WASO and a greater number of awakenings to be associated with poorer language when measured by verbal fluency, (Suemoto et al., 2023) whereas another study has found no association between sleep difficulties and language. (Rezende et al., 2024)

Perceptual-motor control. Two studies have found greater WASO to be associated with poorer visuospatial ability, (Sewell et al., 2025; Troxel et al., 2022) one has found sleep efficiency to be associated with visuospatial ability, (Troxel et al., 2022) and another has found no associations between sleep difficulties and visuospatial ability. (Ling et al., 2016)

Table 3. Previous studies of cross-sectional association between sleep difficulties and specific cognitive domains.

Author	Year	N	Age	Sleep measure-ment method	Cognitive test	Cognitive domain*	Main findings
Schmutte et al.	2007	375	75–85 years	Self-report	Blessed Information-Memory-Concentration test, Fuld Object–memory Evaluation, Selective Reminding Task, Raven's Progressive Matrixes Set A, Purdue Pegboard Test, subtests of the Wechsler Adult Intelligence Scale	Verbal, nonverbal	Those with longer sleep onset latencies showed poorer verbal knowledge, long-term memory, fund of information, and visuospatial reasoning.
Nebes et al.	2009	157	65–80-years	Self-report	N-Back Test, Stroop Test, Hayling Test, TMT B, Test of Nonverbal Intelligence, Logical Memory Test	Information processing speed, Working memory, Inhibitory function, Attention shifting, Abstract reasoning, Episodic memory	Good and poor sleepers scored differently in tests of working memory, attentional set-shifting, and abstract problem-solving but not in processing speed, inhibitory function, or episodic memory.
Blackwell et al.	2011	3132	≥65 years	Actigraphy and self-report	Modified Mini-Mental State Examination, TMT B, Digit Vigilance Test	Global, Attention, Vigilance	Those with greater actigraph-measured WASO showed poorer global cognition and attention than those with shorter WASO. No associations found between self-reported sleep difficulties and cognitive function.
Xu et al.	2011	28 670	50–85 years	Self-report	Delayed Word Recall Test	Memory	Those with insomnia had poorer memory than those without.

Author	Year	N	Age	Sleep measure-ment method	Cognitive test	Cognitive domain*	Main findings
Saint Martin et al.	2012	272	>65 years	Self-report	MacNair, MMSE, Grober and Buschké Selective Reminding Test, Benton Visual Retention Test, TMT A and B, Wechsler Adult Intelligence Scale III, Stroop Test, Alphabetic Fluency and Categorical Fluency	Verbal memory, Episodic functioning, Visuospatial working memory, Attention, Attention switching, Processing speed, Abstract reasoning, Inhibition processes, Integrity of sematic memory, Strategic processes	Poor sleepers showed slower processing speed.
Ling et al.	2016	859	Mean 71.9	Self-report	Digit Span, Rey Auditory Verbal Learning Test, Story Memory, Brief Visuospatial Memory Test-Revised, Color Trails Test (1 and 2), Block design, Verbal fluency	Attention, Verbal memory, Visuospatial ability, Executive function	Early-morning awakening was associated with poorer executive function. Difficulty initiating sleep and difficulty maintaining sleep were not associated with cognitive function.
Spira et al.	2017	782	≥71 years	Actigraphy	Modified Mini-Mental State Examination, California Verbal Learning Test-II-Short Form, Digit Span, verbal Fluency tests, TMT B	Global, Memory, Attention, Working memory, Verbal fluency, Executive function	Greater WASO was associated with poorer verbal memory.
Tsapanou et al.	2017	1589	≥65 years	Self-report	Greek Verbal Learning Test, Medical College of Georgia Complex Figure Test	Memory	Those who had poor sleep quality had poorer memory than those who did not.

Author	Year	N	Age	Sleep measure-ment method	Cognitive test	Cognitive domain*	Main findings
Scarlett et al.	2021	1520	≥50 years	Self-report	MMSE, MoCA, Verbal Fluency, Immediate and Delayed Verbal Recall, Color Trails, Choice Reaction Test	Global cognition, Memory, Processing speed, Executive function	A greater number of sleep problems were associated with slower performance in Choice Reaction test's cognitive response time and total response time.
Swanson et al.	2021	1126	Mean 65 years	Actigraphy	Immediate and Delayed Verbal Recall, Symbol Digit Modalities Test, Digit Span Backwards Task	Immediate and delayed verbal memory, Working memory, Information processing speed	Greater WASO and sleep fragmentation were associated with slower information processing speed.
Suemoto et al.	2023	703	>55 years	Polygraphy for 1 night, actigraphy for 7 nights	10-word List, Verbal Fluency, TMT	Memory, Language and executive ability, Executive function, Processing speed, Visuospatial organization	Greater WASO and number of awakenings were associated with poorer verbal fluency.
Rezende et al.	2024	7248	Mean 62.7 years	Self-report	CERAD: Memory, verbal fluency, TMT B	Memory Language processing, Executive function, Attention, concentration, and Psychomotor speed	Insomnia was associated with poorer executive function.

Author	Year	N	Age	Sleep measure-ment method	Cognitive test	Cognitive domain*	Main findings
Sewell et al.	2025	589	65–80 years	Actigraphy and self-report	MoCa, Letter Comparison Test, Digit Symbol Substitution Test, TMT, N-back Working Memory task, Spatial Working Memory task, List Sorting Working Memory task, Matrix Reasoning, Spatial Relations, Brief Visuospatial Memory Test, Picture Sequencing Test, Hopkins Verbal Learning Test, Logical Memory Test, Verbal Paired Associates, Flanker task, Stroop task (incongruent trial), Dimensional Change Card Sort Task	Episodic memory, Processing speed, Working memory, Visuospatial processing, Executive function/attentional control	Greater WASO was associated with poorer cognitive function in all domains.

*Cognitive domain as characterized by the authors or general practice. Abbreviations: CERAD=the Consortium to Establish a Registry for Alzheimer's Disease, MMSE=Mini-Mental State Examination, MoCa=Montreal Cognitive Assessment, TMT= Trail Making Test, WASO=Wake After Sleep Onset

2.4.2 Longitudinal associations between sleep difficulties and cognitive function

Table 4 summarizes the results of previous longitudinal studies of sleep difficulties and cognitive function. When reviewing *sleep duration at baseline and cognitive function later in life*, one study found an association between greater sleep difficulties in mid-life and poorer cognitive function in old age. (Virta et al., 2013) One study also showed that sleep disturbance at the age of 60 was associated with poorer cognitive function at the ages of 66 and 72. (Behrens et al., 2023)

Studies of *the change in cognitive function in relation to sleep difficulties at baseline,* showed that greater overall sleep difficulties, WASO, sleep fragmentation, poorer percentage of sleep, more wake bouts, and excessive daytime were associated with a higher rate of cognitive decline in a four- to five-year follow up. (McSorley et al., 2019; Nakakubo et al., 2018; Overton et al., 2024) Similarly, another study found that greater WASO, more long wake periods, and poorer sleep efficiency were associated with a greater decline in executive function in a three-year follow up. (Blackwell et al., 2014) In its long follow up of 25 years, another study found early-morning awakenings to be associated with a more pronounced decline in processing speed (*complex attention*), problems falling asleep to be associated with a more pronounced decline in immediate recall (*learning and memory),* and severe night awakenings to be associated with a more pronounced decline in global cognition. (Sarsembayeva et al., 2025) Another study showed that insomnia was associated with greater memory decline in a 10-year follow up. (Arévalo et al., 2023) Interestingly, one study showed that excessive daytime sleepiness, poorer sleep efficiency, and insomnia were only associated with declining global cognition in physically robust (i.e., not frail) people in a 5.5-year follow up. (Chuang et al., 2022) However, some studies found no association between sleep difficulties and the change in cognitive function in a two- to seven-year follow up. (Lo et al., 2014; Ramos et al., 2020; Sha et al., 2019; Tang et al., 2025; Tworoger et al., 2006)

Only two previous studies have examined *the change in sleep difficulties and its association with cognitive function later in life*. One showed that increasing daytime somnolence was associated with a slower processing speed in a three-year follow up. (Tsapanou et al., 2016) The other found, in a follow up of five years, that improved sleep efficiency was associated with better executive function, language, and immediate recall—but not attention, visuospatial ability or delayed recall—and that increasing WASO was associated with poorer attention, executive function, and visuospatial ability—but not language, or immediate and delayed recall. (Troxel et al., 2022) No previous studies have examined *change in sleep difficulties and change in cognitive function* concurrently.

Table 4. Previous longitudinal studies of sleep difficulties and cognitive domains.

Author	Year	Follow up	N	Age at baseline	Sleep measurement method	Cognitive test	Cognitive domain*	Main findings
Blackwell et al.	2014	3.4 years	2822	>67 years	Actigraphy, self-report	Modified Mini-Mental State Examination, TMT B	Global cognition, Executive function	Greater WASO, long wake episodes and poorer sleep efficiency were associated with a decline in TMT B. Overall sleep difficulties were associated with poorer TMT B.
Lo et al.	2014	2 years	66	≥55 years	Self-report	Symbol Digit Modalities Test, Symbol Search Task of Wechsler Memory Scale–Third Edition, TMT A, Categorical Verbal Fluency Test, Design Fluency Test of Delis-Kaplan Executive Function System, TMT B, Digit Span Test, Spatial Span Test, Verbal Paired Associates Test, Rey Auditory Verbal Learning Test, Visual Reproduction Test, Visual Paired Associates Test	Processing speed, Executive function, Attention, Verbal memory, Visuospatial memory	Sleep quality at baseline had no effect on cognitive change.

Author	Year	Follow up	N	Age at baseline	Sleep measurement method	Cognitive test	Cognitive domain*	Main findings
Tsapanou et al.	2016	3.2 years	1098	≥65-years	Self-report	Selective Reminding Test, 15-item Boston Naming Test, Boston Diagnostic Aphasia Examination, Mattis Identities and Oddities Subtest, raw score on Wechsler Adult Intelligence Scale – Revised Similarities Subtest, mean number of words generated during three 60-second trials, Color Trails Test parts 1 and 2	Memory, Language, Executive functioning, Processing speed	Increasing daytime somnolence was associated with slower processing speed.
Nakakubo et al.	2019	4 years	3151	≥65-years	Self-report	National Center for Geriatrics and Gerontology-Functional Assessment Tool: word list memory, TMT A, TMT B, Symbol Digit Substitution Test	Memory, Attention, Executive function, Processing speed	Excessive daytime sleepiness was associated with a higher rate of cognitive decline.
Sha et al.	2019	5 years	3584	≥60-years	Self-report	TICS & Figure Drawing Test, Immediate and Delayed Verbal Recall	Executive function, Episodic memory	No longitudinal associations.
Ramos et al.	2020	7 years	5247	Mean 63 years	Self-report	Spanish-English Verbal Learning Test, Word Fluency, Digit Symbol Substitution, Six-item Screener	Episodic learning and memory, Language, Processing speed	Daytime sleepiness and insomnia were not associated with cognitive decline.

Author	Year	Follow up	N	Age at baseline	Sleep measurement method	Cognitive test	Cognitive domain*	Main findings
Troxel et al.	2022	5 years	168	Mean 67.7 years	Actigraphy	Pittsburgh Hill/Homewood Research on Neighborhood Change and Sleep Study, Cognitive Assessment Battery	Attention, Visuospatial ability, Language, Delayed recall, Immediate recall, Executive function	Sleep efficiency and WASO were cross-sectionally associated with poorer attention, executive function, and visuospatial ability. Improved sleep efficiency was associated with executive function, language, and immediate recall.
Arévalo et al.	2023	10.5 years	444	45–75 years	Self-report	MMSE, Word List Learning, Word List Recognition, Percent Retention, Stroop, Letter Fluency, Digit Span Forward, Digit Span Backward, Clock Drawing, Weighted Figure Copying	Global cognition, Executive function, Memory	Insomnia was associated with memory decline.
Overton et al.	2024	4 years	5631	Mean 77.7 years	Self-report	Varied between study cohorts	Episodic memory, Verbal Fluency, Perceptual speed, Executive functioning, Global cognition	Insomnia symptoms were cross-sectionally associated with poorer episodic memory. Subjective sleep disturbances were consistently associated with poorer cognition and steeper cognitive decline.

Author	Year	Follow up	N	Age at baseline	Sleep measurement method	Cognitive test	Cognitive domain*	Main findings
Sarsembayeva et al.	2025	25 years	5132	≥55 years	Self-report	MMSE, 15-word Test, Coding Task	Global cognition, Memory, Processing speed	Those with early-morning awakenings showed a more pronounced decline in processing speed. Those with problems falling asleep showed a more pronounced decline in immediate recall. Those with severe night awakenings showed a more pronounced decline in global cognition.
Tang et al.	2025	4 years	2228	≥65 years	Self-report	Chinese Mini-Mental State Examination, Immediate and delayed recall of East Boston Memory Test, Digit Span Backwards Assessment, Symbol Digit Modalities Test	Perceptual speed, Episodic memory, Working memory, General cognition, Global cognition	Poor sleep quality was cross-sectionally associated with poorer global cognition, working memory, episodic memory, and general cognition. Sleep parameters were not associated with cognitive function over time.

