

Effect of sleep-wake habits on cognitive ageing and on functional compensation : an interventional approach

Marine DOURTE

2025



Thèse soumise en vue de l'obtention d'un Doctorat en Sciences
Psychologiques et de l'Education

Effect of sleep-wake habits on cognitive ageing and on functional compensation : an interventional approach

Marine DOURTE

2025



Thèse soumise en vue de l'obtention d'un Doctorat en Sciences
Psychologiques et de l'Education

**Effect of sleep-wake habits on cognitive aging and on
functional compensation :**
an interventional approach

Marine Dourte

*A dissertation presented to meet part of the requirements for the degree of Doctor of
Psychological Sciences at the Faculty of Psychology and Education Sciences.*

Supervisor :

Dr. Christina Schmidt, PhD, GIGA-CRC Human Imaging, Université de Liège, Belgium

Co-supervisor :

Prof. Philippe Peigneux, PhD, UR2NF, Université Libre de Bruxelles, Belgium

Jury members :

Prof. Fabienne Collette , President, GIGA-CRC Human Imaging, Université de Liège, Belgium

Prof. Gilles Vandewalle , Secretary, GIGA-CRC Human Imaging, Université de Liège, Belgium

Prof. Christian Cajochen, Centre for Chronobiology, University of Basel, Switzerland

Prof. Olivier Mairesse, Brain, Body and Cognition, Vrij Universiteit Brussel, Belgium

Université de Liège – October 2025

*“Whatever you can do or dream you can, begin it. Boldness has genius, power
and magic in it.”*

JOHANN WOLFGANG VON GOETHE

Abstract

Ageing is accompanied by profound but highly heterogeneous changes in cognition, brain structure and function, and sleep-wake regulation. While some older adults maintain stable trajectories, others exhibit marked decline. Theoretical models of compensation and cognitive reserve suggest that lifelong resources and neural reorganisation support performance until resource limits are reached. These resources are, however, plastic and vary across individuals. Behavioural interventions may therefore modulate ageing trajectories, opening opportunities to preserve performance and delay decline. Yet, why some individuals preserve compensatory efficiency whereas others fail remains an open question. Sleep-wake habits, and in particular daytime napping, represent a promising but understudied factor. Napping increases with age, reflecting both circadian and homeostatic vulnerabilities, yet it may simultaneously blunt sleep-wake consolidation and undermine circadian integrity. This thesis explored whether habitual napping is either a cause, a consequence or both, of circadian dysregulation, and whether this positions it as an active driver of cognitive decline. We further wanted to assess whether acting on this behaviour could modulate cognitive and brain trajectories.

An interventional framework was implemented, combining behavioural testing, physiological monitoring, and neuroimaging in healthy older adults. First, we examined how ageing reshapes the relationship between thermoregulation and cognition, showing that circadian-homeostatic alterations co-occur with, but are not reducible to, cognitive decline. We then demonstrated that habitual napping modulates thermoregulatory processes linked to sleep propensity in the healthy older population. Building on this, a one-year nap-suppression intervention revealed that reducing daytime napping in both frequency and duration partially protects episodic and working memory trajectories. Finally, functional MRI results showed that manipulating napping habits alters brain recruitment patterns: nap suppression fosters adaptive compensation, whereas continued habitual napping is associated with inefficient overactivation and dedifferentiation.

Altogether, this work provides converging evidence that daytime napping is both a marker and a modifiable determinant of cognitive ageing, as well as circadian dysregulation. By integrating sleep physiology, thermoregulation, and brain correlates, the thesis highlights that behavioural interventions targeting sleep-wake consolidation may recalibrate compensatory mechanisms and preserve cognition. These findings underscore the potential of behavioural interventions, centred on sleep-wake regulation, to promote resilience and successful ageing.

Résumé

Le vieillissement s'accompagne de modifications profondes mais hautement hétérogènes de la cognition, de la structure et du fonctionnement cérébral, ainsi que de la régulation veille-sommeil. Alors que certains adultes âgés maintiennent des trajectoires stables, d'autres présentent un déclin marqué. Les modèles théoriques de la compensation et de la réserve cognitive suggèrent que des ressources accumulées tout au long de la vie, ainsi qu'une réorganisation neuronale, soutiennent la performance jusqu'à ce que les limites de capacité soient atteintes. Ces ressources demeurent toutefois plastiques et varient selon les individus. Des interventions comportementales pourraient donc moduler ces trajectoires de vieillissement, ouvrant des perspectives pour préserver les performances et retarder le déclin. Cependant, la raison pour laquelle certains individus maintiennent une efficacité compensatoire tandis que d'autres échouent reste une question ouverte. Les habitudes veille-sommeil, et en particulier la sieste, représentent un facteur prometteur mais encore peu étudié. La sieste tend à augmenter avec l'âge, reflétant à la fois des vulnérabilités circadiennes et homéostatiques, mais elle peut simultanément réduire la consolidation du cycle veille-sommeil et fragiliser l'intégrité circadienne. Cette thèse a exploré si la sieste habituelle constitue une cause, une conséquence, ou les deux à la fois, de la dysrégulation circadienne, et si elle peut dès lors être considérée comme un facteur actif du déclin cognitif. Nous avons également cherché à déterminer si l'action sur ce comportement pouvait moduler les trajectoires cognitives et cérébrales.

Un cadre interventionnel a été mis en place, combinant évaluations comportementales, mesures physiologiques et neuroimagerie auprès de personnes âgées en bonne santé. Premièrement, nous avons examiné comment le vieillissement reconfigure la relation entre thermorégulation et cognition, montrant que les altérations circadiennes-homéostatiques coexistent avec, mais ne se réduisent pas au, déclin cognitif. Nous avons ensuite démontré que la sieste habituelle module les processus thermorégulateurs liés à la propension au sommeil dans la population âgée. Sur cette base, une intervention de suppression

de la sieste sur un an a révélé qu'une réduction de la fréquence et de la durée des siestes protège partiellement les trajectoires de la mémoire épisodique et de la mémoire de travail. Enfin, les résultats en IRMf ont montré que la manipulation des habitudes de sieste modifie les patrons de recrutement cérébral : la suppression des siestes favorise une compensation adaptative, tandis que la poursuite de la sieste habituelle est liée à une suractivation inefficace et à une dédifférenciation.

Dans l'ensemble, ce travail apporte des preuves convergentes que la sieste est à la fois un marqueur et un déterminant modifiable du vieillissement cognitif, ainsi que de la dysrégulation circadienne. En intégrant la physiologie du sommeil, la thermorégulation et les corrélats cérébraux, cette thèse met en lumière que des interventions comportementales ciblant la consolidation veille-sommeil peuvent recalibrer les mécanismes compensatoires et préserver la cognition. Ces résultats soulignent le potentiel des interventions comportementales, centrées sur la régulation veille-sommeil, pour promouvoir la résilience et un vieillissement réussi.

Acknowledgments

I am now sitting down behind my desk, 350 pages of thesis manuscript written, more than 450 hours spent in the sleep lab, around 560 hours of scanning in the MRI Room, countless sleepless nights and 95 participants met. However, it is not mainly about these or my results that I am thinking about, but rather everyone that made it all happen and allowed my hard work to be accomplished.

I have to start by thanking my dear supervisor, Dr. Christina Schmidt. You have given me the opportunity to pursue a PhD and my goals. We have been through a lot, and our relationship can't be explained. You've been patient, guiding and supportive. You taught me a lot, both in terms of knowledge and scientific rigor, but also in terms of adaptation and creativity. You've never hesitated to push me, even when I thought I was unable. You saw a potential in me and made me work on it. Thank you for everything, for the science, for the laughter, for the great project and the amazing team you built for us to thrive in. This thesis wouldn't have seen the light of day if it weren't also for my co-supervisor, Prof. Philippe Peigneux, who was the one to introduce me to sleep research. Your kindness, goodwill, character and opinions have shaped my thesis journey and myself. I thank you for your availability and having seen my ambitions, my objectives, and put in the work to make them happen. You gently guided me, you directed my efforts without ever taking credit for putting the right ideas in my brain, and most importantly you never fed in my anxiety, but rather soothed it. You were a rock in the storm that is a PhD, without you knowing it.

I also thank my jury members, Prof Gilles Vandewalle, Prof Fabienne Collette, Prof Christian Cajochen and Prof Olivier Mairesse, for accepting to assess my work and for the time you have given me, as well as the opportunity to discuss my work with you during my defence. I extend my gratitude to Prof Steve Majerus who took part in reading this work and evaluated me through my thesis committee.

A kind thought goes to all the participants I met during my PhD, and whom have made CogNap possible. The time and efforts put into this study fostered wonderful human connections that I will cherish forever.

For it is impossible to name everyone, I would like to thank every colleague and friendly face that has accompanied me throughout this PhD journey. Thank you to every PhD student, post-doc, PI, Master's student (especially the ones I supervised: Camille, Gaëlle, Lydie, Maureen), co-authors and other colleagues. You all have made this adventure a magnificent one. To the ones beginning this wild adventure: savour it, and give your all. To the ones who are closing this chapter of their career: keep your eye on the prize, I know it's easy to forget but it is indeed all worth it.

I would like to make a special note to my own team, the Kronos Mannschaft as we called it. **Vincenzo, Marion, Mathilde** and **Michele**, you were not there for all of it, but you have modelled me and my PhD by the early advice you've given me. **Alexia**, thanks for making this whole study happen while still being so radiant and smiling, from the very beginning. It was a pleasure to share a part of this with you. **Gregory**, thank you for always being available, patient and willing to teach me. You are both a scientific resource and a pillar in this team, always ready to step up and ease my worries. You once told me that the PhD is like a marathon and sometimes you hit a wall: thank you for helping me climb it. **Stella**, see? I told you: we made it ! How could I have gone through all of this without my partner? Through all the highs and lows, you were a constant in this part of my life and I couldn't thank you enough for everything, and all the beers we shared. Words fall short to address the amount of support and friendship you have given me. We started as colleagues, but we ended this as friends. I am proud to have done this with you. **Aurora**, the succession, thank you for bringing a breeze of fresh air and motivation to our team during the end of my thesis. I know the lab will be lucky to have you: enjoy every piece of it, and embrace each part of the journey. Finally, **Nikos**, my friend and my shenanigan buddy, thanks for always being there to make me laugh, for having replied to every crisis (existential and real), and for feeding my σπανακόπιτα cravings. I will miss our sibling-like bickering and pranks. I didn't plan on finding such a true and dear

friend so close to leaving, and it's making it harder to say goodbye. Don't have too much fun without me, will you?

I also want to express my gratitude to my second team, from Basel. Although not officially part of the lab, you've made me feel a part of your team and I fostered friendships I didn't believe would happen. You've made me grow both as a researcher and as a human being, and you've shifted my perspective for the better. **Rafa, Noëmi**, thank you for showing me how bright and radiant a human being can be, and how life can be so easy when surrounded by the right people.

As people say, "it takes a village", and I couldn't have done this without mine: my CRC friends. **Islay, Roya**, you're both long gone from the lab now but not from our (my) thoughts. You've paved the way for what a great PhD must be like, and we only had to step in your tracks. **Maëlle, Larry, Paris, David**, I am glad I got to start and experience this part of my life with you, you've made it fun and bright ! **Elise**, Souvlaki, your strong mind and our time together has shaped my journey more than you know. I cherish every moment we spent together, for we laughed and cried and raged together. I hope to cross your path in the future ! **Ilenia**, Moncchichi, I don't know what to say to thank you. You were not only a colleague, you were a dear friend to me. You've always been there both emotionally and scientifically, and always proved present when I needed you. Here's to our journey together and what's to come!

Nawël, merci pour tout. On aura tout traversé ensemble: le beau, le juste, le drôle, l'aventure, tout comme le mauvais, le difficile, l'ennuyant; et même pour finir un bureau. Tu as été mon amie, ma confidente et ma plus grande supportrice à travers tout. Aucun merci ne sera assez grand pour t'exprimer ma gratitude.

John, c'était un sacré voyage, ces années ensemble ! Qui aurait cru que ce student helper allait devenir un ami si cher à mon cœur? TweedleDumb & TweedleDumb, Tic & Tac, John & Marine. J'ai appris à ne plus exister comme une personne seule au sein du labo, mais comme cette entité que tout le monde a assimilé. Où tu allais, j'allais ; et où j'étais, tu étais. Partir va me laisser un grand vide. Ne pas t'avoir dans

mon quotidien avec tes blagues nulles et tes piques, nos pauses cafés et nos balades, ça va être un manque que je n'arrive pas encore à réellement imaginer. Merci pour tout, pour ton amitié, ton soutien, ta foi inébranlable en mes compétences, ta révolte face aux injustices, ta joie sincère pour mes succès, tous nos moments, et m'avoir offert une place dans ta vie. Sache que tu auras toujours ta place dans la mienne.

Un énorme merci va également à mes amies hors du centre, car le soutien a été tout aussi important. **Justine, Lise, Sophie, Nast**, vous avez été des constantes et des rayons de soleil durant ce parcours. Même si vous ne compreniez pas toujours ce que je faisais, vous n'avez jamais cessé de croire en moi. On a déjà traversé un sacré bout de chemin ensemble, et je suis si heureuse de vous avoir autour de moi pour cette étape.

Assi, que dire? Tu m'as écoutée, conseillée, aimée, coachée, secouée, motivée, défendue, consolée, félicitée et célébrée, sans jamais te fatiguer. Aujourd'hui, à la fin de ce chemin long et sinueux, je veux te remercier car il est sûr que sans toi, je n'aurais pas autant persévéré. Tu m'as inculqué la valeur de ne pas seulement faire les choses, mais les faire bien, avec toutes ses tripes. Tu as été une force, parfois sans que tu ne le saches. Ma fierté de finir ce chapitre de ma vie est décuplé par le fait de savoir que je partage cette réussite avec toi, et qu'elle ouvre la porte à tant d'autres chapitres à tes côtés. Le future ne fait pas peur quand on est si bien accompagnée.

À ma famille, un merci ne suffirait pas. **Papa**, tu as été à mes côtés pour mes déceptions et mes peurs, mais aussi mes réussites et mes fiertés. Tu adoucissais le mauvais et tu amplifiais le bon. **Maman**, qui toujours cru silencieusement en moi, ton courage et ton combat m'ont inspiré dans chaque aspect de ma thèse. **Cha**, ma sœur, ne pas t'avoir plus près de moi a été un crève-cœur mais tu n'as jamais laissé la distance physique être un obstacle : je te savais là, toute proche, pour chaque instant. Merci d'avoir su me faire rire quand j'en avais besoin, malgré tes propres combats, d'avoir partagé tout ce qu'on partage, et le cadeau d'avoir si

incroyablement illustré ma thèse. **Didi**, tu as rendu cette thèse plus belle par ta présence, et les réussites plus pétillantes. Nos quelques moments partagés sur le campus, nos virées dans Liège resteront des moments précieux gravés dans ma mémoire. J'ai eu de la chance de t'avoir, et j'espère pouvoir te montrer ne serait-ce que la moitié du soutien que tu m'as donné, pour ton propre parcours. Si je peux te laisser un conseil: on ne faiblit pas. Mes sœurs, vous êtes mes fiertés et le plus beau cadeau que cette vie m'ait donné. Merci d'avoir fait entrer dans ma vie **Gauthier** et **Honoré**, que je considère comme ma famille. Je n'aurais pas pu rêver mieux comme famille que vous. A mes cousines, **Mélanie**, **Delphine**, **Morgane**, **Lou-Anne**, votre présence délirante m'a rappelé que, au final, rien n'est si sérieux que ça ne mérite pas d'en rire. A mes tantes **Chantale** et **Anita**, ma **Marraine**, mes oncles **Willy**, **Emile**, **Michel**, mes cousin(e)s **Jérôme**, **Thomas**, **Julie**, et mes deux petits monstres chéris **Auguste** et **Lou**, votre présence rend la vie plus belle. **Papy**, **Marc**, **Naim**, de là-haut j'espère que vous êtes fiers.

Tonton Guy, tu as été un roc. Sans qu'on ne se le dise, ta présence et ton soutien valaient toutes les déclarations du monde. Merci d'avoir toujours été là pour moi, depuis les tours en camion quand j'étais petite, jusqu'à me déménager d'un bout de la Belgique à l'autre quand j'étais grande, tout en continuant à te moquer de moi pour que je ne prenne pas la grosse tête. Tu as toujours su m'écouter quand j'en avais gros sur le cœur et me rappeler par ta révolte discrète que je méritais le respect et la bienveillance.

Et enfin, **Parrain**, cette thèse est pour toi. Au même titre que tout mon labo sait qui tu es, je pense qu'il est important de te le rappeler. Tu as été mon plus grand soutien, toute ma vie. Je n'ai jamais eu à douter de ton engagement et de ton amour, et tu m'as toujours fait me sentir capable et compétente. Tu m'as donné le courage quand je n'en avais plus, tu m'as donné le sourire quand j'avais des larmes, et surtout tu m'as donné la force par ton exemple. Je n'aurais jamais pu finir ce parcours si tu n'avais pas été à mes côtés. Merci pour tout ce que tu as fait pour moi, pour tout ce que tu m'as donné, pour le confort et la sécurité que tu m'as toujours fait ressentir. J'espère te rendre fier, autant que je suis fière d'être ta filleule.

Table of contents

Abbreviation List	25
Theoretical Background.....	29
Chapter 0. General Introduction	31
Chapter 1. Cognitive And Brain Ageing	33
1. HEALTHY COGNITIVE AGEING	33
1.1. <i>Age-Related Changes In Cognition</i>	35
2. BRAIN AGEING	42
2.1. <i>Structural Modifications</i>	42
2.2. <i>Adaptative And Functional Changes</i>	44
3. FACTORS INFLUENCING INTER-INDIVIDUAL VARIABILITY IN COGNITIVE AND CEREBRAL AGEING	55
Chapter 2. Sleep-Wake Cycle.....	57
1. SLEEP-WAKE CYCLE REGULATION	57
1.1. <i>Sleep</i>	57
1.2. <i>Circadian Rhythms & Homeostatic Regulation</i>	64
1.3. <i>Assessment Of The Sleep-Wake Cycle And Circadian Rhythms</i>	73
2. ASSOCIATION BETWEEN SLEEP-WAKE CYCLE AND COGNITIVE AGEING	84
2.1. <i>Sleep And Cognition</i>	85
2.2. <i>Rest-Activity Cycles And Cognition</i>	86
Chapter 3. Napping	91
1. NAPPING AND THE SLEEP-WAKE CYCLE	91
2. NAPPING AND COGNITION	94
2.1. <i>Underlying Cerebral Correlates</i>	98
Chapter 4. Objectives And Hypotheses	101

EXPERIMENTAL PART	105
Experimental Protocol.....	107
Study 1. Uncorrelated Age-Related Changes In Visuo-Spatial Working Memory Binding And Thermoregulation	115
1. INTRODUCTION	117
2. RESULTS.....	119
3. DISCUSSION.....	124
4. MATERIALS & METHODS	128
Study 2. The Impact Of Napping Habits On The Relationship Between Thermoregulation And Sleep In Healthy Older Adults: A Cross-Sectional Study	135
1. INTRODUCTION	137
2. METHODS.....	140
3. RESULTS.....	147
4. DISCUSSION.....	154
Study 3. Breaking The Nap Habit: Impact Of A One-Year Nap Suppression Intervention On Cognition In The Elderly	165
1. INTRODUCTION	167
2. METHODS.....	167
3. RESULTS.....	176
4. DISCUSSION.....	183
Study 4. Acting On Napping Habits Modulates The Cerebral Correlates Underlying Working Memory In Healthy Ageing	191
1. INTRODUCTION	193
2. METHODS.....	196
3. RESULTS.....	207
4. DISCUSSION.....	214

GENERAL DISCUSSION.....	225
1. CONTEXT AND HYPOTHESES	227
2. MAIN FINDINGS AND INTERPRETATIONS	229
2.1. <i>Napping Modulates Age-Related Changes In Thermoregulation.....</i>	<i>229</i>
2.2. <i>Nap Reduction Partly Protects Episodic Memory Trajectory.....</i>	<i>232</i>
2.3. <i>Nap Reduction Influences Working Memory Trajectory And Its Underlying Cerebral Correlates</i>	<i>235</i>
2.4. <i>Insight Into Preliminary Data Of The Nap-Suppression Intervention Effect On Skin Temperature Modulation, Melatonin And Sleep Propensity</i>	<i>237</i>
3. LIMITATIONS AND FUTURE PERSPECTIVES	243
3.1. <i>Sample Characteristics</i>	<i>243</i>
3.2. <i>Intervention Characteristics</i>	<i>249</i>
4. CONCLUSION : THE “CHICKEN OR THE EGG” QUESTION	254
 APPENDICES.....	 259
Appendix 1 : List Of Publications	261
Appendix 2 : Napping Alters Functional Brain Responses In The Aged	263
ABSTRACT	264
1. INTRODUCTION	265
2. RESULTS.....	268
3. DISCUSSION.....	272
4. METHODS.....	277
Appendix 3 : Preliminary Results.....	291
Appendix 4 : Linap Questionnaire.....	297
 BIBLIOGRAPHY	 303

Abbreviation list

AD : Alzheimer's disease

AIC : Akaike Criterion

BAI: Beck Anxiety Index

BDI: Beck Depression Index

BMI : Body Mass Index

BOLD: Blood-oxygenation-level-dependent

CBT : Core Body Temperature

CR : Constant Routine

CRUNCH: Compensation-Related Utilisation of Neural Circuits Hypothesis

DLMO_n : Dim Light Melatonin onset

DLPFC: Dorsolateral prefrontal cortex

DMH : dorsomedial hypothalamus

DPG : Distal-Proximal Gradient

DTR: Daytime rest

EEG : electroencephalography

EMG : electromyography

EOG : electrooculography

ESS: Epworth sleepiness scale

FCRST: Free and Cued Selective Reminding Test

FD : Forced Desynchrony

fMRI: functional Magnetic Resonance Imaging

GLMM: Generalised linear mixed-model

HAROLD: Hemispheric Asymmetry Reduction in Older Adults

LC : Locus Coeruleus

LI: Laterality Index

LM: Logical Memory

MEQ : Morningness-Eveningness Questionnaire

MMSE: Mini-Mental State Examination

MRI: Magnetic Resonance Imaging

MSS: Memory Set-Size

MST: Mnemonic Similarity Task

NREM : Non-Rapid Eye Movement

PASA: Posterior-Anterior Shift in Aging

PLMS: Periodic Limb Movement Syndrom

PPT-LDT: Pedunculo pontine and laterodorsal tegmental nuclei

PSG : polysomnography

PSQI: Pittsburgh Sleep Quality Index

REM : Rapid Eye Movement

SCN : suprachiasmatic nucleus

SE: Sleep efficiency

SOL : Sleep onset latency

STAC: Scaffolding Theory of Aging and Cognition

SWA: slow-wave activity

SWS: slow-wave sleep

T0: Baseline assessment

T1: one-year follow-up assessment

T2: two-year follow-up assessment

VLPO : Ventrolateral preoptic nucleus

vsWM : visuospatial working memory

WM : Working memory

WMZ: Wake maintenance zone

Theoretical Background

Chapter 0. General Introduction

Ageing is a multidimensional process, which reshapes physiology, brain structure and function, as well as cognition, in a heterogeneous and non-linear manner. Cognitive declines in domains such as processing speed, episodic and working memory, and certain executive processes, contrast with the maintenance or even improvement of crystallised abilities, and the inter-individual variability increases with age. Concomitantly, older adults often recruit broader and more bilateral neural networks to sustain performance, suggesting compensatory engagement of additional resources when primary systems lose efficiency. Compensation, however, knows a high inter-individual variability in its efficiency. These divergent trajectories, both at the cognitive and brain level, are interpreted through frameworks that combine structural brain change, functional reorganisation (reserve, maintenance), and the influence of biological and lifestyle modulators. Among the latter, the temporal architecture of sleep and wakefulness and importantly, their circadian regulation, have emerged as a key candidates for explaining a part of why some older adults maintain cognitive and compensational efficiency while others do not.

Human sleep-wake regulation is described as the interaction between two processes : a homeostatic process, which tracks prior wakefulness and dissipates during sleep, and an endogenous circadian timing system, which orchestrates a near-24-hour rhythm in physiology and behaviour. With advancing age, both of these components seem to be impaired: circadian signals tend to flatten and drift, while homeostatic pressure accumulates and dissipates less efficiently. As a consequence, the usual alternation of a consolidated nocturnal sleep and a sustained daytime wakefulness gives way to a more fragmented pattern marked by frequent nocturnal awakenings, earlier bed- and wake-times, and increased daytime sleepiness. A less examined part of this landscape is the continuity of wakefulness, even though daytime napping is common in later life. It may serve adaptive functions in some contexts, such as relieving accumulated sleep pressure

or enhancing alertness, but it can also fragment the wake period, blunt homeostatic build-up, and interact with circadian timing. Recurrent naps may therefore be both a response to, and a driver of, circadian dysregulation.