*Cognitive domains as characterized by the authors or general practice. Abbreviations: MMSE=Mini-Mental State Examination, TICS= Telephone Interview for Cognitive Status, TMT=Trail Making Test, WASO=Wake After Sleep Onset

2.5 Retirement

Retirement is a prominent milestone and involves major changes in a person's daily life and time use. Consequently, retirement can have a great effect on health behaviors and social activity and subsequently affect health and well-being. Retirement has shown to be associated with improved psychological well-being (Lahdenperä et al., 2022; Mein et al., 2003), to modify physical activity behavior (Suorsa et al., 2022), to increase the risk of chronic disease (Behncke, 2012), and to reduce social networks (Kauppi et al., 2021). However, a recent overview of reviews has suggested that the outcomes of retirement are vastly dependent on socioeconomic status. (Vigezzi et al., 2025) It has also been suggested that retirement affects sleep (Hagen et al., 2016) and cognitive function (Xue et al., 2018).

One review article concluded that people with sleep difficulties are more likely to retire due to health problems, and that retirement increases sleep duration and decreases sleep difficulties. (Myllyntausta & Stenholm, 2018) The results of recent studies are in line with these conclusions, and have similarly shown that sleep duration increases (Garefelt et al., 2021; Myllyntausta et al., 2017, 2020) and sleep difficulties decrease (Mutambudzi & Van Solinge, 2021; Myllyntausta et al., 2018; Peristera et al., 2022) after retirement. Interestingly, Peristera et al. showed that those with greater pre-retirement sleep difficulties benefited the most from retirement in terms of improved sleep quality. However, one study found a decrease in only self-reported—not accelerometer-measured—sleep difficulties after retirement. (Garefelt et al., 2022)

The results regarding changes in cognitive function during the retirement transition are inconclusive. A recent meta-analysis showed that memory function slightly decreased after retirement, but that global cognitive function was not affected by retirement. (Alvarez-Bueno et al., 2021) However, several individual studies have shown an accelerated decrease in cognitive function after retirement. (Carr et al., 2020; De Grip et al., 2015; Hamm et al., 2020; Lee et al., 2019; Meng et al., 2017; Oi, 2019; Xue et al., 2018) Of the specific cognitive domains, verbal memory (Xue et al., 2018), episodic memory (Hamm et al., 2020), and information processing (De Grip et al., 2015) have shown to decrease after retirement. One study found no difference between the cognitive function of retirees and their counterparts who were still active in working life. (Mizuochi & Raymo, 2022)

Examining the determinants of the accelerated decline in cognitive function in post-retirement might provide insights into the factors behind the changes in cognitive function during the retirement transition. It has been suggested that the accelerated decline in cognitive function after retirement only affects individuals with certain characteristics, but these results are inconsistent. One study found that the decline in cognitive function only accelerated among men (Atalay et al., 2019), while others have found it only happens among women. (Hamm et al., 2020; Oi,

2019) Some studies have found that a higher level of mental demand at work protects against the accelerated decline of cognitive function, (Carr et al., 2020; Fisher et al., 2014) although one study has found that individuals with highly complex work suffer the fastest decline in spatial abilities after retirement. (Finkel et al., 2009) Another study found that people with greater job strain show a less prominent decline in cognitive function after retirement. (Nilsen et al., 2021) One study found that postponing retirement was beneficial in terms of post-retirement cognitive decline (Grotz et al., 2016; Hale et al., 2021) but another found that early retirement was beneficial. (Celidoni et al., 2017) These mixed results might be explained by the differences in the measured cognitive domains and populations of these studies.

The findings that sleep characteristics and cognitive function are associated and that both sleep and cognitive function change during the retirement transition raise the question of whether these changes in sleep and cognitive function during retirement are interconnected. No studies have previously examined this.

2.6 Gaps in previous research

Although the association between sleep characteristics and cognitive function has been fairly extensively cross-sectionally studied, several gaps still exist in the research. Firstly, although the association between sleep characteristics and global cognitive function has been repeatedly shown, the specific cognitive domains and sleep characteristics that contribute to these observed associations remain unclear. Secondly, as most studies of the association between sleep duration and cognitive function have been based on self-reported sleep measurements, studies using accelerometer-measured sleep indicators are needed. Thirdly, it remains unknown which individual sleep difficulties are associated with cognitive function. Finally, most previous studies have focused on older populations, with wide age ranges. A wide age range makes populations more heterogeneous in terms of, for example, health. Turning the focus onto a healthy population in a restricted age group of aging workers may reveal the factors behind the forthcoming cognitive decline, even before any clinically significant decline is prevalent.

Only a few population-based studies have examined the association between the duration of the previous night's sleep and cognitive function among adults outside laboratory settings. (Kalanadhabhatta et al., 2021; Neylan et al., 2010; O'Brien et al., 2012; Seelye et al., 2015) Of these studies, none have considered usual sleep duration and how a change in this is associated with cognitive function.

When I started working on this PhD thesis, longitudinal studies of sleep characteristics were scarce. Although the number of studies on the topic have increased in recent years, more research based on accelerometer-measured sleep and

comprehensive cognitive test batteries is still needed, especially in longitudinal settings.

Previous research on cognitive function and retirement has mainly focused on the trends of cognitive function before and after retirement, and thus the change in cognitive function during the actual retirement transition remains unexplored. Moreover, no studies have examined how changes in sleep duration and quality during the retirement transition are associated with changes in cognitive function during and after the retirement transition.

3 Aims

The overall aim of this PhD thesis is to examine the association between sleep characteristics and cognitive function among late mid-life and older adults, focusing on aging workers and on the retirement transition. The PhD study examined the associations between sleep duration and sleep difficulties and cognitive function across multiple cognitive domains before, during and after the retirement transition. **Figure 4** presents an overview of the thesis aims**.**

The specific aims of this PhD thesis are:

1) to examine the cross-sectional associations between sleep duration and sleep difficulties and cognitive function among aging workers (Study I)

2) to examine the association between the duration of the previous night's sleep and cognitive function among older adults (Study II)

3) to examine the concurrent changes in sleep and cognitive function during the retirement transition (Studies III and IV)

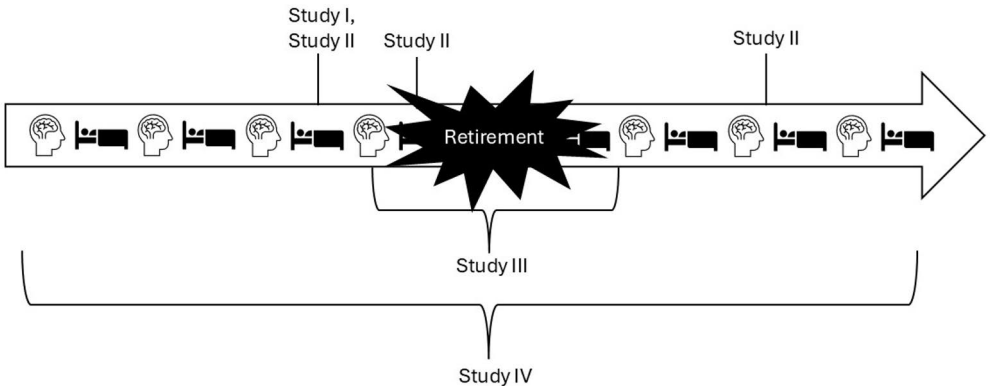

Figure 4. Overview of PhD thesis' aims by sub-study. The arrow represents time, with the retirement transition in the middle.

4 Materials and Methods

4.1 Study populations

To accomplish its aims, this PhD thesis utilizes four cohort studies: the Finnish Retirement and Aging Study (from here on, FIREA), the Cardiovascular Risk in Young Finns Study (from here on, the Young Finns Study), the Turku Senior Health Clinic Study (from here on, the Health Clinic Study), and the Whitehall II Study (from here on Whitehall II). The characteristics of each study cohort are shown in **Table 5** and a flowchart of the sub-study cohorts is shown in **Figure 5**.

Table 5. Characteristics of study populations.

Study characteristics	Study I	Study II	Study III	Study IV
Study cohort	FIREA	FIREA Young Finns Study Health Clinic Study	FIREA	Whitehall II
Sample size	284	2949	259	2980
Setting	Cross-sectional	Cross-sectional	Longitudinal	Longitudinal
Age	59–64	59–92	59–66*	46–78*

* Age during study phase immediately before retirement

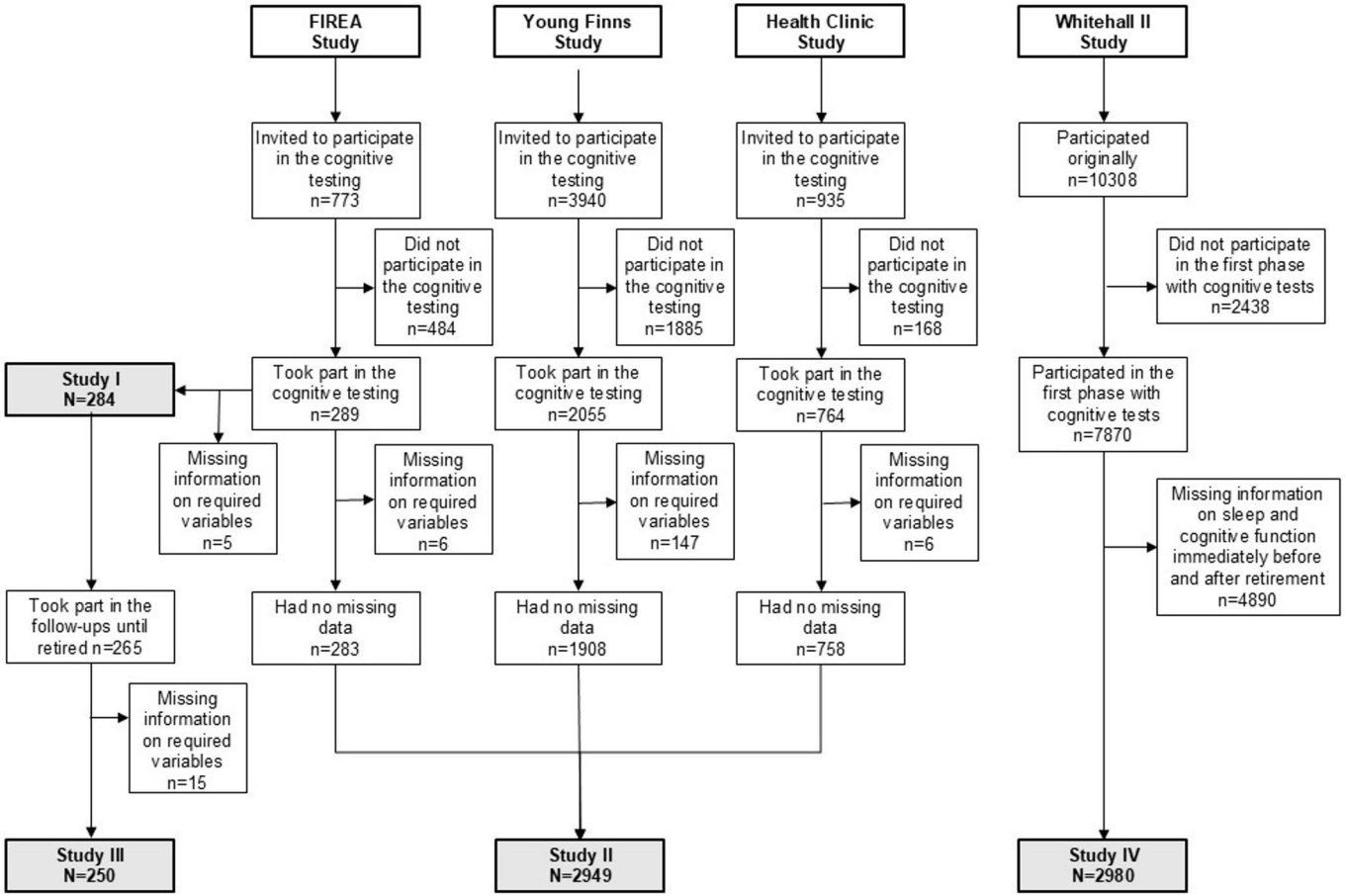

Figure 5. Flowchart of participants of each sub-study. Modified from flowchart in Study II.

4.1.1 Finnish retirement and aging study

FIREA is a longitudinal cohort study of public sector workers in Finland, which began in 2013. Its aim is to follow workers from employment to full-time retirement and to examine their health behaviors, clinical risk factors, and health before, during, and after their transition to statutory retirement. (Stenholm et al., 2023) Informed consent has been obtained from all the participants and FIREA has been approved by the Ethics Committee of the Hospital District of Southwest Finland.

Public sector employees whose individual retirement dates were in 2014–2019 and who worked in one of the 27 municipalities in Southwest Finland or the 11 selected cities or five hospital districts around Finland in 2012, were eligible for inclusion in the study population (n=10 629). Individual retirement dates were obtained from the institution for public sector earnings-related pensions in Finland (Keva). The participants were first contacted via a postal questionnaire 18 months prior to their estimated retirement date. By the end of 2017, 63% of the eligible study sample had responded at least once, resulting in a study sample of 6673.

After responding to the first questionnaire, Finnish-speaking participants whose individual retirement date was between 2017 and 2019, who lived in Southwest Finland and who were still working, were invited to participate in the clinical sub-study (n=773). Of these, 290 (38%) participated in the first clinical examination of the sub-study between September 2015 and May 2018. After this, the participants underwent annual measurements until each of them had retired. The mean number of annual measurements was 3.0 (range 1–5, SD 0.6).

Studies I and II utilized the initial clinical measurements, accompanied by the questionnaire responses and accelerometer readings. The participants were also required to have information on sleep characteristics and study-specific covariates, and the resulting analytic study populations consisted of 284 (Study I) and 283 (Study II) participants.

For Study III, the participants were required to have information on cognitive function and sleep characteristics from the study waves immediately before and after the retirement transition, as well as specific covariates. The resulting analytic sample consisted of 250 participants.

4.1.2 Young Finns Study

The Young Finns Study is a longstanding, national multi-center study originally designed to provide evidence on the importance and timing of early life exposures for the development of cardiovascular disease. (Raitakari et al., 2008) It began in 1980 and was carried out in all five Finnish university cities with medical schools and their rural surroundings. To obtain a representative sample of Finnish children,

a sample of 4320 children and adolescents aged 3, 6, 9, 12, 15, and 18 years were randomly chosen from the population registers of these areas.

The first cross-sectional study was conducted in 1980, in which 3596 (83%) of the eligible children participated. The participants were followed up every three to nine years. In the 2018–2020 study wave, data collection expanded to include the parents and offspring of the original participants.

Study II used data collected from the parents of the original Young Finns Study participants. A total of 3940 parents of the original Young Finns Study participants were invited to attend a detailed clinical examination. Of these, 2149 attended the clinical examination and 2055 underwent cognitive testing. For Study II, participants were eligible if they had information on cognitive function, sleep characteristics, and covariates. This resulted in an analytic sample of 1908.

4.1.3 Health Clinic Study

The Health Clinic Study participants are home-dwelling 75-year-old citizens (in 2020) in the city of Turku. (Salminen et al., 2023) At the beginning of 2020, all home-dwelling citizens of Turku who were born in 1945 were contacted (N=2044). Those receiving municipal home care (n=196) were excluded, 33 died before the invitation, 391 declined to participate, and 128 were unreachable. This left a study sample of 1296 participants. Each participant whose clinical examination was between January 2020 and February 2021 was invited to participate in detailed cognitive testing (n=935), and of these, 766 (82%) accepted. For Study II, participants were eligible if they had information on cognitive function, sleep characteristics, and covariates. This resulted in an analytic sample of 758.

4.1.4 Whitehall II Study

Whitehall II is an ongoing longitudinal cohort study, which began in 1985. (Marmot & Brunner, 2005) Eligible participants were 35–55-year-old civil servants working in the London offices of 20 Whitehall departments in 1985–1988 (N=10 308).

The participants have been followed up every 2.5 years with postal questionnaires (every study phase) and clinical examinations (every other study phase). Cognitive testing was introduced into the clinical examinations in Phase 5, and therefore this PhD study used data from Study Phases 5 (1997–1999, n=7870), 7 (2002–2004, n=6967), 9 (2007–2009, n=6761) and 11 (2012–2013, n=6318). The study population was further restricted to those who retired during these phases and who had data on sleep and cognitive function from at least one study phase before retirement and one after retirement. This resulted in an analytic sample of 2980 participants for Study IV.

4.2 Assessment of sleep

This PhD thesis uses both self-reported and accelerometer-based sleep characteristics. **Table 6** shows these study-specific sleep characteristics.

Table 6. Sleep characteristics in each study.

	Study I	**Study II**	**Study III**	**Study IV**
Sleep duration	Accelerometry	Self-reported Accelerometry	Accelerometry	Self-reported
Categorization	**Short** <7 h, **Intermediate** 7–9 h, **Long** ≥9 h			
Sleep difficulties	Jenkin's Sleep Problem Scale		Jenkin's Sleep Problem Scale	Jenkin's Sleep Problem Scale
Categorization	**No difficulties**: never, 1–3 nights per month, 1 night per week **Difficulties**: 2–4 nights per week, 5–6 nights per week, nearly every night		**No difficulties**: never, 1–3 nights per month, 1 night per week **Difficulties**: 2–4 nights per week, 5–6 nights per week, nearly every night	**No difficulties**: not at all, 1–3 days/month, 4–7 days/month, 8–14 days/month **Difficulties**: 15–21 days/month, 22–31 days/month

4.2.1 Self-reported sleep duration

Usual sleep duration was elicited using questionnaires in each study cohort.

In FIREA, the participants responded to the survey question "How many hours do you usually sleep per 24 hours?" The response categories were 6 h or less, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, and 10 h or more. In the Young Finns Study, nightly sleep duration was elicited separately for weekdays and weekend days. The response categories were 1, 2, 3, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5, 11, 11.5, 12, 13, and 14 h. The following formula was used to calculate the weighted average to obtain the participants' usual sleep duration: (5 * usual sleep duration on weekdays + 2 * usual sleep duration on weekends)/7. In the Health Clinic Study, the participants were asked "What time do you usually go to sleep?" and "What time do you usually wake up in the morning?" Based on the responses, usual sleep duration was calculated at 0.5-hour intervals. Finally, in Whitehall II, the participants responded to the question "How many hours of sleep do you get on an average week-night?" The response options were 5 hours or less, 6 hours, 7 hours, 8 hours, and 9 hours or more.

Sleep duration was categorized as short (<7 hours), intermediate (7–<9 hours) and long (≥9 hours), according to the National Sleep Foundation's guidelines for optimal duration of sleep. (Hirshkowitz et al., 2015)

Sleep duration the night prior to cognitive testing was examined in FIREA, the Young Finns Study and the Health Clinic Study, and was elicited before the cognitive tests were conducted. Based on their usual sleep duration and their sleep duration the night prior to cognitive testing, the participants were categorized as having 1) shorter than usual sleep duration, 2) same as usual sleep duration, and 3) longer than usual sleep duration. Sleep duration was considered shorter/longer than usual if the difference between usual sleep duration and sleep duration the night prior to cognitive testing was at least one hour.

The change in self-reported sleep duration during the retirement transition was examined in Whitehall II, which evaluated sleep duration data in the study phases directly before and after the participant's retirement. As there were only a few long sleepers (0.7% before and 2.0% after retirement), these were excluded. Based on the last report before retirement and the first after retirement, the participants were categorized into four groups indicating the change in sleep duration during the retirement transition: 1) constantly short sleep, 2) increasing sleep duration (i.e., short sleepers before and intermediate sleepers after retirement), 3) decreasing sleep duration (i.e., intermediate sleepers before and short sleepers after retirement), and 4) constantly intermediate sleep.

4.2.2 Self-reported sleep difficulties

FIREA and Whitehall II evaluated sleep difficulties using the self-administered Jenkins Sleep Problem Scale. (Jenkins et al., 1988) It asks participants to report how often during the previous four weeks they have: 1. had difficulties falling asleep (i.e. "have trouble falling asleep"), 2. had difficulties maintaining sleep during the night (i.e. "wake up several times per night"), 3. stayed asleep (i.e. "have trouble staying asleep (including too early awakening)"), and 4. experienced nonrestorative sleep (i.e. "wake up after your usual amount of sleep feeling tired or worn out"). Each difficulty was reported separately and the response options in FIREA were 1) never, 2) 1–3 nights per month, 3) 1 night per week, 4) 2–4 nights per week, 5) 5–6 nights per week, and 6) nearly every night; and in Whitehall II 1) not at all, 2) 1–3 days/month, 3) 4–7 days/month, 4) 8–14 days/month, 5) 15–21 days/month, and 6) 22–31 days/month.

The items of the Jenkins Sleep Problem Scale correspond to the DSM-5 diagnostic criteria for insomnia (excluding nonrestorative sleep). The DSM-5 defines insomnia as any of these symptoms occurring at least three nights per week. Following this diagnostic criterion, we defined sleep difficulty as any of the four individual sleep difficulties occurring at least two to four night per week (FIREA) or at least 15–21 days/month (Whitehall II). To examine any sleep difficulties, we created a variable on the basis of the most frequent symptom reported by the participant, and dichotomized the responses into *no sleep difficulties* and *sleep difficulties*.

In Study I, each individual sleep difficulty (i.e., falling asleep, maintaining sleep, staying asleep (including waking up too early in the morning), and nonrestorative sleep) was also analyzed separately using a similar categorization of *no sleep difficulties* and *sleep difficulties*.

In the studies that had longitudinal designs (Studies III and IV), the effect of retirement was evaluated by examining the dichotomized sleep difficulty responses in the phases immediately before and after retirement. Sleep difficulties during the retirement transition were categorized into 1) constantly without sleep difficulties, 2) increasing sleep difficulties (i.e., no difficulties before retirement but difficulties after), 3) decreasing sleep difficulties (i.e., difficulties before retirement but none after), and 4) constant sleep difficulties.

4.2.3 Accelerometer-measured sleep

Accelerometry-measurements were used in Studies I, II and III, taken from the FIREA data. Sleep was measured by wrist-worn triaxial ActiGraph wActiSleep-BT and wGT3X-BT (**Figure 6**) accelerometers (ActiGraph, Pensacola, Florida, US) which were initialized to record at 80 Hz.

Figure 6. Actigraph wGT3X-BT.

The accelerometer was mailed to the participants before their clinical examination and they were asked to continuously wear it on their nondominant wrist for at least seven days and nights, including at least two working days and two days off (while still active in working life). In an accompanying log, participants were asked to record the date, in bed time, out of bed time, and information about the working day (working day or day off) on each day that they wore the devices.

Study I used the R package GGIR version 1.7-1 to analyze raw acceleration data from the wrist-worn accelerometer in R statistical software, version 3.5.1 (R Foundation for Statistical Computing, Vienna, Austria, https://cran.r-project.org/). Sleep time was detected on basis of the combined GGIR-package algorithm and daily logs, (van Hees et al., 2015) so that sleep was defined as periods of time during which there was no change greater than 5° in the arm angle over at least five minutes, if that period was within a sleep window defined in the daily log (in bed time and out of bed time). Study I utilized the sleep time parameter, which indicates the time

between the beginning of the first sleep period (initial sleep onset) and the end of the last sleep period (final awakening). This was categorized into short (<7 hours), intermediate (7 to <9 hours), and long sleepers (≥9 hours)—similar to self-reported sleep duration—in accordance with the National Sleep Foundation's sleep time duration recommendations. (Hirshkowitz et al., 2015)

Studies II and III used the manufacturer's ActiLife software to download and convert the raw data into 60-second epochs. The Cole-Kripke algorithm (Cole et al., 1992) was used to define all the epochs as either sleep or wake, and the ActiGraph algorithm (Actigraph, 2018) was used to detect sleep periods. The data handling (e.g., restricting the analyses to the main sleep period), checking procedures, and the used algorithms have been described in more detail elsewhere. (Myllyntausta et al., 2020) Again, for sleep duration, participants were categorized into short (<7 hours), intermediate (7 to <9 hours), and long sleepers (≥9 hours), in accordance with the National Sleep Foundation's sleep time duration recommendations. (Hirshkowitz et al., 2015)

In Study II, the duration of sleep the night prior to cognitive testing was obtained in a similar way as that used to obtain usual sleep duration. Based on their usual sleep duration (excluding the night prior to cognitive testing) and their sleep duration the night prior to cognitive testing, the participants were categorized as: 1) shorter than usual sleep duration, 2) same as usual sleep duration, or 3) longer than usual sleep duration. Sleep duration was considered shorter/longer than the usual if the difference between usual sleep duration and sleep duration the night prior to cognitive testing was at least one hour.

Study III examined the change in accelerometer-measured sleep duration during the retirement transition, and evaluated the sleep duration data in the study phases directly before and after the participant's retirement. As there were only a few long sleepers (0.87% before and 0% after retirement), these were excluded. On the basis of their last measurement before retirement and their first after retirement, the participants were categorized into four groups indicating the change in sleep duration during the retirement transition: 1) constantly short sleep, 2) increasing sleep duration (i.e., short sleepers before and intermediate sleepers after retirement), 3) decreasing sleep duration (i.e., intermediate sleepers before and short sleepers after retirement), and 4) constantly intermediate sleep.