Integrating these elements suggests a circadian-cognitive view of ageing in which the stability of the 24-hour physiological modulation, as well as the integrity of consolidated wakefulness, shape cognitive trajectories. Disrupted circadian signalling may erode the temporal coordination of neural processes that underpin cognition, including memory. On the other hand, behavioural adjustments that restore circadian consolidation could, at least partially, preserve cognitive function. In this perspective, habitual napping is not treated merely as a benign lifestyle choice but as a behavioural marker of underlying temporal dysregulation whose modulation might yield cognitive benefits.

The work presented in this thesis is grounded in this theoretical stance. We examine how age-related changes in circadian (thermo)regulation and wake continuity relate to fluctuations in cognitive performance and neural activity, and whether modifying the single, tractable behaviour that is daytime napping can recalibrate circadian physiology. By combining behavioural, physiological and neuroimaging measures, the thesis aims to move from descriptive associations towards a more mechanistic account of how circadian integrity interfaces with cognitive and brain ageing. From this standpoint, we first set the broader theoretical background: Chapter 1 positions cognitive and brain ageing within contemporary theoretical frameworks of reserve, maintenance and compensation. Chapter 2 then details the dual (homeostatic-circadian) regulation of the sleep-wake cycle, putting the emphasis on thermoregulatory processes, linking them to cognition trajectory in ageing. Chapter 3 synthesises current evidence on daytime napping and wakefulness fragmentation in older adults, and its impact on cognition. We then describe the experimental protocol and cohort before presenting four studies that each probe a complementary facet of the circadian-cognition interface.

Chapter 1. Cognitive and brain ageing

1. Healthy cognitive ageing

Ageing is a complex and multidimensional process characterised by progressive physiological, neurological, cognitive and social changes that vary greatly across individuals (López-Otín et al., 2013). One the most prominent aspects is cognitive ageing, which refers to the heterogeneous and dynamic process by which cognitive functions change across the lifespan, usually involving decline in certain domains. However, cognitive ageing also includes preserved or even improved capacities in some processes, notably influenced by the interplay between compensatory mechanisms, and environmental, psychosocial, and biological factors (Harada et al., 2013; Lupien & Wan, 2004; D. C. Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2010). The cognitive trajectory is far from uniform, with inter-individual variability increasing with advancing age. A growing body of research highlights the existence of *healthy* cognitive ageing, being the relative preservation of cognitive function and autonomy despite the passage of time, as opposed to *pathological* ageing (Cabeza et al., 2018; Nyberg et al., 2012). Healthy cognitive ageing may represent a key component of what is often referred to as "successful ageing", although the boundaries and definitions of this broader concept remain subject to debate (Lupien & Wan, 2004).

Indeed, the concept of successful ageing lacks a consensus definition, with variations between *research-driven* and *multidimensional, general*, perspectives. Research-driven definitions often focus on biomedical aspects such as physical functioning and the absence of disabilities (Cosco et al., 2014; Depp & Jeste, 2006). For example, in the context of biomedical definitions, successful ageing is linked to the lack of objective cognitive impairment or age-related diseases such as cardiovascular weakness. Lay perspectives however emphasize psychosocial factors such as family, social interactions, and activities (Cosco et al., 2014; Jan Długosz University in Częstochowa & Kozerska, 2022). An example of successful ageing in such definitions would be that old adults communicate satisfaction

towards their life, their social environment or have little to no subjective (cognitive) complains. Studies which have explored the relationship between cognitive, physical, and psychosocial factors in the context of successful aging, have linked quality of life to physical and cognitive ability (Castro-Lionard et al., 2011; Depp & Jeste, 2006; Inui, 2003; Newman et al., 2003; Strawbridge et al., 1996). It has to be noted that well-being and meaningful social interactions also play a significant role in the subjective perception of successful ageing (Von Faber et al., 2001). Some authors argue for a multi-dimensional model of successful ageing that incorporates both general and research-driven perspectives, and uses a continuum rather than dichotomous cut-offs (Bowling, 2007; Inui, 2003; Von Faber et al., 2001).

The complexity of this concept is further demonstrated by the different ways of characterizing successful ageing. Indeed, when attempting to define what constitutes “success”, the question arises: to what are we comparing it? There are multiple comparative frameworks (Lupien & Wan, 2004). It is of importance to take a stance on the way in which we talk about successful ageing, whether cross-sectionally by comparing with young adults, cross-sectionally in relation to standardised norms, cross-sectionally in relation to people from the same age-group, or longitudinally by using the subjects' own baseline as a point of reference (Lupien & Wan, 2004). Each of these approaches carries its own methodological and interpretative limitations, particularly due to the increased interindividual variability observed with ageing, and the risk of elitist or biased classifications depending on the chosen reference point. Indeed, comparisons with young adults may overemphasize age-related decline and foster a deficit-based narrative. Reference to standardized norms, while convenient, often neglects contextual and lifestyle variability. Age-group comparisons can suffer from cohort effects and may mask individual trajectories. Longitudinal approaches, while powerful for capturing intraindividual change, can be influenced by practice effects and attrition biases, and may still overlook broader normative shifts. In the context of this thesis, we will be using a mix of these stances, with a focus on the last two. First, we will focus on healthy ageing in terms of physical and cognitive health, using here a

research-driven definition based on the lack of physical and cognitive disability, comparing to both young and same-age groups. We will also focus on how people evolve with regard to their own baseline and how this evolution can vary according to sleep-wake cycle differences at baseline.

1.1. Age-related changes in cognition

Whilst age-related cognitive changes are common in healthy ageing, their onset and trajectory exhibit high inter-individual variability (Nyberg et al., 2012; D. C. Park & Reuter-Lorenz, 2009). In addition to differences between individuals, there are also intra-individual variations, as cognitive performance across different domains may evolve in distinct ways and to varying degrees over time.

1.1.1 Attentional processes

The attention domain encompasses a set of cognitive processes that enable the detection, selection, and sustained processing of relevant stimuli, while managing or inhibiting responses to distractions (Posner & Petersen, 1990). It is a basic cognitive function involved in all aspects of daily life, from intellectual performance to behaviour: attentional processes are required whatever the type of cognitive activity undertaken (Leclercq & Zimmermann, 2014).

A useful framework is the Posner & Petersen (1990) attentional-network model, which divides attention into three networks : alerting, orienting and executive control.

Alerting refers to the ability to maintain a state of readiness over time (*tonic alertness*) and transiently increasing reactivity after a warning (*phasic alertness*). *Processing speed*, one of the main fundamental attentional process, maps primarily onto the alerting network and especially phasic alertness (Posner & Petersen, 1990). With healthy cognitive ageing, a decline in processing speed is frequently observed, due to a slowing of the underlying neuronal mechanisms, affecting phasic alerting more than tonic alerting (Mahoney et al., 2012; Wiegand & Sander, 2019). This decline impacts several cognitive functions, influencing performance

in complex tasks requiring a rapid response (Salthouse, 1996). *Vigilance*, the ability to maintain a state of cognitive readiness and detect rare stimuli over long periods of time, is also primarily associated with the alerting network. It relies on neurocognitive mechanisms to prevent the progressive decline in attention in the absence of frequent stimulation (Oken et al., 2006). Older people show a decline in vigilance, attributed mainly to a reduction in the effectiveness of the attentional networks involved in maintaining alertness and executive control (Staub et al., 2013). This decline is reflected by a progressive decrease in responsiveness during prolonged tasks, particularly those with low external stimulation (Berardi et al., 2001). *Sustained attention*, being the capacity to stay on task over long durations, depends largely on the alerting network too, and declines in tandem with slowed processing speed (Staub et al., 2013).

Orienting refers to the selection of spatial or modality-specific inputs, for example shifting between auditory and visual sources. Within this part of Posner & Petersen's framework, *auditory* and *visual attention* are found, and remain relatively preserved with age (Harada et al., 2013).

Executive control is the capability of resolving conflict among competing stimuli or responses, for example by inhibiting distractors. This calls for *selective attention*, which refers to the capacity to concentrate on relevant information while disregarding irrelevant stimuli in the environment, as well as for *divided attention*, involving the management of information from at least two sensory sources simultaneously (Leclercq & Zimmermann, 2014); although both are also recruited by the orienting part of the model. These more complex attentional processes show a more marked age-related decline (Harada et al., 2013). This means that, in older adults, decline in attentional performance can be linked to other cognitive domains' decline, such as inhibition capacity (Introzzi et al., 2020).

An alternative perspective is provided by Kahneman's (1973) capacity-model of attention, which conceptualizes attention as a limited pool of cognitive resources. As task demands rise, whether through increased cognitive load or dual-task

conditions, resources are flexibly allocated, but older adults hit their capacity ceiling sooner (Drag & Bieliauskas, 2010). To compensate or to maintain their performance levels, they bolster executive control and employ alternative cognitive strategies, such as increased reliance on top-down control, more frequent self-monitoring, or strategic allocation of attentional resources (Vallesi et al., 2021). For instance, they may consciously pace their response, take brief self-initiated pauses to preserve energy, or use inner speech and conscious rehearsal strategies to stay focused (Glisky, 2007; Staub et al., 2013). Either a reduction in cognitive resources or a preference for less risky strategies is thought to partly explain the age-related decline in attentional performance. (Forstmann et al., 2008; Rienäcker et al., 2018). This dovetails with Wickens' (1984) multiple-resource theory, which predicts the greatest performance decrements when tasks compete for the same resource pool. Indeed, the effects of ageing on attention vary depending on the presentation type, notably in divided attention, with old individuals experiencing the greatest difficulty in auditory tasks when accompanied by visual distractions (Rienäcker et al., 2018).

1.1.2 Executive functions

Executive functions are a set of cognitive processes regulating goal-directed behaviour, including : updating, planning, inhibition, cognitive flexibility, and partly working memory (Miyake et al., 2000; Van der Linden et al., 2014).

Updating refers to the ability to encode and manipulate information while keeping only the most relevant content for a given task. This process involves continuously replacing outdated and irrelevant information to optimize efficiency (Miyake et al., 2000). **Planning** is to the aptitude to mentally represent and organize a sequence of actions to achieve a specific goal. This involves anticipating obstacles, prioritizing steps, and adjusting strategies as needed (Miyake et al., 2000). **Inhibition** is the capacity to suppress dominant or automatic responses in a controlled, conscious manner (Miyake et al., 2000; Van der Linden et al., 2014). Finally, **flexibility** involves the ability to disengage from an ongoing cognitive

process and shift to an alternative strategy better suited to the task at hand, or in response to new information. Successfully switching between strategies requires not only efficient disengagement, but also effectively managing interference from prior cognitive operations (Miyake et al., 2000; Van der Linden et al., 2014).

In regards to age-related changes, older adults generally perform worse than younger individuals across all executive functions (Maldonado et al., 2020), but the age effect appears to be less pronounced for updating (Maldonado et al., 2020). Although older adults require more time to update information while simultaneously maintaining it in short term memory (updating), they are still perform the task effectively, albeit at a slower pace (Artuso et al., 2017). This is also true for planning: older adults often require more time and demonstrate a more cautious approach compared to younger individuals (Zook et al., 2005). This aligns with the speed-accuracy trade-off phenomenon, which states that older individuals tend to prioritize accuracy over speed, adopting a more deliberate response strategy to compensate for potential cognitive decline (Forstmann et al., 2008).

1.1.3 Memory processes

Memory is the ability to encode, store, and retrieve information over time, either it being on the short or long term (Baddeley, 2000).

Working memory, is the ability to temporarily maintain some pieces of verbal or visuo-spatial information, in an active and conscious manner (Majerus, 2014). This is a main basic function for everyday life, as it enables the individual to plan, link a stimulus perception to the appropriate behavioural response, and more generally serves for multiple other more complex cognitive functions. Multiple models of working memory have been proposed. The original Baddeley & Hitch (1974) model proposed that working memory is composed of 3 intertwined parts: (a) the phonological loop, temporarily storing verbal information through an articulatory loop system linked to an acoustic store; (b) the visuo-spatial sketchpad, temporarily storing visuo-spatial information; (c) the central executive, which oversees and coordinates the phonological loop and visuo-spatial sketchpad, and

is responsible for actively manipulating and transforming the information held in these systems. The model was later on improved with the addition of (d) the episodic buffer, being the consciously-accessible interface between short and long term memory (Figure 1)(Baddeley, 2000, 2012).

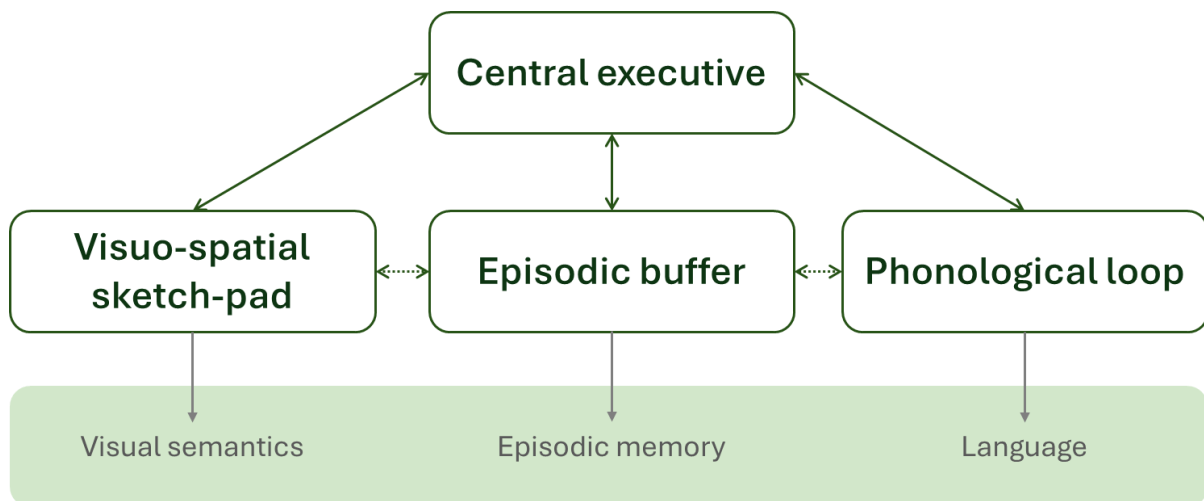


Figure 1. Updated version of the multicomponent model, including the episodic buffer and link to long-term memory (adapted from Baddeley, 2010).

However influential and vastly referenced, this model has now been reviewed and updated and is no longer a stand-alone model in the field. Indeed, working memory performance relies on the association of attentional and sensorial processes (Majerus, 2010; Majerus et al., 2012, 2016, 2018), but only a few models take into account the role that attentional processes play in working memory. Cowan's embedded-process working memory model (Cowan, 1995) stipulates that working memory can be understood as a temporary storage system with limited capacity, relying significantly on attention and central executive functions to manipulate stored information and coordinate with long-term memory. This model considers working memory as a sub-part of long-term memory, and not a specific kind of memory itself (Figure 2).

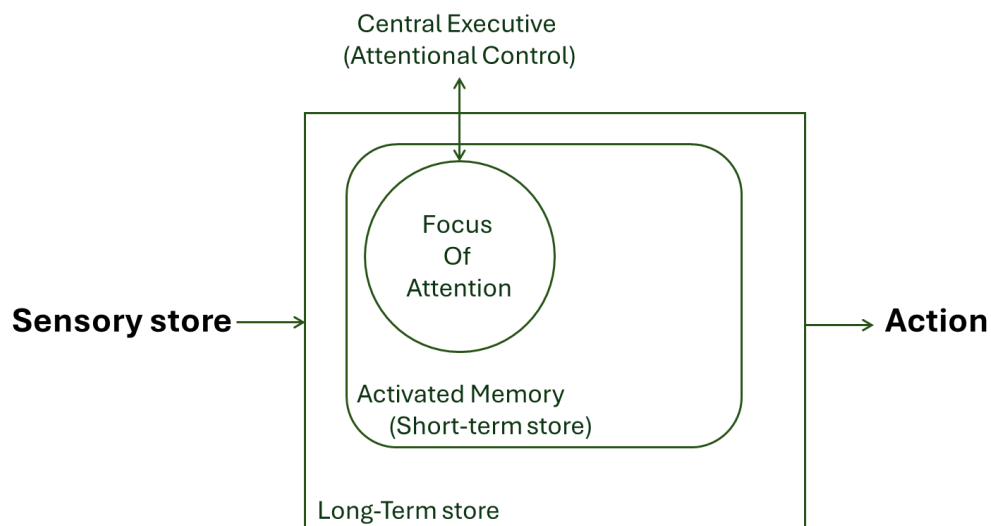


Figure 2. Simplified diagram of Cowan's embedded-process model of working memory (adapted from Morrison, 2005).

Independent of the model used to represent it, working memory seems to undergo an age-related decline which is even more pronounced when task difficulty and cognitive load increase (Angel & Isingrini, 2015, 2015; Cappell et al., 2010). Multiple theories have been brought forward to explain the mechanisms underlying this decline, including reduced cognitive processing resources (Craik & Byrd, 1982; Salthouse, 1990), reduced processing speed (Babcock & Salthouse, 1990; Salthouse, 1996), or a decline in selective attention and inhibition capacity (Gazzaley et al., 2005). Moreover, it has to be noted that visuospatial working memory performance in its entirety, but also the more specific object-location binding process, declines with age (Babcock & Salthouse, 1990; Gazzaley et al., 2005; W. Johnson et al., 2010; M. Parra et al., 2009; Pertzov et al., 2015).

Long-term memory is comprised of 2 main parts: explicit (declarative) and implicit (non-declarative) memory. When considering how long-term memory works, 3 essential stages emerge (Van der Linden, 2014): (1) encoding, during which information is acquired, (2) storage, during which the information is maintained for a more or less long period, and (3) retrieval, the process of accessing the encoded and stored information. The distinction between explicit and implicit memory relates primarily (but not only) to how retrieval occurs (Van der Linden, 2014): is the search for and access to information voluntary, and thus explicit? Or

is it involuntary, automated, and therefore implicit? However, it is important to note that information can be encoded through either explicit or implicit processes as well, reflecting different learning mechanisms. Amongst others, implicit memory contains **procedural memory**, referring to skills and actions, as diverse as they are preponderant in our daily activities, since nearly all of which depend on it in some form; and **emotional conditioning** (LeDoux, 2000; Schacter & Tulving, 1994; Squire, 2004). On the other hand, declarative memory is comprised of both **semantic memory**, being general knowledge and concepts, lacking context (*"I know Guns n Roses was founded in 1985, but I don't know when or where I learned this information"*), and **episodic memory**, being experienced events for which we have kept context (when, how, where we learned the information) (Tulving, 1972).

Episodic memory was shown to decline with healthy cognitive ageing (Tromp et al., 2015), but the underlying mechanisms are complex. Indeed, ageing affects encoding (Craik & Rose, 2012), but also retrieval. Evidence shows a predominant impact on the precision of memories recalled, with finer details becoming less accurate, rather than on the ability to retrieve the memories themselves (Duarte & Dulas, 2020; Korkki et al., 2020). Older adults tend to exhibit reduced mnemonic precision for both item-based and contextual information. In particular, ageing disproportionately disrupts the ability to recall contextual details of an event, such as spatial or temporal aspects, while more global familiarity-based retrieval remains relatively preserved (Angel et al., 2013; Bastin et al., 2004). This leads to a dissociation between 3 processes. *Familiarity*, which is mostly unconscious, automatic, and decontextualised, is typically maintained. The active, conscious process of *remembering* is based more on specific details, particularly spatio-temporal ones, and declines with advancing age (Angel et al., 2013; Bastin et al., 2004). However, the trajectory of episodic memory ageing is highly heterogeneous, associated by both subjective and objective cognitive health factors (Chamberlain et al., 2022). Longitudinal evidence shows that changes in subjective health perceptions are linked to memory performance fluctuations in older adults (Chamberlain et al., 2022; Wahlin et al., 2003). Subjective memory performance

partly reflect actual memory function but is also influenced by mood and personality traits, which can moderate this relationship (Hülür et al., 2015). Individual differences in this evolution may be partially explained by factors such as cognitive and cerebral mechanisms in place, that can in turn modulate age-related memory impairments (Bastin et al., 2013).

2. Brain ageing

2.1. Structural modifications

Healthy ageing is associated with structural brain changes, such as global volume loss and regional atrophy (Bethlehem et al., 2022; Fjell & Walhovd, 2010; Long et al., 2012). The most significant changes are observed in the frontal and temporal regions, as well as in subcortical structures such as the thalamus and putamen (Fjell & Walhovd, 2010; Long et al., 2012). However, recent work have highlighted the vulnerability of other subcortical areas and brainstem nuclei critical to sleep-wake regulation, notably the hypothalamus and the locus coeruleus (Engels-Domínguez et al., 2023; Lew et al., 2021). In the older population, gyrification in paracentral and inferior frontal regions is linked to REM sleep propensity (Deantoni, Reyt, Berthomier, et al., 2023), further strengthening this claim. These alterations seem to be linked to age-related cognitive decline, more specifically in processing speed, executive functions, and episodic memory (Fjell & Walhovd, 2010).

In healthy ageing, global grey matter volume reduction has been observed (Bethlehem et al., 2022; Filippini et al., 2012; Raz & Rodrigue, 2006). Yet, the extent of grey matter atrophy could have been overestimated. While some research do indeed suggest overall grey matter decline particularly in frontal regions (Farokhian et al., 2017; Kalpouzos et al., 2009), other authors found no significant age-related grey matter atrophy in cognitively stable healthy older adults (Burgmans et al., 2009). Regardless, the frontal cortex is one of the most vulnerable to age-related grey matter deterioration (Manard et al., 2016), and structures such

as the anterior hippocampus and posterior cingulate cortex are more resistant (Kalpouzos et al., 2009). Moreover, age-related reductions in cortical thickness have been observed in several brain regions (Deantoni, Baillet, Hammad, et al., 2023), notably in central and occipital (Manard et al., 2016). The relationship between structure and cognitive function has been evidenced by positive correlations between prefrontal cortex activity and medial temporal lobe grey matter volume in healthy aging (Maillet & Rajah, 2013). Altogether, these structural grey matter age-related modifications have been linked to cognitive decline, mainly in executive functions (Manard et al., 2016; Montembeault et al., 2012; Naumczyk et al., 2018) and episodic memory due to the observed hippocampus atrophy (Klinzing et al., 2019).

In regards to white matter, it appears that both its microstructure and integrity are affected by ageing (Burzynska et al., 2010; Raz & Rodrigue, 2006; Westlye et al., 2010), and even more so than grey matter (Callaghan et al., 2014; Salat et al., 1999). These structural changes are notably characterized by decreased fractional anisotropy (FA) and increased mean diffusivity (MD), especially in frontal areas (Lockhart & DeCarli, 2014; Molloy et al., 2021; Salat et al., 2005). FA measures the directionality of water diffusion along white matter fibres, with lower values indicating loss of fibre integrity. MD reflects overall water diffusion, with higher values signalling tissue degeneration. Together, decreased FA and increased MD reveal compromised white matter microstructure affecting brain connectivity. These changes are associated with reduced white matter volume (Gunning-Dixon et al., 2009; Guttmann et al., 1998), with FA being more sensitive to early white matter alterations (Salat et al., 2005). Grey and white matter alterations are due to different mechanisms. Age-related reductions in grey matter volume and integrity are linked to neuronal death, mostly in the case of pathological and neurodegenerative ageing. (Uttara et al., 2019). In the context of healthy ageing, these reductions are mostly attributable to reduced synaptic density rather than neuronal loss (Dickstein et al., 2007; Resnick et al., 2003; Terry & Katzman, 2001). Age-related changes in white matter are thought to be the reflection of underlying

biological processes, such as demyelination or axonal damage (Molloy et al., 2021), as well as a weakening in oligodendrocytes maturation (Chapman & Hill, 2020). Of note, white matter integrity shows stronger correlations with cognitive performance than grey matter changes (Colcombe et al., 2006).

2.2. Adaptative and functional changes

Healthy cognitive ageing features distinct structural and functional adaptations, with complex patterns of brain reorganisation, plasticity and compensation that enable preserved cognitive function. While structural age-related degeneration occurs, the brain employs various compensatory mechanisms to maintain performance.