4.3 Assessment of cognitive function

In each cohort, cognitive function was measured during clinical examinations by a trained study nurse. The computer-based Cambridge Neuropsychological Test Automated Battery (CANTAB®) was used in Studies I–III, and additional paper-and-pencil tests were used in Studies I and IV. **Table 7** shows the cognitive tests used to cover the specific cognitive domains in each study cohort. CANTAB® is a

standardized computer-based method for assessing cognitive function and it is widely used in clinical trials and for research purposes. The tests are performed on a touch-screen computer system, and a suitable test battery may be selected from among the existing individual tests to cover the cognitive subdomains of interest in each specific study. **Figure 7** shows the set-up and examples of the CANTAB tests used in this study, which were the Rapid Visual Information Processing Test (from here on *visual information processing*), the Spatial Working Memory Test (from here on *spatial working memory*), the Reaction Time Test (from here on *reaction time*), the Attention Switching Task (from here on *set-shifting*), and the Paired Associates Learning Test (from here on *episodic memory and associative learning*). Several paper-and-pencil tests covering multiple cognitive domains were also used. These tests included TMT (from here on *cognitive flexibility*), the Alice Heim 4-I (AH4-I) (from here on *inductive reasoning*), and verbal recall and 20-word free recall (from here on *verbal recall*).

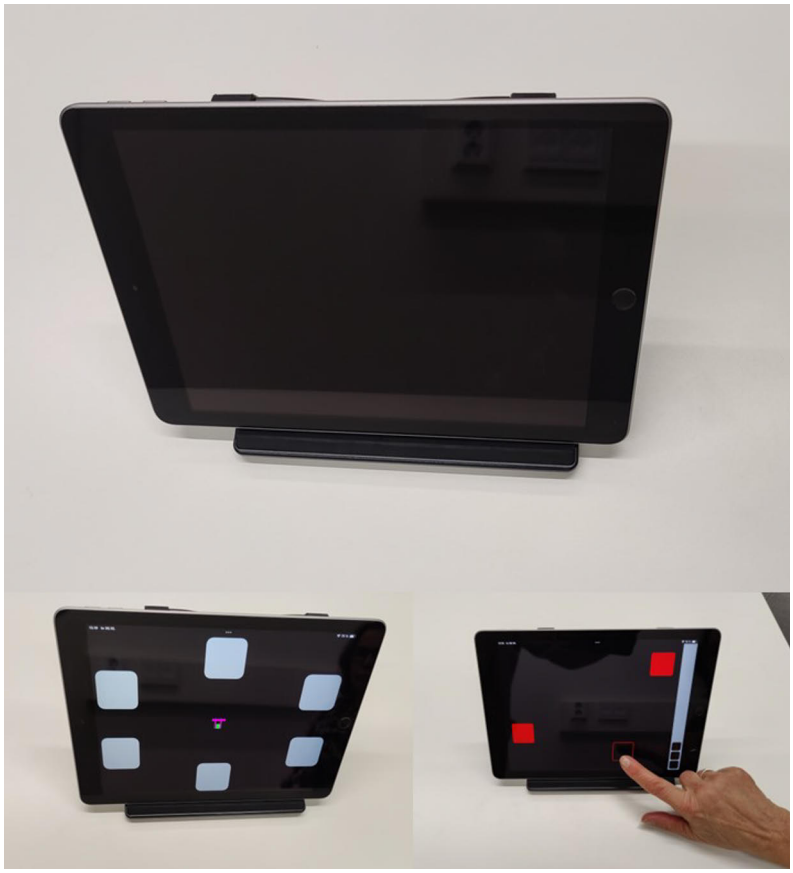

Figure 7. Cambridge Neuropsychological Test Automated Battery (CANTAB®). First row: set-up of CANTAB. Second row: examples of CANTAB tests

Table 7. Cognitive tests and their domains used in this PhD thesis.

Cognitive domains	Study I	Study II	Study III	Study IV
Complex attention				
CANTAB: Rapid Visual Information Processing (*Visual information processing)*	x	x	x	
Executive function				
CANTAB: Spatial Working Memory (*Spatial working memory)*	x	x	x	
CANTAB: Reaction Time *(Reaction time)*	x	x	x	
CANTAB: Attention Switching Task (*Set-shifting)*	x		x	
Trail Making Test B-A (*Executive function*)	x			
Alice Heim 4-I (*Inductive reasoning*)				x
Learning and memory				
CANTAB: Paired Associates Learning (*Episodic memory and associative learning*)	x	x	x	
CERAD: Verbal Recall (*Verbal recall*)	x			
20-word free recall (*Verbal recall*)				x

Abbreviations: CANTAB=Cambridge Neuropsychological Test Automated Battery, CERAD= Consortium to Establish a Registry for Alzheimer's Disease

Visual information processing (complex attention) was measured using the Rapid Visual Information Processing Test (CANTAB). The participant was instructed to react to a certain number sequence (e.g., 3-7-5), which was presented on the screen next to a box showing numbers from 2 to 9, one at a time, in a pseudorandom order at the pace of 100 numbers per minute. The participant was instructed to touch the screen when the sequence was shown.

Spatial working memory (executive function) was measured using the Spatial Working Memory Test (CANTAB). During the test, the screen displayed four to eight boxes. The participant was instructed to find tokens hidden inside the boxes. The computer hid only one token at a time but did not hide a token twice in the same box. Therefore, once they had found a box containing a token, the participant was not supposed to revisit the same box.

Reaction time (executive function) was measured using the Reaction Time Test (CANTAB). The participant was instructed to touch the stimulus appearing on the screen as soon as possible. Reaction time was studied in two stages: In the first stage, the stimulus was predictable (simple location task) and in the second stage it was unpredictable (five-choice location task).

Set-shifting (executive function) was measured using the Attention Switching Task (CANTAB). An arrow pointing either left or right appeared on either side of the screen (left or right). In each phase, a cue appeared at the top of the screen for the participant to focus on the location or the direction of the arrow. The participant was instructed to press either the left or the right button.

Executive function was also measured using parts A and B of the TMT (TMT A and TMT B). (Reitan, 1958) TMT A consisted of tracing randomly placed numbers on paper from 1 to 25 in the correct order, which reflected the participant's processing speed. In TMT B, the numbers and letters alternated in a numeric, alphabetical order (i.e., 1-A-2-B-3-C, etc.). If they made an error, the participant was informed and given the opportunity to instantly correct it. Both parts were timed and the overall TMT score (TMT B-A) was calculated as the difference between the TMT A and TMT B times.

Inductive reasoning (executive function) was measured using the AH4-I (Heim, 1970). This test consisted of 65 increasingly difficult reasoning tasks (32 verbal and 33 mathematical) with a ten-minute completion time limit and a maximum score of 65. Based on the number of correct answers, each participant was assigned a total AH4-I score (0-65).

Episodic memory and associative learning was measured using Paired Associates Learning (CANTAB). During the five stages, six or eight boxes appeared on the screen with 2, 2, 3, 6, and 8 patterns hidden within them. The boxes were first revealed one by one. In the first three stages, some of the boxes were empty. After this a pattern was shown in the middle of the screen, and the participant was instructed to touch the box that contained the same pattern.

Verbal recall (learning and memory) was measured using the CERAD (Morris et al., 1989) verbal recall test (Buschke & Fuld, 1974). The participants were shown ten words one by one, asked to read them aloud and to verbally recall as many as they could immediately afterwards. This was repeated three times. Delayed recall was measured five minutes later after conducting short physical function test in the meanwhile. The list was not shown during the delayed recall phase. The variables used in the analyses were the number of words remembered correctly during the immediate recall phase and the delayed phase, and the percentage of the learned words (the third time) recalled during the delayed trial.

Verbal recall (learning and memory) was also measured using 20-word free recall. (Sabia et al., 2008) The participants were presented with a list of 20 one- or two-syllable words at two second intervals and were then asked to recall, in writing, as many of the words as possible, in any order, over a period of two minutes. Each participant was assigned a total verbal memory score on the basis of the number of correctly recalled words (0–20).

4.4 Assessment of retirement

Studies III and IV focused on the transition from employment to full-time statutory retirement. In both studies, the data centered on the year of retirement. Consequently, the measurements taken before retirement reflected the pre-retirement period, those taken immediately before and after reflected the retirement transition period, and those taken after retirement reflected the post-retirement period.

In Study III, which was based on FIREA, working status was elicited annually during the clinical examination. Participants who reported having retired full-time were considered *retired*.

In Study IV, which was based on Whitehall II, the participants reported their employment status during each data collection phase. They were considered to be *in employment* if they were either still in active civil service or were in paid employment elsewhere, either full or part time. They were considered *retired* if they had moved from employment to retirement directly, or from employment to unemployment/other and then to retirement. Participants who had retired directly from the civil service provided the exact year of exit from the civil service (i.e., retirement). For those who had retired from employment other than civil service, the exact year of retirement was not known, but a midpoint between the last study phase when still working and the subsequent study phase when no longer working was used as the point of retirement.

4.5 Assessment of covariates

Potential confounders for each study were selected *a priori*, on the basis of their known association with either sleep or cognitive function. **Table 8** shows the covariates used.

Table 8. Study-specific covariates.

	Study I	**Study II**	**Study III***	**Study IV***
Sociodemographic factors	Age Sex Occupation	Age Sex Occupation/ Education	Age Sex Occupation	Retirement age Sex Occupation
Health-Related factors	Depression		Depression Blood pressure	Depression
Lifestyle factors			Alcohol risk use Smoking Body Mass Index	Alcohol risk use
Work-related factors	Job strain		Job strain	Job strain
Others		Season		

*Covariates were examined during the study wave immediately before retirement.

Sociodemographic factors. The participants' ages were obtained from the pension insurance institute for the municipal sector in Finland in FIREA, from the digital and population data services agency in the Young Finns Study, and from the questionnaires in the Health Clinic Study and Whitehall II. Their sex was obtained from the pension insurance institute for the municipal sector in Finland in FIREA, and from the questionnaires in the Young Finns Study, the Health Clinic Study, and Whitehall II. The participants' occupational status was obtained from the pension insurance institute for the municipal sector in Finland in FIREA, and from the questionnaires in Whitehall II. In FIREA, occupational status was categorized on the basis of the International Standard Classification of Occupations (ISCO) into three groups according to occupational title: Managers and professionals (ISCO classes 1–2), Associate professionals and Office workers (ISCO classes 3–4), and Service and manual workers (ISCO classes 5–9). Similarly, in Whitehall II, occupational status was categorized into Administrative, Professional/executive, and Clerical/support. In the Young Finns Study and the Health Clinic Study, education level was used as an indicator of socioeconomic status, was derived from the questionnaires, and was classified as higher education, intermediate education, and basic education.

Health-related factors. Depression was measured using the Beck Depression Inventory (BDI) (BECK et al., 1961) with a cut-off point of 10/63 in FIREA, and using the depression subscale of the General Health Questionnaire (GHQ) (Goldberg & Hillier, 1979) with a cut-off of ≥4/12 in Whitehall II. Blood pressure (cut-off ≥140 mmHg systolic or ≥90 mmHg diastolic) was measured during the clinical examinations.

Lifestyle factors. Alcohol use was elicited by the questionnaires. In FIREA, the cut-off value for risky use was >16 drinks per week for women and >24 for men. In Whitehall II, the categories were none, ≤10, and >10 drinks per week. Current smoking (smoker and nonsmoker) was elicited by the questionnaires. Body mass index (BMI) was calculated (weight (kg) / height^2 (m)) using the height and weight measured during the clinical examinations and categorized as <25, 25–30, and ≥30 kg/m^2.

Work-related factors. Job strain was measured using a version of the Job Content Questionnaire (JCQ) in FIREA and Whitehall II. (Fransson et al., 2012; Karasek et al., 1998) The study-specific median scores for job demand and control were measured, and job strain was defined as high demand and low control.

Others. The season (i.e., spring, summer, fall, winter) of the cognitive measurements was derived from the date of the cognitive measurements.

4.6 Statistical analyses

The characteristics of the study populations are shown as percentages for the categorical variables and means and standard deviations (SD) for the continuous variables.

CANTAB was used in Studies I–III. Each CANTAB® test produces several outcome variables. To reduce the number of variables and to obtain outcome variables that would explain most of the variation within the dataset, we created z-score-based summary score variables separately for each CANTAB subtest. First, all the individual variables in the cognition data were transformed into a scale, with a mean of 0 and an SD of 1. Second, the average scores of all the test-specific variables were calculated to represent the testwise score variable. Finally, these variables were converted so that a higher value reflected better cognitive function. In Study III, the data were similarly transformed into a scale with a mean of 0 and an SD of 1 at baseline, and in the follow-up measurements, the standardization was conducted in respect to the baseline distribution.

In Study I, the association between accelerometer-based sleep duration and self-reported sleep difficulties and cognitive function was studied by comparing the mean levels of the cognitive test results across the categories of sleep characteristics, using analysis of variance (ANOVA). Pairwise comparisons were conducted using Tukey's Post Hoc Test. The analyses were adjusted for age, sex, occupational status, depression, and job strain.

In Study II, the data from the three study cohorts were pooled. The Generalized linear model (GLM) was used to compare cognitive function in groups categorized by self-reported usual sleep duration. The intermediate sleep duration (7 to <9 hours) group was used as the reference. Sleep duration the night prior to the cognitive function test was also analyzed by creating sleep change categories: sleeping the same as usual, sleeping less than usual, and sleeping more than usual. The level of cognitive function was studied in these sleep duration groups, and sleeping the same as usual was used as the reference group. Finally, similar analyses were conducted on a subgroup of FIREA participants, using accelerometer-based sleep duration. The analyses were adjusted for age, sex, socioeconomic status, and the season of the measurements.