2.2.1. Cognitive reserve

A first mechanism by which older adults maintain cognitive performance is **cognitive reserve** (Stern, 2002), which represents the brain's capacity to maintain cognitive function despite age-related changes or pathology (Soldan et al., 2017) by adapting its functioning, flexibility, as well as accumulating resources that will attenuate age-related decline (Stern, 2002; Stern et al., 2020, 2023). This reserve is built throughout the entire life, and is comprised of both innate (genetic factors) and acquired and modifiable factors, notably through lifestyle (Cabeza et al., 2018; Stern et al., 2020), such as education, physical activity and social interactions (Bastin et al., 2013). This construct is furthermore estimated by various indices, including educational attainment, occupational complexity, premorbid intelligence, and engagement in cognitive activities (Solé-Padullés et al., 2009). The measure of such a reserve cannot be done directly, and therefore relies on proxies such as genetic measures, electrophysiology, neuroimaging or neuropsychological assessments (Pappalettera et al., 2024).

It is important to underline a key difference. *Cognitive* reserve is not *cerebral* reserve : the former relates to the link between factors affecting the cognitive decline and cognitive performance, while the latter refers to the structural integrity

of brain correlates (Stern et al., 2019). Nonetheless, higher cognitive reserve is associated with larger grey matter volumes in frontal and parietal regions among healthy older adults (Bartrés-Faz et al., 2009; Ramanoël et al., 2018). Overall white matter integrity has also been found to be moderated by cognitive reserve, contributing to better cognitive function (Baker et al., 2017; Lin et al., 2023). Additionally, individuals with higher cognitive reserve show lower amyloid deposition in critical brain regions, including the temporoparietal cortex, parahippocampal gyrus, hippocampus, and left frontal cortex (Ali et al., 2020; Oh et al., 2014). From a functional point of view, cognitive reserve operates by using more efficient or flexible neural networks, as well as the recruitment of alternative brain regions (Oh et al., 2014; Solé-Padullés et al., 2009).

In terms of protective effects, cognitive reserve has been associated with a delayed onset of negative cognitive symptoms and better baseline cognitive performance (Soldan et al., 2017). Notably, individuals with higher cognitive reserve can tolerate more advanced brain pathology before showing clinical symptoms, suggesting a compensatory mechanism (Soldan et al., 2020). This is particularly evident in the relationship between cognitive reserve and Alzheimer's disease biomarkers, where cognitive reserve moderates the impact of neuronal injury markers, such as elevated phosphorylated tau, increased neurofilament light chain levels, or hippocampal atrophy, on cognitive function (Soldan et al., 2017). One's ability and need to adapt can differ, leading to a high inter-individual variability.

A final important distinction from the notion of *reserve*, which is commonly applied to describe the brain's capacity to compensate for physiological alterations, is the term *resilience* which refers to the dynamic processes that support resistance to the onset or progression of neurodegenerative diseases (Arenaza-Urquijo & Vemuri, 2018, 2020; Pascual-Leone & Bartres-Faz, 2021). Resilience is considered an active mechanism, encompassing neuroplastic changes in both brain structure and function across the lifespan. It enables individuals to maintain higher-than-expected cognitive performance in the presence of neuropathology (Pappalettera

et al., 2024; Stern et al., 2023). In parallel, the prevention or delay of neuropathological damage before it emerges, meaning a lower-than-anticipated levels of pathology in old populations, refers to the concept of *resistance* (Arenaza-Urquijo & Vemuri, 2018, 2020).

2.2.2. Maintenance

Another mechanism at play for the preservation of cognitive performance in healthy ageing is **maintenance** (Cabeza et al., 2018; Stern et al., 2019, 2020), that is the preservation of neuronal resources allowing the brain to reduce the impact of age and pathologies (Cabeza et al., 2018; Stern et al., 2019, 2020). While cerebral reserve refers to greater neuronal resources, maintenance is the brain's ability to counteract cellular or molecular impairments (Nyberg et al., 2012). Maintenance is present during all the individual's life, but its importance is truly shown with advancing age as risks for neural deterioration are higher (Cabeza et al., 2018). Maintenance is highly variable between individuals, as it is driven from genetic and environmental factors (Stern et al., 2019, 2020), and depends on both the extent of cognitive decline and the efficacy of the repairs made (Cabeza et al., 2018). Because maintenance refers to the brain's ongoing ability to preserve function by preventing or repairing cellular and molecular damage, it is best assessed through longitudinal studies that track changes over time rather than cross-sectional snapshots (Cabeza et al., 2018; Nyberg et al., 2012; Raz & Lindenberger, 2011; Stern et al., 2019, 2020).

2.2.3. Compensation

The concept of compensation involves the engagement of supplementary neural resources to cope with higher cognitive demands (Cabeza et al., 2018). Compensation is observed through greater or more widespread brain activation or functional connectivity in older adults as compared to younger individuals (Festini et al., 2018). The increased BOLD response observed in older adults reflects a neural manifestation of a mismatch between the available neural resources and the cognitive demands of the task. This means older adults recruit additional brain

activity because their existing neural capacity is insufficient to meet task demands or because the task imposes increased cognitive load. For this heightened activation to be considered compensation, it should correlate with preserved or improved cognitive performance (Festini et al., 2018).

Compensation is actually an umbrella term, comprised of multiple mechanisms. We can distinguish between compensation by upregulation, by selection, and by reorganisation (Cabeza et al., 2018) :

- ***Compensation by upregulation*** refers to improved cognitive performance through increased activation of the task-relevant neural network (Cabeza et al., 2018). In this case, older and younger adults engage the same neural mechanisms, with the difference being the intensity of activation, which is higher in older individuals (Grady, 2012). As task difficulty rises, the BOLD response increase accordingly, until it reaches a plateau indicating the upper limit of neural resource availability. Beyond this breaking point, BOLD response declines, accompanied by a drop in cognitive performance (Grady, 2012; Persson & Nyberg, 2006; Rajah & D'Esposito, 2005). Consistently with reduced neural resources, it has been shown that older adults not only exhibit increased neural activity, but also a lower plateau and therefore an earlier decline than young adults (Persson & Nyberg, 2006; Rajah & D'Esposito, 2005; Reuter-Lorenz & Cappell, 2008).
- ***Compensation by selection*** refers to the recruitment of neural networks by older adults that, although accessible, are not typically engaged by younger individuals under equivalent task conditions (Cabeza et al., 2018). This is a trade-off, in the sense that older adults tend to choose less effective but also less demanding processes, while young adults tend to stick to more effective but more demanding processes. The cognitive processes engaged by the older adults are qualitatively different from the ones engaged by the younger adults, and are likely to involve the engagement of a different set of brain regions instead of the same region with higher intensity (as it is the case in the upregulation compensation; Cabeza et al., 2018).

- ***Compensation by reorganization*** refers to the alternative use of neural mechanisms to respond to age-related impairments which are not available to young adults (Cabeza et al., 2018). The recruitment of alternative circuits, that are not typically used for the task at hand, remains less effective than using the original pathways, but still benefit performance (Cabeza et al., 2018). This compensation by reorganization underlines the often observed reduction in brain asymmetry associated with ageing (Cabeza et al., 2002; Dolcos et al., 2002). This type of compensation reflects the use of a new process created in response to a loss, while the two other types of compensation are based on the use of an already existing process (upregulation) and/or an already existing strategy (selection) (Cabeza et al., 2018).

With the increasing interest in the phenomenon of healthy cognitive ageing and the development of more precise functional neuroimaging techniques, the field has fostered emerging compensation models trying to better link the maintenance of good cognitive performance in ageing with brain correlates and activation (Festini et al., 2018). We are now going to skim through the four most prevalent models.

2.2.3.1. CRUNCH model

The Compensation-Related Utilisation of Neural Circuits Hypothesis (CRUNCH; Reuter-Lorenz & Cappell, 2008) was initially formulated in the context of age-related behavioural and neural changes under increasing cognitive load. The CRUNCH model posits that older adults may exhibit heightened brain activation even under low cognitive load (e.g., Cappell et al., 2010; Mattay et al., 2006; Nyberg et al., 2009; Reuter-Lorenz et al., 2000; Schneider-Garces et al., 2010), which contrasts with the typically lower or more focused activations observed in younger adults under the same conditions. As cognitive load intensifies, young adults are able to progressively recruit additional neural resources to meet task demands, reflected in a corresponding increase in the BOLD signal. However, because older individuals often engage compensatory networks even under minimal cognitive

demands, they approach faster their functional resource limits. This earlier engagement results in a ceiling effect at higher task difficulty levels, marked by reduced BOLD response and a concomitant decline in task performance (Cappell et al., 2010; Mattay et al., 2006; Schneider-Garces et al., 2010). The point at which neural activity peaks, beyond which performance deteriorates and activation declines, is referred to as the "CRUNCH point" (see Figure 3, Reuter-Lorenz & Cappell, 2008).

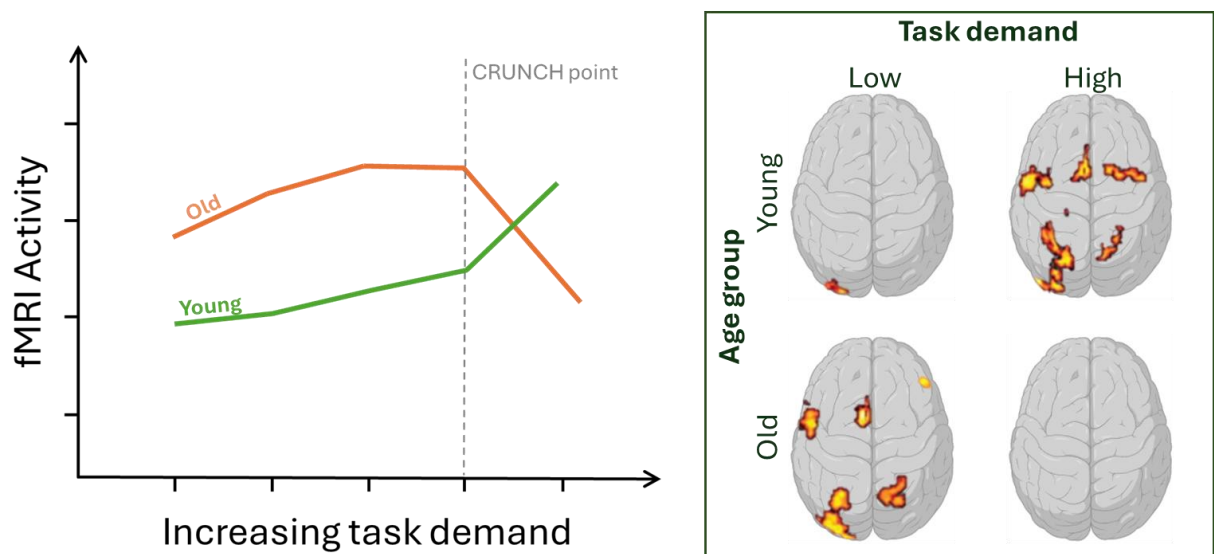


Figure 3. **Left panel:** Graphical depiction of the hypothesised relationship between fMRI activity and task demands according to the CRUNCH model. As task demands increase, older adults show a rise in fMRI activity until reaching a capacity limit, the 'CRUNCH' point, beyond which both fMRI activity and behavioural performance decline. Younger adults, in contrast, exhibit increased fMRI activity only at high task demands. Adapted from Soloveva et al. (2018) **Right panel:** Illustration of BOLD activation patterns. Under low cognitive load, older adults (bottom left) display bilateral brain activity compared to younger adults (top left). With increasing cognitive load, younger adults recruit additional brain regions (top right) to meet task demands, whereas older adults reach maximal neural resource capacity and show decreased brain activity (bottom right). Adapted from Schneider-Garces et al. (2010).

This inflection can be modulated by several factors, including sleep deprivation, physical activity, cognitive training, brain pathology, and genetic predispositions (Jordan et al., 2020; Lustig et al., 2009; Mian et al., 2025; Tsapanou et al., 2025). The prediction that neural activation scales with task difficulty, as greater cognitive demands necessitate the recruitment of additional brain resources, is central to this model. Supporting this, empirical evidence consistently showed increased neural engagement across various regions of interest as working memory load intensifies, both in younger and older adults (Heinzel et al., 2014; Kennedy et al.,

2017; Nagel et al., 2009; Saliassi et al., 2014; Toepper et al., 2014). The dorsolateral prefrontal cortex (DLPFC), particularly in the left hemisphere, plays a pivotal role in WM functioning (Barbey et al., 2013; Haque et al., 2021; Mirino et al., 2024), and its recruitment reflects the system's effort to maintain performance (Blumenfeld & Ranganath, 2006). In classic working-memory paradigms, younger adults show a largely left-lateralized increase in the BA 9/46 area of the DLPFC activation as memory load grows, with BOLD signal rising linearly up to high loads. By contrast, older adults recruit the BA 9/46 area bilaterally even at low memory loads, and their activation in these regions plateaus or even declines when moderate or higher load are reached, illustrating an earlier CRUNCH point in DLPFC (Cappell et al., 2010).