In Studies III and IV, to estimate the mean level of each cognitive domain, we used linear regression analyses with generalized estimating equations (GEE) with an exchangeable correlation structure. The mean levels of each cognitive domain by sleep duration and sleep difficulty status before retirement were studied using ANOVA. The association between changes in sleep duration or difficulties and changes in cognitive function were examined using GEE models. The analyses were adjusted for age, sex, and occupational position.

The original publications described several sensitivity analyses of, for example, sex-specific differences in the association between sleep characteristics and cognitive function (Study I), whether the clinical sub-study participants differed from the questionnaire-only FIREA participants (Study I), and the association between tiredness and cognitive function (Study IV). Details of these analyses are presented in the original publications.

All statistical analyses were performed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA).

5 Results

Table 9 shows the characteristics of the population of each study. The mean age of the participants varied from 59.0 years in Study IV to 72.6 years in Study II. The majority of the participants were female in Studies I (83%), II (64%), and III (84%), whereas in Study IV, the participants were 74% male. Different socioeconomic groups were represented quite equally in Studies I, II, and III (26–39% in each category), but in Study IV, only 10% of the participants were from the lowest socioeconomic group, which reflects the focus of Whitehall II on civil servants.

Sleep difficulties were reported by 46% (Study I), 53% (Study III), and 30% (Study IV) of the participants. Sleep difficulties were not evaluated in Study II. Sleep duration was examined by applying both a cross-sectional (Study I, II) and longitudinal (Study III, IV) approach. Sleep duration varied between the studies, which could be due to the different measurement methods used, as well as the difference between retirement statuses. Only 14% were short sleepers in Study I and 19% in Study II, whereas in Study III, 68% of the participants were short sleepers and in Study IV, 44%. Most of the participants were intermediate sleepers in Studies I (81%), II (64%), and IV (55%), but only 31% in Study III. Five percent were long sleepers in Study I and 17% in Study II, but only a few in Studies III (0.8%) and IV (0.7%).

Table 9. Characteristics of populations of each study.

	Study I	Study II	Study III*	Study IV*
Study cohort	FIREA	FIREA Young Finns Study Health Clinic Study	FIREA	Whitehall II
Number of participants	289	2949	250	2980
	Mean (SD)	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**
Age, years	62.4 (1.0)	72.6 (5.7)	63.1 (1.1)	59.0 (4.8)
	n (%)	**n (%)**	**n (%)**	**n (%)**
Sex				
Male	50 (17%)	1074 (36%)	40 (16%)	2210 (74%)
Female	239 (83%)	1875 (64%)	210 (84%)	770 (26%)
Occupation/education				
High	102 (35%)	1008 (34%)	87 (35%)	1396 (47%)
Intermediate	98 (34%)	1162 (39%)	84 (34%)	1277 (43%)
Low	89 (31%)	779 (26%)	79 (32%)	307 (10%)
Sleep difficulties	131 (46%)	N/A	131 (53%)	728 (30%)
Sleep duration				
Short <7 hours	38 (14%)	574 (19%)	162 (68%)	1313 (44%)
Intermediate 7 TO <9 hours	227 (81%)	1878 (64%)	74 (31%)	1638 (55%)
Long ≥9 hours	14 (5.0%)	497 (17%)	2 (0.8%)	21 (0.7%)

* During study phase immediately before retirement. N/A=not applicable

5.1 Cross-sectional associations between sleep duration and cognitive function

The cross-sectional association between sleep duration and cognitive function was examined in a late mid-life working population (Study I) and in a larger study sample of participants in late mid-life and retirees (Study II).

The association between sleep characteristics and cognitive function in late mid-life was analyzed by examining healthy participants who were still active in working life around 18 months before their estimated time of retirement (Study I). The mean cognitive test scores based on accelerometer-measured sleep duration are shown in **Table 10**. Long sleepers had poorer *learning and memory,* measured by immediate verbal recall, than short sleepers (p=0.01) and intermediate sleepers (p=0.03). Long sleepers also tended to perform more poorly in most of the other measured cognitive tests, but these results did not reach statistical significance. No differences were observed between the cognitive function of short and intermediate sleepers.

The association between self-reported sleep duration and cognitive function was similarly evaluated in a larger population (**Table 11**) (Study II). Long sleepers had poorer *visual information processing* (p=0.003), *reaction time* (p=0.006) and *episodic memory and associative learning* (p=0.004) than intermediate sleepers. The cognitive function of short and intermediate sleepers did not differ.

Table 10. Associations between accelerometer-based sleep duration and cognitive domains.

	Short, <7 h (n=38)		Intermediate, 7–9 h (n=227)		Long, ≥9 h (n=14)		p-values for group comparison		
	Mean	95% CI	Mean	95% CI	Mean	95% CI	short vs. intermediate	long vs. intermediate	short vs. long
Complex attention									
Visual information processing	0.15	(-0.11 to 0.41)	0.15	(0.00 to 0.30)	0.13	(-0.26 to 0.51)	1.00	0.99	1.00
Executive function									
Spatial working memory	0.06	(-0.16 to 0.28)	0.03	(-0.10 to 0.16)	-0.15	(-0.48 to 0.17)	0.97	0.48	0.49
Set-shifting	-0.04	(-0.28 to 0.20)	0.12	(-0.02 to 0.26)	0.15	(-0.20 to 0.51)	0.36	0.98	0.61
Cognitive flexibilty	43.8	(35.1 to 52.5)	49.0	(43.9 to 54.1)	44.3	(31.3 to 57.3)	0.43	0.74	1.00
Learning and memory									
Episodic memory and associative learning	0.01	(-0.24 to 0.25)	-0.04	(-0.18 to 0.11)	-0.19	(-0.56 to 0.17)	0.93	0.67	0.61
Verbal recall, immediate	6.45	(5.88 to 7.01)	6.17	(5.84 to 6.50)	5.08	(4.24 to 5.93)	0.57	0.025	0.013
Verbal recall, delayed	8.17	(7.62 to 8.71)	8.32	(8.00 to 8.64)	7.71	(6.89 to 8.52)	0.84	0.28	0.57
Verbal recall, percent	88.0	(83.0 to 92.9)	92.1	(89.2 to 95.0)	86.3	(79.0 to 93.7)	0.20	0.26	0.92

Analyses are adjusted for age, sex, occupational position, depression, and job strain. Modified from table originally published in Study I.

Table 11. Associations between self-reported sleep duration and cognitive domains.

	Short, <7 h (n=574)		Intermediate, 7–9 h (n=1878)		Long, ≥9 h (n=497)		p-values	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Short vs. intermediate	Long vs. intermediate
Complex attention								
Visual information processing	-0.01	(-0.08 to 0.06)	-0.03	(-0.07 to 0.02)	-0.15	(-0.22 to -0.07)	0.697	0.003
Executive function								
Spatial working memory	0.01	(-0.05 to 0.07)	-0.002	(-0.04 to 0.04)	0.03	(-0.04 to 0.09)	0.648	0.412
Reaction time	-0.02	(-0.08 to 0.04)	-0.04	(-0.08 to 0.005)	-0.13	(-0.2 to -0.07)	0.654	0.006
Learning and memory								
Episodic memory and associative learning	-0.02	(-0.08 to 0.04)	-0.01	(-0.05 to 0.02)	-0.1	(-0.17 to -0.04)	0.831	0.004

Analyses are adjusted for age, sex, occupational position, and season of measurements. Modified from table originally published In Study II.

Sleep duration and cognitive function were interrelated immediately before retirement transition (Study III, **Table 12**). Long sleepers were excluded from the analyses due to small numbers (n=2). Short sleepers showed poorer *set-shifting* than intermediate sleepers (p=0.014). A similar tendency was observed in *visual information processing* and *spatial working memory,* but these results did not reach statistical significance. In contrast, short sleepers showed better performance in *episodic memory and associative learning* than intermediate sleepers (p=0.044).

Table 12. Associations between accelerometer-based sleep duration and cognitive domains immediately before retirement.

	Short < 7 h (n=162)		**Intermediate 7–9 h (n=74)**		
	Mean	95% CI	Mean	95% CI	p-value
Complex attention					
Visual information processing	0.15	(0.04 to 0.26)	0.31	(0.16 to 0.47)	0.059
Executive function					
Spatial working memory	0.07	(-0.05 to 0.18)	0.21	(0.06 to 0.36)	0.092
Set-shifting	0.11	(0.01 to 0.21)	0.30	(0.19 to 0.41)	0.014
Reaction time	-0.06	(-0.17 to 0.04)	-0.02	(-0.14 to 0.10)	0.512
Learning and memory					
Episodic memory and associative learning	0.11	(-0.02 to 0.23)	-0.08	(-0.26 to 0.09)	0.044

Analyses are adjusted for age, sex, and occupational position. Modified from table originally published in Study III.

Study II examined the association between the duration of the previous night's sleep and cognitive function. The previous night's sleep duration was evaluated in relation to usual sleep duration, and the groups formed were: less than usual, the same amount as usual, and more than usual. A change of at least one hour was used as a threshold for the sleep change groups (i.e., less than usual and more than usual). Participants who had slept more than usual the night prior to the cognitive tests showed poorer *visual information processing* than those who had slept the same amount as usual (p=0.019) (**Table 13**). Sleeping less than usual was not associated with any of the measured cognitive domains.

The results of the analysis of one sub-cohort of Study II whose sleep duration was accelerometry measured (n=237) echoed those of the analyses of those who self-reported the data; those who had slept less than usual the night prior to cognitive testing showed poorer *visual information processing* than those who had slept the same as usual (p=0.03). No associations were observed between sleeping more than usual and cognitive function.

Table 13. Associations between previous night's sleep duration in relation to participant's usual sleep duration and cognitive domains.

	Slept less than usual (n=1734)		Slept the same amount as usual (n=1042)		Slept more than usual (n=173)		p-value	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	Less vs. same	More vs. same
Complex attention								
Visual information processing	-0.07	(-0.12 to -0.02)	-0.03	(-0.09 to 0.03)	-0.18	(-0.3 to -0.06)	0.21	0.02
Executive function								
Spatial working memory	0.005	(-0.04 to 0.05)	0.02	(-0.03 to 0.07)	0.02	(-0.08 to 0.12)	0.49	0.96
Reaction time	-0.07	(-0.11 to -0.02)	-0.05	(-0.11 to 0.002)	-0.1	(-0.21 to 0.004)	0.59	0.36
Learning and memory								
Episodic memory and associative learning	-0.04	(-0.08 to 0.004)	-0.05	(-0.1 to -0.002)	-0.08	(-0.18 to 0.02)	0.65	0.53

Analyses are adjusted for age, sex, occupational position, and season of measurement. Modified from table originally published in Study II.

5.2 Cross-sectional associations between sleep difficulties and cognitive function

Study I examined the association between individual sleep and cognitive function. Sleep difficulties were quite common, as 53–54% of the participants reported some sort of sleep difficulties. A closer examination of individual sleep difficulties revealed that 10% of the participants had difficulties falling asleep, 47% maintaining sleep, 29% staying asleep, and 25% had nonrestorative sleep. This means that many participants had multiple individual sleep difficulties.

Table 14 shows the mean cognitive test scores separately for each type of sleep difficulty. Difficulties falling asleep were not associated with cognitive function, although this could be due to the small number of participants who had difficulties falling asleep (n=28). Participants with difficulties maintaining sleep showed better immediate *verbal recall* than the participants with no difficulties maintaining sleep (p=0.037). Difficulties staying asleep were associated with poorer *spatial working memory* (p=0.005). Similarly, there was a weak association between nonrestorative sleep and poorer *spatial working memory,* although this did not reach the conventional level of statistical significance (p=0.056). There was also an association between nonrestorative sleep and poorer *cognitive flexibility* (p=0.036).

Table 14. Associations between sleep difficulties and cognitive domains.