Moreover, the CRUNCH model proposes that age-related changes in neural efficiency may lead to the recruitment of additional or alternative brain regions, resulting in more bilateral rather than unilateral activation patterns. This shift is thought to reflect compensatory mechanisms rather than a simple decline in efficiency, and aligns with broader models of functional reorganisation in ageing that we will explain hereunder (Cabeza et al., 2002). For instance, in the Sternberg task, younger adults typically exhibit left-lateralised activation at low WM loads, whereas older adults tend to display bilateral DLPFC engagement under the same conditions (Mattay et al., 2006; Schneider-Garces et al., 2010).

The CRUNCH model does not presuppose specific regional involvement or systematic hemispheric shifts. Rather, it allows for the possibility that increased activation may reflect either successful compensatory recruitment or less efficient processing, whether within the overactive region itself or in other interconnected brain areas. According to this model, compensatory mechanisms are not only triggered by increasing task difficulty but also serve to counteract structural and functional brain changes associated with ageing.

2.2.3.2. PASA model

The Posterior-Anterior Shift in Aging (PASA) model builds up on the observation of a decline in neural activity within the posterior brain regions alongside increased activation in the anterior regions, particularly the frontal cortex (Davis et al., 2008). This ageing-specific model proposes that the relative anterior overactivation enables old adults to maintain, or even enhance, their cognitive performance by compensating for age-related sensory deficits in occipito-temporal areas (Figure 4; Davis et al., 2008; Festini et al., 2018). This functional reorganization is independent of task demands, such that the posterior-anterior shift remains even when performance in old individuals is similar to the one in young individuals (Davis et al., 2008; O'Connell & Basak, 2018).

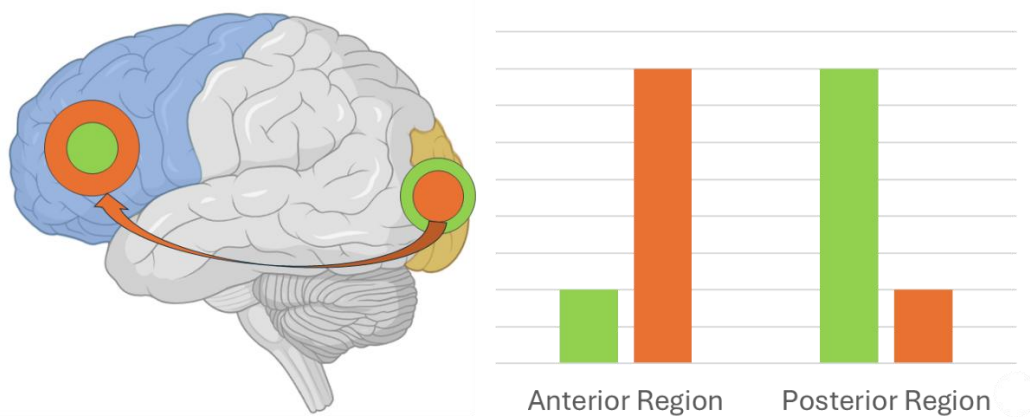


Figure 4. **Illustration of the PASA model.** Older participants (orange) show greater activity in the (pre)frontal cortex and less activity in the occipital areas, while younger adults (green) show the reverse pattern. Adapted from Grant et al. (2014).

2.2.3.3. HAROLD model

The HAROLD model (Hemispheric Asymmetry Reduction in Older Adults, Cabeza, 2002), also specific to ageing, was developed in the context of the compensation by reorganization hypothesis. This model is based on the observation that older individuals engaged in a cognitive task exhibit an hemispheric asymmetry reduction, reflected by a bilateralization of BOLD responses (Cabeza, 2002). In young adults, this BOLD response is rather unilateral. This functional reorganization allows older individuals to maintain similar performance as compared to younger ones, despite age-related brain changes (Figure 5). For

example, in the context of episodic memory, older individuals perform similarly as the younger ones, but recruit both the left and right prefrontal cortex at the encoding and retrieval stages, while young individuals are encoding information using the left prefrontal cortex, and recalling these information recruiting the right hemisphere of this region (Cabeza & Nyberg, 2000). Recruiting contralateral regions in ageing seems to compensate for a loss of efficiency in specialized circuits, and was also observed in other cognitive domains such as semantic memory, working memory, and inhibition (Cabeza, 2002). Within this context, it must be noted that older individuals showing younger-like brain activity¹ are usually performing worse during a cognitive task (Cabeza, 2002; Cabeza & Nyberg, 2000). The recruitment of bilateral resources is therefore an adaptative mechanism allowing for performance maintenance, while potentially compensating for neural decline by maximizing the available resources (Festini et al., 2018).

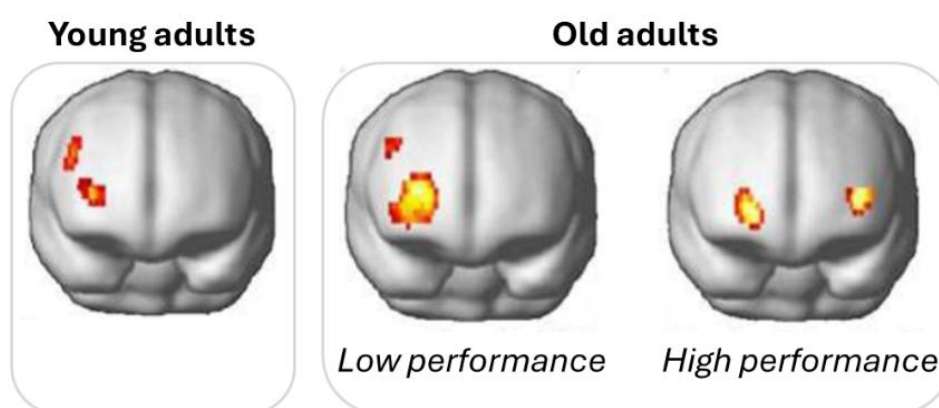


Figure 5. Illustration of the HAROLD model (Hemispheric Asymmetry Reduction in Older Adults): Older adults with performance comparable to that of younger adults exhibit bilateral recruitment of the prefrontal cortex. In contrast, older adults with lower performance show activation restricted to the right prefrontal cortex. Adapted from Cabeza et al. (2018).

2.2.3.3. STAC model

The Scaffolding Theory of Aging and Cognition (STAC) is a most recent model that represents a comprehensive framework incorporating not only cognitive processes but also brain structure. Its goal is to explain how the cerebral mechanisms adapt to support cognitive functioning. The STAC model subsumes the hypotheses

¹ Left-dominant prefrontal activation

brought forward by earlier models while extending their scope (Park & Reuter-Lorenz, 2009). The central assumption of the STAC model is that compensatory mechanisms are adaptive responses to age-related decline both in brain structure and function. Within this framework, the recruitment of additional neural resources is viewed as supportive of specialised circuits, thereby contributing to the maintenance of cognitive performance (Park & Reuter-Lorenz, 2009). It also posits, in line with the CRUNCH model, that this compensatory recruitment may occur throughout the whole brain. Finally, it also aligns with the PASA model by proposing that decreased activation in certain areas (notably visual regions) may enable increased activity in regions associated with higher-order cognitive processes, such as the frontal cortex.

The interplay between reserve, maintenance, and compensation processes, highlighting the crucial role of preserved brain structure in sustaining cognition, plays a crucial role in the STAC model. Moreover, a revised version (STAC-r, Figure 6, Reuter-Lorenz & Park, 2014) further expands this perspective by integrating the longitudinal aspect of neural and cognitive changes. It also incorporates life-course variables that can either enhance or deteriorate brain health. The model suggests that lifestyle modifications have the potential to improve or even restore brain structure and function.

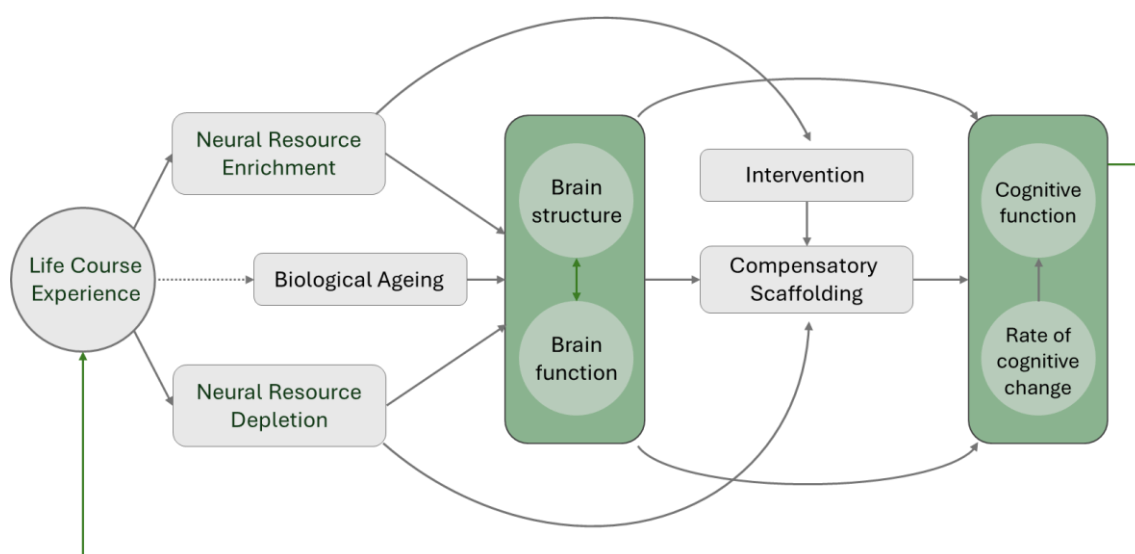


Figure 6. **Illustration of the STAC-R model (Scaffolding Theory of Aging and Cognition - Revised).** The model integrates life course factors that enrich or deplete neural resources, influencing brain structure,

function, and compensatory scaffolding, defined as the brain's adaptive response to cognitive challenge. These processes shape cognitive performance and its trajectory over time. STAC-R also acknowledges feedback loops, where cognitive ability influences life experiences, and highlights the impact of these variables across developmental stages. New additions include the explicit role of biological ageing and bidirectional links between cognition and experience. Adapted from Reuter-Lorenz & Park (2014).

2.2.4. Neural dedifferentiation

The hemispheric asymmetry reduction observed in older adults cannot be explained by models of compensation alone (McDonough et al., 2013; Roe et al., 2020), for they might also be the sign of less specific brain activation patterns and less distinct neural response. This is a phenomenon called dedifferentiation (Knights et al., 2021; Morcom & Henson, 2018), characterised by a reduction in neuronal selectivity and a decline in the functional specialisation of brain networks, that can be interpreted as a deterioration in the efficiency of cognitive processing. The key component to distinguish neural compensation from neural dedifferentiation is the nature of the task, its behavioural responses, as well as the BOLD response dynamics in task-related brain regions : compensation links increased neural activation and improved (or maintained) cognitive performance at the task at hand (Cabeza et al., 2018), while dedifferentiation-induced increase in neural activity does not lead to increased performance (Knights et al., 2021; Morcom & Henson, 2018). It is merely a reduced difference between the neuron's task-specific activation and their non-specific activation (Koen & Rugg, 2019). This may be accounted for either by a reduced activity in response to specific stimuli, an increased activity in response to non-specific stimuli, or a combination of both mechanisms (Koen & Rugg, 2019). It suggests a gradual decline in cognitive specialisation, characterised by less specific and more widespread brain activation during the performance of cognitive tasks (Park et al., 2004; Payer et al., 2006). Animal studies have shown that neural selectivity decreases with age (Ding et al., 2017; Hua et al., 2006; Schmolesky et al., 2000). In humans, it has also been shown that dedifferentiation is an age-related alteration, associated with a decline in cognitive performance (Park et al., 2010).

In this context, cognitive ageing is thought to go along with less efficient reorganisation of cerebral resources, which may impair the precision of neural processing and, in consequence, be associated with cognitive decline (Koen & Rugg, 2019). However, it should be nuanced that the observed overactivation and wider recruitment in brain activity may result from both dedifferentiation and compensatory mechanisms taking place at the same time (Carp et al., 2010). Rather than opposing dedifferentiation and compensation processes, these should be conceptualized within an adaptive range of brain responses. Dedifferentiation provides a neural substrate from which compensatory strategies may emerge, and compensation can therefore lead to the preserved, or even improved, cognitive performance (Festini et al., 2018; Knights et al., 2021; Stern et al., 2019). That said, this functional reorganization does not always yield behavioural benefits: compensation can also be ineffective, resulting in a decline in cognitive performance (O'Connell & Basak, 2018).