	Falling asleep					Maintaining sleep				
	No difficulties (n=252)		Difficulties (n=28)			No difficulties (n=150)		Difficulties (n=134)		
	Mean	95% CI	Mean	95% CI	p-value	Mean	95% CI	Mean	95% CI	p-value
Complex attention										
Visual information processing	0.12	(-0.03 to 0.28)	0.24	(-0.05 to 0.53)	0.42	0.13	(-0.05 to 0.31)	0.16	(0.00 to 0.33)	0.72
Executive function										
Spatial working memory	0.05	(-0.08 to 0.18)	-0.06	(-0.30 to 0.18)	0.37	0.12	(-0.03 to 0.27)	0.01	(-0.13 to 0.14)	0.14
set-shifting	0.09	(-0.06 to 0.25)	0.05	(-0.24 to 0.34)	0.76	0.06	(-0.13 to 0.24)	0.13	(-0.03 to 0.29)	0.41
cognitive flexibilty	48.0	(42.8 to 53.2)	52.3	(42.7 to 61.9)	0.37	47.4	(41.4 to 53.5)	48.5	(43.1 to 54.0)	0.71
Learning and memory										
episodic memory and associative learning	-0.03	(-0.18 to 0.12)	-0.18	(-0.45 to 0.09)	0.26	-0.07	(-0.24 to 0.11)	-0.04	(-0.19 to 0.12)	0.74
Verbal recall, immediate	6.06	(5.72 to 6.40)	6.25	(5.64 to 6.86)	0.52	5.90	(5.51 to 6.30)	6.30	(5.94 to 6.65)	0.037
Verbal recall, delayed	8.20	(7.87 to 8.53)	8.49	(7.89 to 9.08)	0.34	8.16	(7.79 to 8.52)	8.40	(8.07 to 8.73)	0.16
Verbal recall, percent	90.6	(87.6 to 93.6)	93.1	(87.7 **to** 98.6)	0.36	90.3	(87.0 to 93.7)	92.6	(89.6 to 95.6)	0.16
	Staying asleep					**Nonrestorative sleep**				
	No difficulties (n=199)		Difficulties (n=83)			No difficulties (n=212)		Difficulties (n=71)		
	Mean	95% CI	Mean	95% CI	p-value	Mean	95% CI	Mean	95% CI	p-value
Complex attention										
Visual information processing	0.11	(-0.06 to 0.28)	0.14	(-0.05 to 0.32)	0.78	0.16	(-0.01 to 0.32)	0.11	(-0.09 to 0.31)	0.68
Executive function										
Spatial working memory	0.14	(0.001 to 0.29)	-0.08	(-0.24 to 0.07)	0.005	0.10	(-0.04 to 0.23)	-0.07	(-0.24 to 0.09)	0.056
set-shifting	0.11	(-0.06 to 0.28)	0.08	(-0.10 to 0.27)	0.78	0.15	(-0.02 to 0.32)	0.02	(-0.17 to 0.22)	0.23
cognitive felxibilty	48.6	(42.9 to 54.4)	48.1	(41.9 to 54.2)	0.86	45.7	(40.2 to 51.1)	52.9	(46.3 to 59.4)	0.036
Learning and memory										
episodic memory and associative learning	-0.04	(-0.20 to 0.12)	-0.05	(-0.23 to 0.12)	0.85	-0.03	(-0.19 to 0.13)	-0.07	(-0.26 to 0.11)	0.64
Verbal recall, immediate	6.04	(5.67 to 6.41)	6.20	(5.80 to 6.60)	0.45	6.04	(5.68 to 6.40)	6.34	(5.91 to 6.77)	0.18
Verbal recall, delayed	8.23	(7.87 to 8.58)	8.25	(7.87 to 8.63)	0.94	8.23	(7.89 to 8.58)	8.36	(7.95 to 8.77)	0.55
Verbal recall, percent	90.9	(87.6 to 94.2)	91.5	(88.0 to 95.0)	0.74	91.6	(88.4 to 94.8)	90.8	(87.0 to 94.5)	0.66

Adjusted for age, sex, occupational position, depression, and job strain. Modified from table originally published in Study I.

5.3 Changes in sleep and cognitive function before, during, and after the retirement transition

In the longitudinal study settings, changes in sleep characteristics and cognitive function before, during and after the retirement transition were examined, as were the associations between these changes (Study III, IV). Study III focused specifically on the transition to retirement, with annual measurements taken around the retirement transition, whereas Study IV had a longer follow up of up to 16 years from pre-retirement to post-retirement.

Figure 8 shows the changes in cognitive function during the retirement transition. *Episodic memory and associative learning* remained stable before retirement (mean change before retirement 0.025, p=0.64), but showed a clear improvement during the retirement transition (mean change during retirement transition 0.17, p=0.0030), and then plateaued after retirement. The trends in the pre-retirement and retirement transition differed statistically significantly (p=0.026). Similarly, *spatial working memory* did not change before retirement (mean change before retirement -0.003, p=0.96), but clearly improved during the retirement transition (mean change in retirement transition 0.13, p=0.014), only to plateau after retirement. However, the *spatial working memory* trends before retirement and during the retirement transition did not quite reach statistical significance (p=0.091). Both *visual information processing* and *set-shifting* improved throughout the retirement transition follow up (mean change before retirement 0.048, p=0.29; mean change during retirement transition 0.11, p=0.012; and mean change before retirement 0.064, p=0.13; mean change during retirement transition 0.13, p=0.015, respectively). The difference in the trends was not statistically significant (p=0.47 for *visual information processing*; and p=0.66 for *set-shifting*). *Reaction time* remained stable throughout the follow-up period, from pre-retirement to post-retirement (mean change before retirement -0.004, p=0.93; mean change during the retirement transition 0.02, p=0.51). To examine whether occupation would moderate the change in cognitive function during retirement transition, interaction “occupational group x time” was examined as an additional analysis. No statistically significant interactions were found across any cognitive domains.

The long-term changes in cognitive function by sleep change group across the 16-year follow up before and after retirement are shown in **Figure 9**. Cognitive function declined throughout the follow-up period in all the sleep change groups.

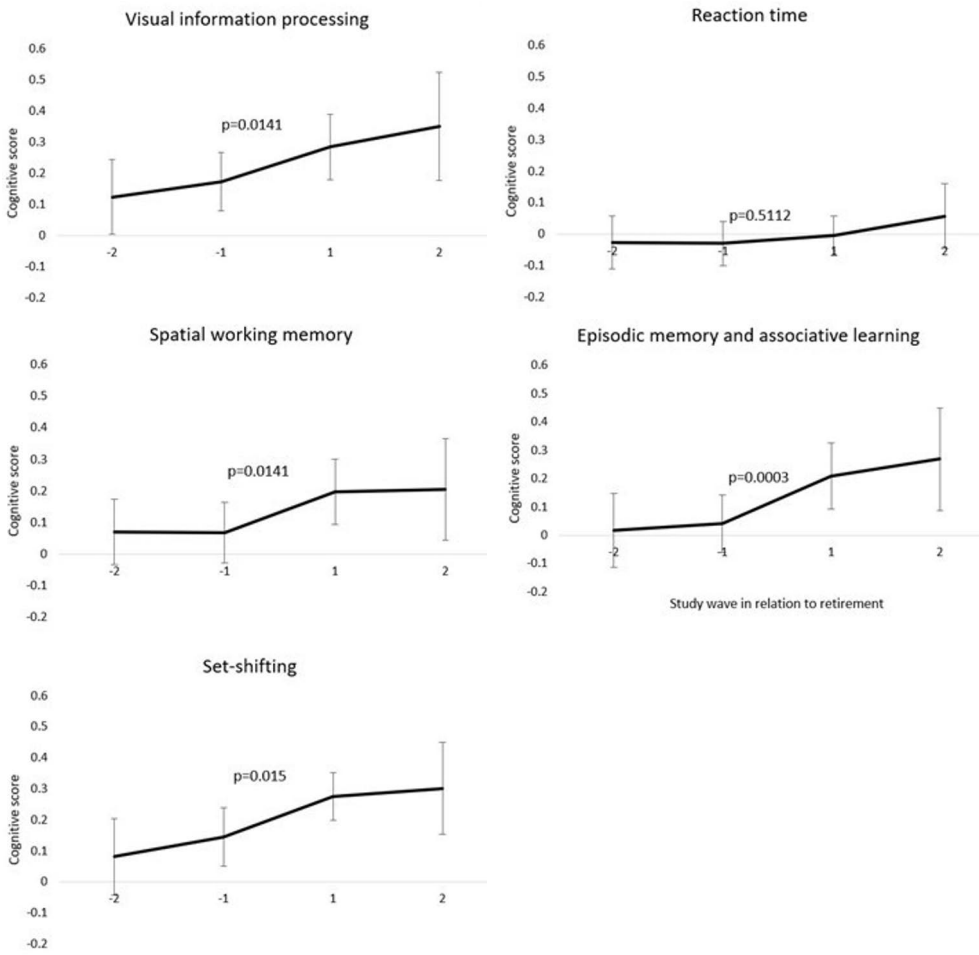

Figure 8. Mean levels and their 95% confidence intervals in each cognitive domain before and after retirement over a three-year follow up. Adjusted for age, sex, and occupational position. P-values are from the change in cognitive function during the retirement transition (wave -1 to 1). Modified from figure originally published in Study III.

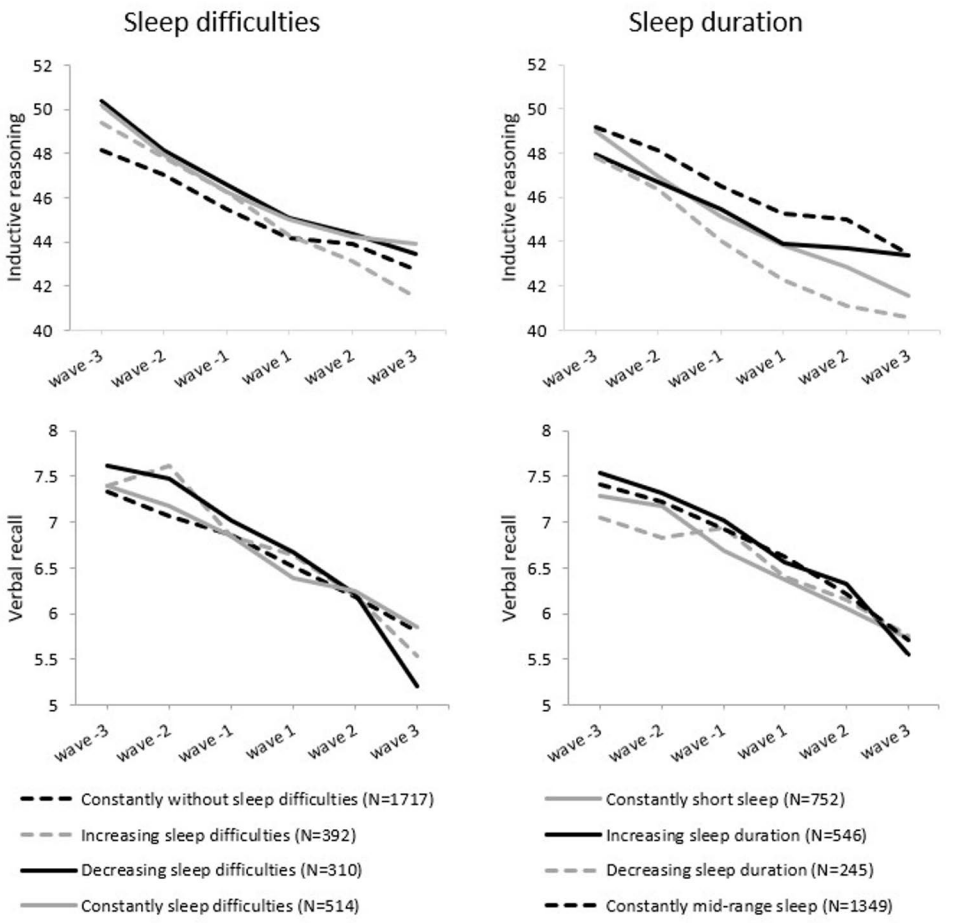

Figure 9. Mean levels of inductive reasoning and verbal recall by sleep change group before and after retirement over a 16-year follow up. Unadjusted values. Inductive reasoning range 0–65, verbal recall range 0–20. Modified from figure originally published in Study IV.

In Study III, 49% of the participants were constantly short sleepers, for 19% sleep duration increased, for 7% sleep duration decreased, and 25% were constantly intermediate sleepers during the retirement transition. In Study IV, intermediate sleep duration was more common, but the sleep duration change groups were similar to those in Study III: 26% of the participants were constantly short sleepers, for 19% sleep duration increased, for 8% sleep duration decreased, and 47% were constantly intermediate sleepers

As regards sleep difficulties during the retirement transition in Study III, 36% of the participants were constantly without sleep difficulties, for 10% sleep difficulties increased, for 16% sleep difficulties decreased, and 38% had constant sleep difficulties. Sleep difficulties were less common in Study IV: 59% of the participants

were constantly without sleep difficulties, for 13% sleep difficulties increased, for 11% sleep difficulties decreased, and 18% had constant sleep difficulties.

Examination of the association between changes in sleep duration and changes in cognitive function during the retirement transition revealed no associations in either Study III or Study IV. Similarly, no associations were found between the changes in cognitive function after retirement of the sleep duration change groups.

No associations were found between changes in sleep difficulties and changes in cognitive function when the retirement transition was specifically focused on (Study III). However, in Study IV, differences between the changes in cognitive function were examined over a longer time period. The pre-retirement levels of cognitive function and mean changes in cognitive function during and after the retirement transition are shown in **Table 15**. Those with increasing sleep difficulties showed a more pronounced decline in *inductive reasoning* than those constantly without sleep difficulties (p=0.018) and who constantly had sleep difficulties (p=0.048) during the retirement transition when adjusted for age, sex, and occupational position. No differences between the *inductive reasoning* of the sleep difficulties groups were observed after retirement, and no differences between the *verbal recall* of the sleep difficulties groups were observed during the retirement transition. However, after retirement, those with decreasing sleep difficulties showed a more pronounced decline in *verbal recall* than those constantly without sleep difficulties (p=0.039).

Table 15. Mean levels of cognitive function before retirement and mean levels of change in cognitive function during and after the retirement transition. Change estimated over 5 years.

	Pre-retirement		Retirement transition		Post-retirement	
	Mean level	95% CI	Mean change	95% CI	Mean change	95% CI
Executive function						
Inductive reasoning*						
Constantly without sleep difficulties	41.4	(40.9 to 41.9)	-1.25	(-1.52 to -0.98)	-0.92	(-1.16 to -0.67)
Increasing sleep difficulties	42.5	(41.6 to 43.4)	-1.96	(-2.52 to -1.41)	-1.00	(-1.51 to -0.48)
Decreasing sleep difficulties	42.9	(41.9 to 43.9)	-1.48	(-2.02 to -0.95)	-1.13	(-1.72 to -0.55)
Constant sleep difficulties	42.2	(41.3 to 43.0)	-1.26	(-1.75 to -0.78)	-0.92	(-1.43 to -0.42)
Memory and learning						
Verbal recall*						
Constantly without sleep difficulties	6.75	(6.62 to 6.87)	-0.34	(-0.45 to -0.23)	-0.42	(-0.52 to -0.32)
Increasing sleep difficulties	6.73	(6.50 to 6.95)	-0.22	(-0.46 to 0.02)	-0.57	(-0.75 to -0.38)
Decreasing sleep difficulties	6.83	(6.55 to 7.11)	-0.35	(-0.59 to -0.11)	-0.64	(-0.86 to -0.43)
Constant sleep difficulties	6.65	(6.43 to 6.87)	-0.47	(-0.67 to -0.26)	-0.40	(-0.59 to -0.21)

*range 0–65, ** range 0–20. Modified from table originally published in Study IV.

6 Discussion

This PhD study found sleep duration and sleep difficulties to be cross-sectionally associated with cognitive function, on the basis of both self-reported and accelerometer-measured sleep characteristics, and computer-based and paper-and-pencil cognitive tests that covered multiple cognitive domains. Those who slept more than usual the night prior to cognitive testing showed poorer complex attention than those who slept the same amount as usual.

The participants' sleep characteristics and cognitive function were repeatedly measured before and after their retirement transition. Interestingly, during the retirement transition, their cognitive function temporarily improved. This improvement was independent of the changes in sleep characteristics. However, examinations of changes in sleep and cognitive function over a longer time period and at less frequent intervals revealed that the decline in cognitive function was more pronounced during and after the retirement transition among those whose sleep difficulties increased or decreased than among those whose sleep difficulty status did not change.

This PhD study was the first to examine the association between the previous night's sleep duration and cognitive function while taking into consideration usual sleep duration. It also produced novel evidence of simultaneous changes in sleep characteristics and cognitive function during and after the retirement transition.

6.1 Cross-sectional association between sleep and cognitive function

Self-reported long sleep duration was associated with poorer learning and memory, complex attention, and executive function than intermediate sleep duration, which is in line with the results of previous research. Like this PhD study, another study has shown long sleep duration to be associated with poorer complex attention than intermediate sleep duration. (Low et al., 2019) Other studies of sleep duration and complex attention have only found short sleep duration to be associated with poorer complex attention than intermediate sleep (Blackwell et al., 2011; Sewell et al., 2025) or have found no associations between sleep duration and this cognitive domain. (Scarlett et al., 2021; Spira et al., 2014; Swanson et al., 2021) The

association found between long sleep duration and poorer executive function compared with intermediate sleep duration has also been shown by several other studies. (Blackwell et al., 2011; Ihle-Hansen et al., 2024; Low et al., 2019; Okuda et al., 2021; Rezende et al., 2024; Scarlett et al., 2021) The association found between long sleep duration and poorer learning and memory when compared with intermediate sleep duration is also in line with previous research findings. (Kondo et al., 2021; Low et al., 2019; Rezende et al., 2024; Scarlett et al., 2021; Schmutte et al., 2007; Tsapanou et al., 2017; Xu et al., 2011)

In contrast to the findings of this PhD thesis, previous research has found self-reported short sleep duration to be associated with cognitive function. This discrepancy could be explained by differences in the categorization of sleep duration. This PhD study used the US National Science Foundation's guidelines for optimal sleep duration as the thresholds for short (<7 hours), intermediate (= recommended duration; 7 to <9 hours), and long sleep duration (≥9 hours). (Hirshkowitz et al., 2015) Most previous research has used lower thresholds for short sleep duration (i.e., 4 or 6 hours) which might explain the difference in results. (Ding et al., 2020; Gildner et al., 2014; Ma et al., 2020; Zhang et al., 2021) However, the aim of this PhD study was to examine the sleep of a healthy aging population and not sleep deprivation.

The added contribution of this PhD thesis is the use of accelerometer-based sleep duration. Accelerometer-measured long sleepers had poorer learning and memory than intermediate and short sleepers. Participants with accelerometer-measured long sleep duration also tended to perform more poorly in other cognitive domains, but these results did not reach statistical significance. One explanation for the difference in statistically significant results between self-reports and accelerometer measurements in this PhD thesis may be the size of its study population (N=2949 vs. N=289). Another reason may be that self-reported sleep duration was elicited categorically at 30-minute intervals, whereas the accelerometer measurements were continuous.

Previous research on accelerometer-based sleep duration and cognitive function is scarce and inconclusive. Long sleep duration has been shown to be associated with poorer global cognitive function when compared with intermediate sleep duration. (Blackwell et al., 2011; Spira et al., 2017) However, one study found that short sleep duration was associated with poorer global cognitive function when compared with intermediate sleep duration. (Scarlett et al., 2021) Contrary to the findings of this PhD thesis, some studies have found no associations between accelerometer-measured sleep duration and learning and memory. (Scarlett et al., 2021; Sewell et al., 2025; Spira et al., 2017; Swanson et al., 2021) Yet, others have found accelerometer-measured short (Okuda et al., 2021) and long (Sewell et al., 2025) sleep duration to be associated with poorer executive function when compared with intermediate sleep duration.

In the case of those with individual sleep difficulties, staying asleep and nonrestorative sleep were associated with poorer executive function than among those without such difficulties. Surprisingly, difficulties in maintaining sleep were associated with better learning and memory when compared to those without these difficulties. To my knowledge, this specific association between maintaining sleep and verbal recall has not been studied previously. One study of greater WASO—a somewhat similar sleep difficulty to maintaining sleep—found it to be associated with poorer verbal memory, (Spira et al., 2017) but another found no associations between WASO and verbal recall. (Troxel et al., 2022) Those with insomnia, and more specifically, those with difficulties initiating sleep, typically had poorer memory function than those without these difficulties. (Arévalo et al., 2023; Nebes et al., 2009; Overton et al., 2024; Schmutte et al., 2007; Tang et al., 2025; Tsapanou et al., 2017; Xu et al., 2011) As previous research makes no mentions of any sleep difficulty being associated with better cognitive function in any domain, the positive association that the PhD study found between difficulties maintaining sleep and verbal recall could be due to other factors, such as residual or unmeasured confounding factors. It may even be spurious, due to the large number of statistical tests in Study I.

Most previous studies of sleep difficulties and cognitive function have focused on overall sleep difficulties as opposed to specific types of sleep difficulties. (Amer et al., 2013; Gildner et al., 2014; Nebes et al., 2009; Rezende et al., 2024; Saint Martin et al., 2012; Tsapanou et al., 2017; Xu et al., 2011) Studies utilizing accelerometer measurements typically analyze individual sleep difficulties, mainly WASO. (Blackwell et al., 2011; Sewell et al., 2025; Spira et al., 2017; Suemoto et al., 2023; Swanson et al., 2021) Only a few studies have used self-reported individual sleep difficulties. Like this PhD study, one study found that early-morning awakening was associated with poorer executive function, but that difficulty initiating sleep and difficulty maintaining sleep was not associated with cognitive function. (Ling et al., 2016) Others have also shown an association between sleep difficulties and executive function. More specifically, overall sleep difficulties, early-morning awakening, WASO, poor sleep efficiency, and insomnia have been associated with poorer executive function. (Nebes et al., 2009; Rezende et al., 2024; Sewell et al., 2025; Tang et al., 2025; Troxel et al., 2022) Additionally, long sleep onset latency has been associated with several cognitive subdomains, such as poorer verbal knowledge, long-term memory, fund of information, visuospatial reasoning (Schmutte et al., 2007) and poorer global cognitive function (Wu et al., 2025).

To conclude, although the cross-sectional associations between sleep characteristics and cognitive function have been studied fairly extensively, this PhD thesis expands the cross-sectional knowledge of this subject by simultaneously

examining self-reported and accelerometer-measured sleep duration, individual sleep difficulties, and multiple cognitive domains. The association found between sleep difficulties and poorer executive function offers interesting insights into how people could possibly improve their cognitive function. Executive function plays an important role in today's working life, as it comprises significant subdomains such as working memory and cognitive flexibility. These results showed that sleeping more than the recommended amount can be harmful to cognitive functioning across multiple cognitive domains. As these studies were cross-sectional, further studies are needed to examine the prospective association between sleep characteristics and cognitive function.

6.2 Previous night's sleep duration and cognitive function

In clinical practice, a common complaint among patients is sleeping poorly before examinations—for example, cognitive tests before renewing one's driving license—and worrying that this will lead to poor results. Yet, this topic has scarcely been studied. This PhD study showed that sleeping more than usual the night prior to cognitive testing was associated with poorer complex attention but that sleeping less than usual did not affect cognitive testing performance. Usual sleep duration was also taken into consideration and was adjusted for in the analyses, as longer sleep of, for example, 6 to 7 hours, would be vastly different than that of 9 to 10 hours.

Most studies of the previous night's sleep duration and cognitive function have been sleep deprivation studies, and typically carried out in laboratory settings. These studies usually focus on extremely short sleep durations and their association with cognitive function. The few studies conducted out-of-the-laboratory have shown that short sleep duration is associated with poorer cognitive function than longer sleep duration. (Kalanadhabhatta et al., 2021; Neylan et al., 2010; O'Brien et al., 2012) However these studies were conducted among small, selected groups of young workers and did not take into account the participants' usual sleep duration. One previous study of the previous night's sleep characteristics in an older population found no association between sleep duration or difficulties the previous night and cognitive function. (Seelye et al., 2015) Contrary to our study, one study of the previous night's sleep duration and self-reported daytime functioning, measured using the Daytime Insomnia Symptom Scale (DISS) (Buysse et al., 2007) showed that longer previous night's sleep duration was associated with better daytime functioning in both usually poor and good sleepers (i.e., those with and without sleep difficulties) in a similar-aged population to that of this study. (Smith et al., 2015)

As the main findings regarding previous night's sleep duration in this study were obtained through self-reports, additional analyses were conducted in a smaller

sample using accelerometer measurements. In contrast to the self-reports, no associations between sleeping more than usual the previous night and cognitive function were observed in the cases of accelerometer-based sleep duration. However, accelerometer-measured less sleep than usual the previous night was associated with poorer complex attention than the same amount of sleep as usual. This is in line with the findings of Neylan et al. that short accelerometer-measured sleep duration the night prior to cognitive testing was associated with poorer complex attention, although they did not take the participant's usual sleep duration into consideration. (Neylan et al., 2010) However, another study of the previous night's accelerometer-measured sleep duration showed no association between the previous night's sleep duration and self-reported thinking ability. (Parsey & Schmitter-Edgecombe, 2019)

To the best of my knowledge, none of the prior studies of the association between previous night's sleep duration and cognitive function have taken into account the participant's usual sleep duration, making this PhD study the first to specifically examine short-term changes in one's own usual sleep duration and its association with cognitive function in an older population. As sleeping poorly the night prior to clinical examinations such as cognitive testing is a common complaint, these results offer useful understanding that sleeping less than usual is not associated with poorer performance in cognitive testing.

6.3 Sleep and cognitive function during the retirement transition

Although some studies have examined sleep during the retirement transition and others have examined cognitive function during the retirement transition, this PhD thesis comprises the first two studies to examine sleep and cognitive function concurrently during the retirement transition. It shows that learning and memory temporarily improves during the retirement transition. This improvement is independent of changes in sleep characteristics. A longer follow up with less frequent examination intervals showed that changing sleep difficulties were associated with a more pronounced decline in cognitive function during and after the retirement transition.

Two previous studies have shown that sleep duration increased during the retirement transition in the FIREA population. (Myllyntausta et al., 2019, 2020) Similar results have also been found in other cohorts. (Hagen et al., 2016; Myllyntausta et al., 2017) Sleep difficulties have also been shown to decrease after retirement. (Myllyntausta et al., 2018; Vahtera et al., 2009) This study expands on these results by examining concurrent changes in sleep characteristics and cognitive function during and after the retirement transition.