3. Factors influencing inter-individual variability in cognitive and cerebral ageing

The inter-individual variability in both cognitive and brain ageing represents a challenge in understanding the mixed trajectories observed across the ageing population (Mella et al., 2018; Patel et al., 2022; Salthouse, 2017). This heterogeneity arises from the interaction of biological, cognitive, and environmental factors. Cognitive reserve, which is supported by factors such as education, intellectual engagement, social interactions and physical activity, plays a central role by allowing some individuals to efficiently compensate for age-related neural changes through more intense or alternative recruitment of brain regions (Perani et al., 2017; Stern, 2009). In parallel, cerebral reserve, more structurally oriented, is underpinned by the integrity of neural tissues, particularly grey and white matter, the degradation of which is directly associated with reduced cognitive stability (X. Xu et al., 2023). Another critical determinant of this inter-individual variability is functional compensation, which mediates executive and

attentional performance, and shows significant differences between individuals of the same age (Geerligs et al., 2015; Varangis et al., 2019). High-performing older adults usually show bilateral (Cabeza et al., 2002) and more widespread (Park & Reuter-Lorenz, 2009) brain activation, as well as a posterior-anterior shift in activation patterns (Davis et al., 2008). In addition, enhanced activation in task-related regions, such as the (pre)frontal cortex, may provide as a compensatory mechanism for maintaining cognitive performance (Cabeza et al., 2018; Eyler et al., 2011).

From a biological point of view, chronic stress, reflected by elevated cortisol levels, has been shown to accelerate cortical ageing, particularly in the prefrontal cortex, with genetic vulnerability further modulating these effects (Lupien et al., 2009). Sleep (and circadian rhythms) are also recognised as important modulators of brain ageing variability. Inter-individual differences in sleep quality, duration, regularity, as well as chronotype, significantly influence cognitive resilience in ageing (J. C. Lo, Ong, et al., 2016; Phillips et al., 2017). Individuals with a more proper circadian alignment or preserved sleep architecture tend to exhibit greater resistance to the deleterious age-related effects on attention, memory, and executive function (Carlson et al., 2023; Djonlagic et al., 2021; Parker et al., 2022). Hence, inter-individual differences in chronobiology and sleep regulating aspects now represent essential dimensions in understanding inter-individual differences in cognitive ageing.

Chapter 2. Sleep-wake cycle

1. Sleep-wake cycle regulation

Sleep is a physiological process necessary for maintaining health and cognitive function through life (Cirelli & Tononi, 2008). In the past, sleep was seen as a passive state, characterised by reduced brain activity, and rest being its only scope. In the early 20th century, however, discoveries using electroencephalography (EEG) showed that sleep is actually an active, dynamic state with multiple distinct stages, including rapid eye movement (REM) and non-REM sleep (Rechtschaffen, 1968). These stages are regulated by two interacting systems: the circadian timing system, which controls the near 24-hour rhythmicity of sleep and wakefulness, and the homeostatic process, which tracks sleep need based on prior wakefulness (Borbély, 1982; Daan et al., 1984). Together, these systems maintain the temporal organisation of sleep and wakefulness, guaranteeing adequate restorative function and optimal cognitive performance (Cajochen et al., 2005, 2006).

In the context of healthy ageing, both the architecture and the regulation of the sleep-wake cycle undergo changes, including reduced slow-wave sleep (SWS), fragmentation, and phase advance, which may contribute to cognitive decline (Mander et al., 2017; Scullin & Bliwise, 2015). Moreover, disruptions in circadian rhythms and in rest-activity cycles have been increasingly associated with neurodegenerative diseases and impaired cognition (Musiek & Holtzman, 2016). This chapter will first review the characteristics of human sleep, then detail the mechanisms of circadian and homeostatic regulation as well as experimental protocols used to assess rhythmicity, putting the emphasis on age-related changes. Finally, it will examine current evidence linking sleep-wake cycle evolutions with cognitive outcomes in older adults.

1.1. Sleep

As introduced, it is the growing interest of neuroscience in the sleep phenomenon, and more specifically the introduction EEG, that transformed our understanding of

sleep over the past century. Once thought of as a passive and inert state with only a restorative purpose, sleep is now recognised as an active and dynamic process that supports a wide range of neurobehavioural and physiological functions, essential for both physical and cognitive health.

EEG captures the electrical activity of the brain, which results from electrochemical signals between neurons, especially the hyperpolarization and depolarization of cortical pyramidal cells located in the deeper layers of the cortex (Cohen, 2017; Kirschstein & Köhling, 2009). In sleep research, a standard EEG configuration involves placing electrodes on the scalp following the international 10-20 system, defined based on four anatomical reference points: the nasion (the intersection between the frontal and nasal bones), the inion (the protruding part of the occipital bone), and the left and right mastoids (Carden, 2009). The necessity for a standardized method to classify sleep stages based on EEG recordings was soon evident, and Rechtschaffen and Kales (1968) introduced one of the first formal scoring systems, which was subsequently refined and adopted by the American Academy of Sleep Medicine (AASM) (Berry et al., 2015; Iber, 2007). To provide a more comprehensive assessment of sleep architecture and related physiological functions, modern sleep studies typically employ polysomnography (PSG), rather than EEG recording alone. PSG combines EEG with additional measures such as electrooculography (EOG), electromyography (EMG), respiration, and often heart rate. This multimodal approach is considered the gold standard for sleep assessment in both clinical and research contexts.

1.1.1. Wakefulness

In humans, wakefulness is recognisable by its low-amplitude, high-frequency EEG activity that varies according to the state of alertness (Figure 7). During active wakefulness with eyes open, the EEG is dominated by mixed beta (14-30 Hz) and alpha (8-14 Hz) frequencies. Eye closure typically induces a prominent alpha rhythm, especially in the occipital cortex, accounting for a relaxed but awake state (Chan & Nicholas, 2018; Iber, 2007). This alpha activity is highly sensitive to arousal

levels, with attention, sensory input, and increased alertness suppressing or “blocking” alpha rhythms (Stampi et al., 1995). PSG recordings further reveal that wakefulness is characterised by low-voltage fast EEG activity, spontaneous eye blinks, random eye movements, and relatively high and variable muscle tone as measured by EMG (Kumar et al., 2013).



Figure 7. EEG recording during wakefulness in human. Adapted from Brown et al. (2012).

As individuals transition from wakefulness to sleep, cortical and subcortical EEG patterns evolve, with faster frequencies gradually replaced by slower oscillations, coinciding with reductions in blink rate and the emergence of slow eye movements (Chan & Nicholas, 2018).

1.1.2. Non-rapid eye movement sleep

Non-Rapid Eye Movement (NREM) sleep is associated with a slowing of respiratory and heart rate, lower internal body temperature, as well as a reduced responsiveness to external stimuli (Parmeggiani, 2003; Saper et al., 2005). NREM sleep is further divided into sub-stages encompassing increasing sleep depth, based on EEG features (Figure 8, Iber, 2007).

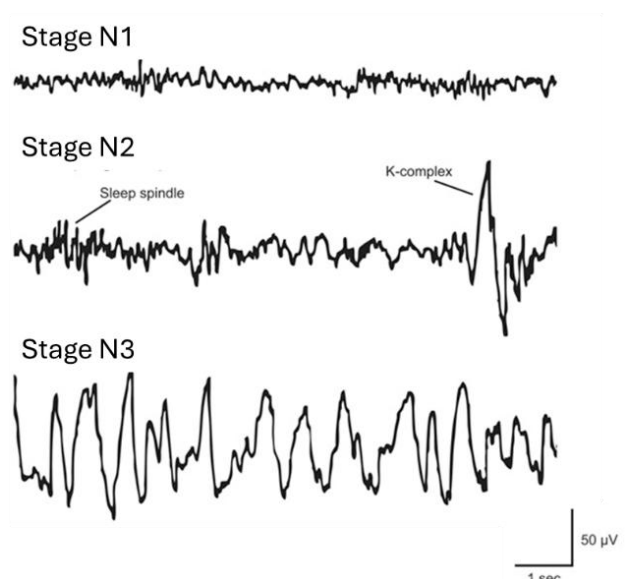


Figure 8. EEG recordings during slow-wave sleep in human, with stages N1, N2 and N3 depicted separately. Adapted from Brown et al. (2012).

Stage N1 usually marks the transition from wakefulness to sleep, or between sleep stages, and is the lightest sleep stage. It is usually the first to occur during sleep. It is characterised by low-amplitude EEG features with mixed-frequency activity, a progressive decline in alpha rhythms and the appearance of predominantly theta (4-7 Hz) waves (Iber, 2007). During this stage, EOG records slow eye movements, while muscle activity remains present but reduced compared to wakefulness (Iber, 2007).

Stage N2, the second stage of NREM sleep, accounts for almost half of total sleep duration in healthy adults. It is recognisable thanks to two specific EEG features: sleep spindles and K-complexes. *Sleep spindles* are of brief bursts of oscillatory activity (11-16 Hz), which originate from the interaction between thalamic and relay neurons, which then propagate to the cortex (Timofeev et al., 2012). *K-complexes* are large, well-defined biphasic waves featuring a sharp negative deflection followed by a positive component, lasting at least 0.5 seconds. They stem from widespread cortical areas, more specifically in the middle and upper cortical layers, and engage thalamic networks to coordinate their propagation and synchronisation across the cortex (S. S. Cash et al., 2009; Colrain, 2005; Mak-McCully et al., 2014). During N2, there is an absence of eye movements, while muscle tone remains variable but generally sustained (Iber, 2007).

Stage N3 is commonly referred to as slow-wave sleep (SWS). It is characterised by high-amplitude slow waves within the delta frequency range (0.5-4 Hz), which constitute at least 20% of this sleep stage (de Andrés et al., 2011; Kurth et al., 2010). These slow waves, generated by synchronized firing of thalamocortical neurons, mostly come from the frontal cortex and spread towards posterior areas (Timofeev et al., 2012). Slow-wave activity (SWA) indicates the depth and restorative quality of N3 sleep (Greene & Frank, 2010). Eye movements are absent during N3, while muscle tone is variable but generally lower than in N2 (Figure 8)(Iber, 2007).

1.1.3. Rapid-Eye-Movement Sleep (REM)

REM sleep takes its name from the presence of rapid eye movements that characterize this sleep stage. It differs significantly from NREM sleep by displaying fast, low-amplitude, and desynchronized EEG activity, similar to the patterns observed during wakefulness (Figure 9)(Iber, 2007). EEG activity during REM is dominated by theta and alpha frequencies, along with distinctive “sawtooth waves”, being sharp oscillations (2-6 Hz) mainly in frontal-central regions (Bernardi et al., 2019; Fraigne et al., 2023).



Figure 9. EEG recording during REM sleep in human. Adapted from Brown et al. (2012).

REM sleep is also defined by pronounced muscle atonia, interrupted only by brief twitches in facial and limb muscles, creating a paradoxical state combining wake-like brain activity with muscle paralysis. REM sleep is closely linked to vivid dreaming, which is why it is also named “paradoxical sleep” (Fraigne et al., 2023). From a thermoregulatory point of view, the body's ability to regulate temperature is significantly impaired during REM, behaving as a poikilothermic state, where body temperature fluctuates with the environment (Cerri et al., 2017; Hashizume, 1997; Jennings et al., 1993).