Previous research on cognitive function and retirement in the Whitehall II population has found that the trend of cognitive function changed between the pre- and post-retirement phases in terms of verbal memory and inductive reasoning. (Roberts et al., 2011; Xue et al., 2018) Building on these results, this PhD study examined how cognitive function changes specifically during the retirement transition through more frequent annual examinations in FIREA. It showed that learning and memory improved during the retirement transition but seemed to later return to the same trend as that prior to retirement. A similar improvement was seen in working memory (i.e., executive function), but this result did not quite reach statistical significance. Only one previous study has shown a similar improvement in cognitive function during the retirement transition. (Celidoni et al., 2017) One has also shown that the decline in cognitive function after retirement is not instantaneous. (Bonsang et al., 2012) Both Celidoni et al. and Bonsang et al. focused on memory functions rather than a wider spectrum of cognitive domains. Other studies have not found retirement to have a positive impact on cognitive function, although this could be due to the longer intervals between follow ups in these studies and to their focus on the trends before and after retirement rather than on the retirement transition. (Atalay et al., 2019; Carr et al., 2020; De Grip et al., 2015; Denier et al., 2017; Finkel et al., 2009; Fisher et al., 2014; Grotz et al., 2016; Hale et al., 2021; Lee et al., 2019; Nilsen et al., 2021) Similarly, in Study IV of this PhD thesis, the follow-up phases were five years apart and no clear change in the trend of cognitive function during the retirement transition was observed. However, possible selection bias might also affect the seen trends in cognitive function, as the participants who underwent cognitive testing were overall healthier as survey-only FIREA participants.

As regards the role of sleep characteristics in the change in cognitive function during the retirement transition, the improvement in learning and memory was independent of the changes in sleep characteristics. On the other hand, this PhD study also found that at five-year intervals, changes in sleep difficulties were associated with an accelerated decline in cognitive function during and after the retirement transition. No previous studies have examined the concurrent changes in sleep characteristics and cognitive function during the retirement transition.

When I started this PhD thesis, longitudinal studies on sleep characteristics and cognitive function were rare. Research on this topic has increased over the last few years, but longitudinal studies using accelerometer-measured sleep and an extensive battery of cognitive tests that cover multiple cognitive domains are still limited. Moreover, most previous longitudinal studies have only examined sleep at baseline and focused on either cognitive function later in life or changes in cognitive function. Only one previous study has examined concurrent changes in sleep characteristics and cognitive function. It found that intermediate sleepers whose sleep duration increased showed a greater decline in cognitive function over four years of follow

up. (Gildner et al., 2019) This PhD study was unable to examine an increase in sleep duration from intermediate sleep duration, as it had too few long sleeper participants.

To summarize, this study is the first to examine concurrent changes in sleep characteristics and cognitive function during the retirement transition. It also shows that cognitive function might improve during the retirement transition. This may be a significant finding, as it suggests that something hinders working people from reaching their full cognitive potential in their last working years. Further research is warranted to find the underlying cause of this cognitive improvement and thus potentially improve people's work ability, possibly even extend their working lives.

6.4 Potential mechanisms

Several processes that happen during sleep may account for the associations found between sleep characteristics and cognitive function.

One of the most recognized purposes of sleep is to enable neuroplasticity. Neuroplasticity depends on the renewal of synapses, i.e., forming new neural pathways and disposing of old, unused ones. This renewal of synapses is believed to mainly take place during sleep. (Krueger et al., 2016; Tononi & Cirelli, 2014) Neuroplasticity is essential for learning new skills, which also makes it crucial for cognitive function.

Sleeping also activates the astrocyte-neuron lactate shuttle, which produces lactate that the brain can use as energy. (Magistretti & Allaman, 2015; Pellerin & Magistretti, 2012) This process requires glutamate, the release of which has been suggested to increase during physical activity. (Yu et al., 2025) This means that the more active a person is during wakefulness, the more glutamate is released, and the more effectively the astrocyte-neuron lactate shuttle is able to produce energy during sleep. Therefore, a combination of being physically inactive during the day and sleeping poorly during the night can reduce the activation of the astrocyte-neuron lactate shuttle, leading to insufficient energy supply for the brain, which in turn can compromise cognitive function.

Another possible process that is mainly active during sleep is that of the glymphatic system, which clears the brain from harmful metabolic waste. (Nedergaard, 2013; Nedergaard & Goldman, 2020) The glymphatic system was first observed in rodents, but later also in humans. (Rasmussen et al., 2018; Xie et al., 2013) The system is mostly activated during NREM sleep (non-rapid eye movement), and therefore inadequate sleep duration and sleep difficulties reduce its activation. It has been theorized that neurodegenerative diseases, such as Alzheimer's disease, could be partly driven by an obscured glymphatic system. (Rasmussen et al., 2018)

Sleep is also explicitly important for memory and learning. It has been shown that different stages of sleep are needed for different types of memory: For example, REM sleep is needed for implicit memory ("unconscious" recall), and NREM sleep is needed for declarative memory ("conscious" recall). (Born, 2010; Stickgold & Walker, 2005) Sleep difficulties may alter the stages of sleep, which can lead to deficits in memory functions. As any cognitive task usually activates several cognitive domains, the possibly affected memory functions—especially implicit memory—are also needed for many other cognitive functions, such as executive function. Therefore, this possible mechanistic route between disturbed sleep and memory functions may also extend to other cognitive function domains.

In addition to the abovementioned biological mechanisms behind the associations found between sleep characteristics and cognitive function, multiple external cause may also simultaneously cause disturbed sleep and cognitive function. Possible examples are diseases and health behaviors such as restless leg syndrome, sleep apnea, depression, or dementing diseases. (Pase et al., 2023; S. Wang et al., 2023; Zhao et al., 2024) Some conditions may also mediate these effects—for example, impaired mood or physical inactivity. To account for these possible causes, the analyses in this PhD study were adjusted for several potential confounders.

Several variables may also explain the changes in cognitive function during and after the retirement transition. The retirement transition represents a massive change in a person's life, and typically frees up around 40 hours per week for chosen activities. This newfound spare time could lead to completely opposite outcomes, depending on a person's personality, choices, and circumstances. For example, someone might take up new hobbies that offer physical activity, mental challenges, and social activities. In contrast, someone may become isolated at home and give up the physical activities, mental challenges, and social activities that were part of their working life. All of these can affect cognitive function.

The shift to full-time retirement typically means that work stress ceases, and this may have positive outcomes for cognitive function. However, the shift to retirement can also cause stress and anxiety due to, for example, a poor financial situation or the loss of daily routines. Naturally, sleep structure also changes, and as shown in this thesis, changes in sleep difficulties can change cognitive function during and after the retirement transition.

6.5 Methodological considerations

6.5.1 Study populations

This PhD study utilized four study cohorts, which enabled the association between sleep characteristics and cognitive function in late mid-life and old age to be

examined in multiple ways. In Studies I, II, and III, using data from FIREA enabled the use of objective sleep measurements based on accelerometer measurements, and in Study III, the annual measurements enabled sleep and cognitive function to be examined specifically during the retirement transition. However, the sample sizes in these cohorts were quite small which can result in selection bias. This was seen in FIREA, as the sub-study participants who underwent cognitive testing were healthier and had higher occupational positions than FIREA's survey-only participants. This selection might limit the generalizability of the results. Combining the data from FIREA, the Young Finns Study and the Health Clinic Study in Study II resulted in a large study sample of people in late mid-life and old age with computer-based cognitive measurements. However, the distributions of age, socioeconomic status, and sleep duration were different in these cohorts, which might have influenced the results to some degree. Similarly, in Study IV, the Whitehall II data provided a large study sample with repeated measurements and a long follow up from working life to retirement. However, in this setting, the sleep characteristics were self-reported and the cognitive tests were carried out in paper-and-pencil format. The majority of the Whitehall II participants were male white-collar workers, which might also limit the generalizability of the results.

6.5.2 Sleep and cognitive measurements

This PhD thesis utilized both self-reported and accelerometer-measured sleep characteristics. Self-reported sleep characteristics moderately correlate with objective measurements, but self-reports may cause some overestimation. (Lauderdale et al., 2008; Van Den Berg et al., 2008) The use of accelerometer-based sleep duration is a significant strength of this study. However, the accelerometer-based sleep duration in Study I may have led to some overestimation, because at the time, no information on WASO was available, and so wakefulness during the night could not be deducted from sleep duration. Similar overestimation from self-reports might be evident in the sleep duration of the Health Clinic Study participants, as they were asked to report their usual bedtime and wake time, which also fails to take WASO into consideration. As this PhD study analyzed several individual sleep difficulties, it provides new perspectives on previous research on sleep difficulties and cognitive function. However, it also led to some groups being quite small, which limits the associations found. Similarly, the number of long sleepers in most studies of this PhD thesis was so small that they had to be excluded from the analyses.

As regards cognitive measurements, both computer-based and paper-and-pencil tests were used. A significant strength of this study was that it covered a broad spectrum of cognitive domains. As some of the studies examined relatively young participants in late mid-life, the cognitive measurements used had to be complex

enough to differentiate the participants from one another and to show some change longitudinally. Using computer-based cognitive tests helped achieve this, as they more precisely record latency times and accuracy, for example, than traditional paper-and-pencil tests. They can also more easily be optimized to avoid the ceiling effect compromising the results.

However, the multitude of cognitive domains and even more subdomains cannot function purely alone: Any task simultaneously activates multiple cognitive domains and/or subdomains. Therefore, studying individual cognitive domains is also somewhat artificial, and the discussed cognitive domains and subdomains are only those that the given cognitive test mostly represents. As this PhD study utilized repeated cognitive measurements, the possibility of the practice effect must be considered. This most applies to Study III, in which cognitive measurements were taken once a year. However, the improvement shown during the retirement transition cannot really be explained by the practice effect, as this would also require an improvement in the post-retirement cognitive function.

6.6 Implications and future directions

This PhD thesis increases the knowledge on the associations between sleep characteristics and cognitive function. As the population ages, cognitive deficits are becoming increasingly prevalent. Therefore, research should focus on the underlying mechanisms to identify the modifiable risk factors behind declining cognitive function. Sleep characteristics have comprehensively shown to be associated with global cognitive function, but more longitudinal research on how sleep characteristics and cognitive function change was still needed. This PhD study implies that changes in sleep characteristics are associated with an accelerated decline in cognitive function. Although this study narrows the gap in knowledge on this topic, further evidence and replication of our findings are still needed.

The results of this PhD thesis suggest that sleeping less than usual the night prior to cognitive testing does not affect cognitive function. As patients often complain about sleeping poorly, it would be interesting to examine whether having more or less sleep difficulties than usual the night prior to cognitive testing is associated with cognitive function.

The improvement in cognitive function during the retirement transition found by this study also warrants further research. As the improvement was independent of sleep characteristics, it must have some other underlying cause. Finding this cause could potentially help workers reach their full cognitive capacity while still working and even help extend their working lives. A possible cause could be decreased work-related stress factors (e.g., work stress, time pressure, shift work, and physical stress factors), which could offer an interesting future direction for research.

It would also be interesting to see how cognitive function changes as retirees age, i.e., whether cognitive function starts to decline in the years following retirement. FIREA is an ongoing study and data collection will continue after retirement, thus enabling future investigation.

A growing number of intervention studies are attempting to improve people's cognitive health through lifestyle factors, for example, FINGER and World-Wide FINGERS. (Kivipelto et al., 2013) Several intervention studies are also aiming to improve people's sleep. (Albakri et al., 2021; Redeker et al., 2019) However, it would be important to include cognitive function as one of the potential health outcomes to gain a better understanding of whether improving sleep could improve cognitive health. Some ongoing intervention studies of cognitive function have included sleep in one of their interventions. (Rosenberg et al., 2024; Sala et al., 2025) These results could potentially have a huge impact, as most major health organization (e.g., the Lancet Commission) have concluded that research on the association between sleep characteristics and cognitive function or dementia is still inconclusive, thus rendering it impossible to make recommendations regarding sleep. (Livingston et al., 2024) On a nonclinical level, these results could also offer insights into how people could live up to their cognitive potential in working life by improving their sleep. This could potentially lead to improved work efficiency or even to extended working lives.

7 Conclusions

This PhD thesis has examined sleep characteristics and cognitive function in late mid-life and old age, when people were still actively working and then when they are retired. Sleep characteristics were evaluated using both self-reports and accelerometer measurements. A broad spectrum of cognitive domains were examined, using both computer-based and paper-and-pencil tests. This PhD thesis had a special focus on retirement, and the study followed participants from work to retirement, observing the concurrent changes in sleep characteristics and cognitive function. The main conclusions of the PhD study are the following:

1. Long sleep duration associates with poorer learning and memory, complex attention and executive function when compared to intermediate sleep duration. Participants with sleep difficulties showed poorer executive function than those without sleep difficulties. Thus, promoting good sleep might lead to better cognitive health in late mid-life and old age.

2. Sleeping more than usual the night associates with poorer complex attention when compared with sleeping the same amount as usual. Sleeping less than usual did not affect cognitive function.

3. Cognitive function temporarily improved during the retirement transition, and this was most evident in learning and memory. The improvement was independent of the concurrent changes in sleep characteristics. This cognitive improvement suggests that workers have unused cognitive reserves, and future research should focus on identifying the determinants of the improvement.

4. Changes in cognitive function across a longer time period, both before and after retirement, were not associated with changes in sleep duration. However, increasing and decreasing sleep difficulties were associated with a more pronounced decline in cognitive function during and after the retirement transition, which suggests that sleep difficulties play a role in the changes in cognitive function around the retirement transition.

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