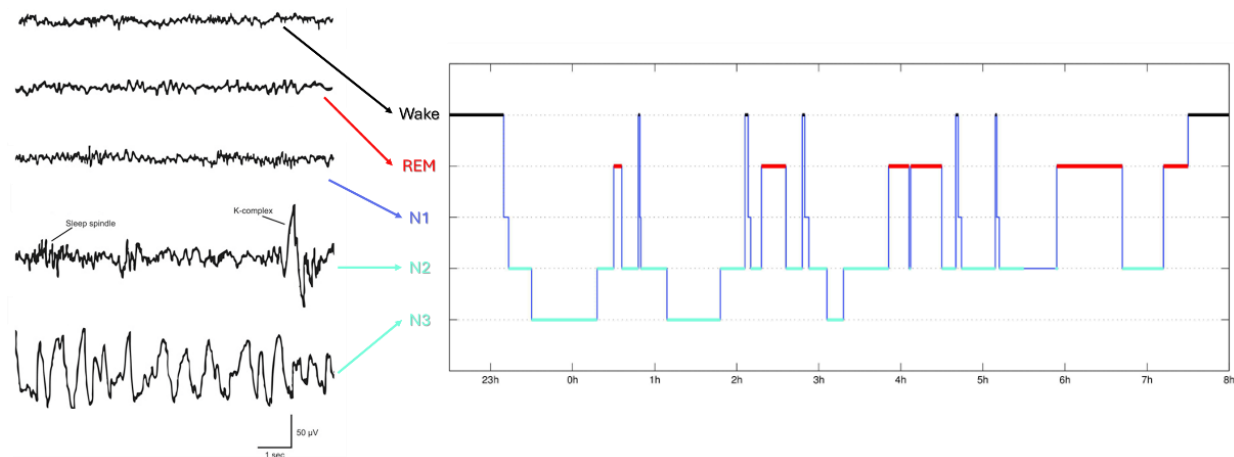


Figure 10. Summary of the main EEG patterns observed in each sleep stage (left, adapted from Brown et al. (2012)) and their typical alternation during a night of sleep (hypnogram).

An adult night's sleep is composed of repeated cycles of sleep stages (N1-N2-N3-REM), each lasting about 90 minutes, with 4 to 5 cycles per night. This cyclical pattern, often illustrated by a hypnogram (Figure 10, right), is not a simple repetition of identical cycles. Sleep depth decreases across the night, shown by reduced N3 duration and fewer SWA, reflecting the dissipation of sleep pressure (Borbély, 1982; Vyazovskiy & Faraguna, 2015). On the contrary, REM and N2 stages lengthen and become denser towards morning, highlighting the influence of circadian rhythms (Czeisler et al., 1980; Kales et al., 1967).

1.3.4. Age-related changes in sleep architecture

Age-related changes in NREM sleep are diverse and already start at the N1 stage, depicting reduced sleep consolidation and increased fragmentation, characterized by more frequent awakenings (Cajochen, Münch, Knoblauch, Blatter, & Wirz-Justice, 2006; Chinoy et al., 2014; Park et al., 2021). Older adults also experience more superficial sleep and tend to go to bed earlier than younger counterparts (Münch, 2014), show overall reductions in total sleep time and sleep efficiency, as well as longer sleep onset latency and greater wake time after sleep onset (Ohayon et al., 2004). In N2, older individuals exhibit reduced sleep spindle frequency and decreased SWA (Cajochen et al., 2006; Chinoy et al., 2014), along with lower global EEG connectivity compared to younger people (Bouchard et al., 2021). The rise

time of SWA is blunted in older adults during N1 and N2, suggesting a diminished capacity to respond to accumulated sleep pressure (Chinoy et al., 2014; Park et al., 2021). However, when slow-wave amplitude detection criteria are adapted to account for age-related EEG amplitude reductions, these age-related differences in SWA rise time and SW density are markedly attenuated (Carrier et al., 1996, 2011; Rosinvil et al., 2021). Despite lower overall delta power in NREM, older adults show increased short-term stability in delta, theta, sigma, and alpha power (Park et al., 2021), indicating that while global sleep architecture seems to deteriorate, certain spectral features remain more temporally consistent. N3 sleep declines markedly with age: SWA and sleep spindles are reduced (Cajochen et al., 2006; Dzierzewski et al., 2021). Paradoxically, EEG connectivity in stage N3 can be higher in older individuals than in younger ones, especially during the first sleep cycle (Bouchard et al., 2021), suggesting compensatory network adjustments. REM sleep percentage also linearly declines with age, , albeit proportionally less than slow-wave sleep during the first decades of ageing (Floyd et al., 2007; Ohayon et al., 2004), and reduced REM in later life correlates with elevated evening cortisol levels (Van Cauter et al., 2000).

Although sleep goes along with age-related changes across the whole human lifespan, findings are actually mixed in individuals over 60 years old. Some studies suggest that age-related sleep changes tend to stabilize from that point on (Li, Vitiello, et al., 2018; Ohayon et al., 2004), whereas others report a continued decline in sleep parameters such as SWS, and increased fragmentation (Taillard et al., 2021). Regardless, total sleep time, sleep efficiency, and REM percentage tend to decrease with age, while sleep latency and wake after sleep onset increase (Ohayon et al., 2004). Moreover, biological sex mediates these changes, such that increased sleep fragmentation and insomnia symptoms tend to be more frequent in women, particularly around and after menopause (J. Li, Vitiello, et al., 2018; Mander et al., 2017). For instance, women often experience longer sleep onset latency and more frequent nocturnal awakenings after menopause, compared to men from the same

age-group (Mander et al., 2017). In contrast, older men may exhibit greater reduction in SWA than women of the same age (Taillard et al., 2021).

Taken together, these sleep changes in ageing may reflect both weakened circadian regulation and changes in the homeostatic process. On the circadian side, this is underlined by reduced nocturnal melatonin secretion, as well as reduced circadian modulation of REM sleep propensity and spindle frequency (Cajochen et al., 2006; Münch, 2014). In parallel, homeostatic processes, such as the rise time and amplitude of SWA, are attenuated with advancing age (Chinoy et al., 2014; Park et al., 2021). As a result, older adults' sleep-wake cycles become more vulnerable to circadian disruptions and environmental factors such as insufficient daytime light exposure (Alessi & Martin, 2018; Münch, 2014).

1.2. Circadian Rhythms & Homeostatic regulation

The human sleep-wake cycle regulation is the result of the dynamic interplay between two core biological processes: circadian rhythmicity and homeostatic sleep pressure. Together, they form the foundation of the two-process model of sleep regulation (Borbély, 1982; Borbély et al., 2016; Daan et al., 1984), which has guided sleep research for decades (Figure 11).

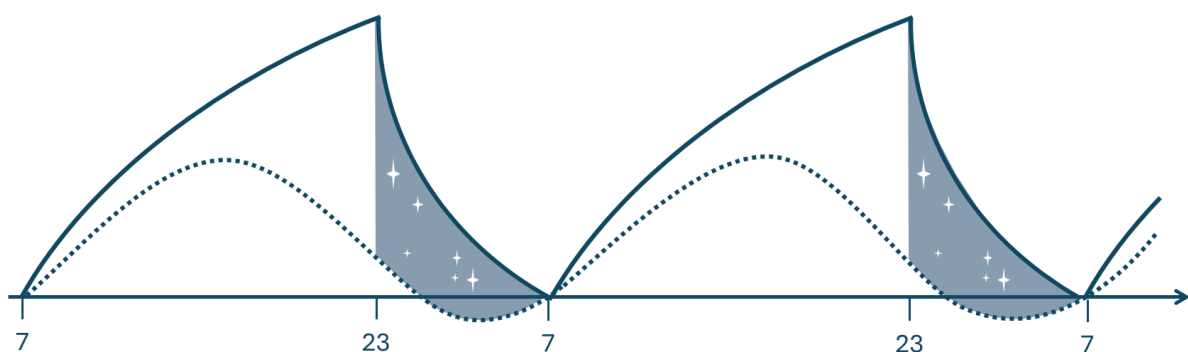


Figure 11. Illustration of the two-process model of sleep-wake regulation, adapted from Borbély, (1982) and Daan et al. (1984). The homeostatic process (solid blue line), or Process S, represents sleep pressure, increasing with time spent awake and decreasing with time spent sleeping. Process C, being the circadian rhythm component is depicted in dashed blue line. When positive and higher, this reflects the circadian wake-promotion signal, whereas being low or negative reflects the circadian sleep-promoting signal. Sleep is consolidated when sleep pressure is high and circadian wake-promotion is low (shaded blue with stars).

The homeostatic process (process S) reflects the accumulation of sleep pressure during wakefulness and its dissipation during sleep. This pressure is indexed by SWA during NREM sleep, particularly during the earliest parts of nighttime sleep (Dement & Kleitman, 1957; Williams et al., 1964). In fact, the duration of prior wakefulness predicts the amount of SWA during subsequent NREM sleep (Dijk et al., 1990). In turn, SWA during sleep correlates negatively with theta frequency power during wakefulness (Finelli et al., 2000), with sleep deprivation evidence showing an increase in theta activity during wakefulness (Cajochen et al., 1995). These markers serve as the primary indices of sleep-homeostatic buildup.

In parallel, circadian rhythms (process C) are endogenous, near 24-hour oscillations that persist in constant conditions, relatively independent of prior sleep-wake cycle history (Dijk et al., 1999). Circadian rhythms are synchronized by external cues (*zeitgebers*), predominantly the light-dark cycle. Other known zeitgebers are physical activity, sleep, social interactions and meals, and all these cues contribute in different degrees to the synchronization of the circadian rhythms, a mechanism known as entrainment (Czeisler & Buxton, 2017). However, slow-wave characteristics (incidence, amplitude, slope) are also modulated by circadian phase (Lazar et al., 2015), and it is well established that sleep-homeostatic and circadian processes are fundamentally intertwined and cannot be completely disentangled (Cajochen & Schmidt, 2025; Franken & Dijk, 2024).

In humans, and the mammal specify more generally, the suprachiasmatic nucleus (SCN) of the anterior hypothalamus is the principal circadian pacemaker (Hastings et al., 2018; Welsh et al., 2010). It is a small group of neurons which sustain endogenous rhythmic activity and coordinates the timing of physiological events across the whole body (Stoynev et al., 2022). The SCN modulates sleep-wake regulation not only through circadian timing, but also thanks to interactions with specific arousal- and sleep-related neural circuits. It projects indirectly to several brain regions implicated in these functions, including the dorsomedial hypothalamus (DMH), the ventrolateral preoptic nucleus (VLPO), and the locus coeruleus (LC) (Cajochen & Schmidt, 2025).

Wakefulness and its continuity are underpinned by the ascending arousal pathways. They come from the brainstem and divide into two major branches: a dorsal and a ventral pathway (Figure 12, left)(Saper et al., 2001, 2005). The dorsal pathway involves cholinergic neurons in the pedunculopontine and laterodorsal tegmental nuclei (PPT-LDT), which are active during both wakefulness and REM sleep, and promote cortical activation through their connections with thalamocortical neurons (Saper et al., 2001, 2005). They also project to other key areas such as the thalamus, lateral hypothalamus, basal forebrain, and prefrontal cortex (Saper et al., 2010). The ventral branch, on the other hand, includes noradrenergic, serotonergic, dopaminergic, and glutamatergic neurons, notably in the LC, raphe nuclei, and parabrachial region (Saper et al., 2010; Saper & Fuller, 2017). Additional contributors include glutamatergic neurons in the parabrachial nucleus and the pre-coeruleus area, which project to the lateral hypothalamus, basal forebrain, and the prefrontal cortex (Saper & Fuller, 2017). These neurons show high activity during wakefulness, reduced activity in NREM sleep, and near silence during REM. The lateral hypothalamus integrates arousal signals via orexin-producing neurons (Sakurai, 2007; Saper et al., 2010), which are crucial for maintaining arousal and preventing unstable transitions between sleep and wake states.

In contrast, the initiation and maintenance of sleep are mediated by GABAergic and galaninergic neurons located in the VLPO (Sherin et al., 1996, 1998). These sleep-promoting neurons inhibit arousal centres, thereby facilitating the onset and continuity of sleep. The SCN also sends circadian signals to the VLPO indirectly by the DMH (Gooley et al., 2006; Saper et al., 2005), aligning sleep timing with the circadian rhythm. Differences in neuronal activity patterns within these systems suggest the existence of distinct networks for NREM and REM sleep regulation (Saper et al., 2005; Scammell et al., 2017). Furthermore, the VLPO receives reciprocal inhibitory inputs from arousal-promoting nuclei, and this mutual inhibition forms the basis of the so-called “flip-flop switch” (Saper et al., 2001): activation of one system actively suppresses the other, promoting rapid transitions

between sleep and wake states. The orexin system acts as a stabiliser, reinforcing arousal and preventing inappropriate or fragmented state transitions (Sakurai, 2007).

Importantly, the SCN undergoes structural and functional changes with age, including reduced amplitude and synchrony of circadian outputs (Hood & Amir, 2017). Age-related neuronal loss or dysfunction in the VLPO and orexin system may also contribute to sleep fragmentation and reduced sleep consolidation observed in older adults (Lew et al., 2021; A. S. P. Lim et al., 2014; Scammell et al., 2017).

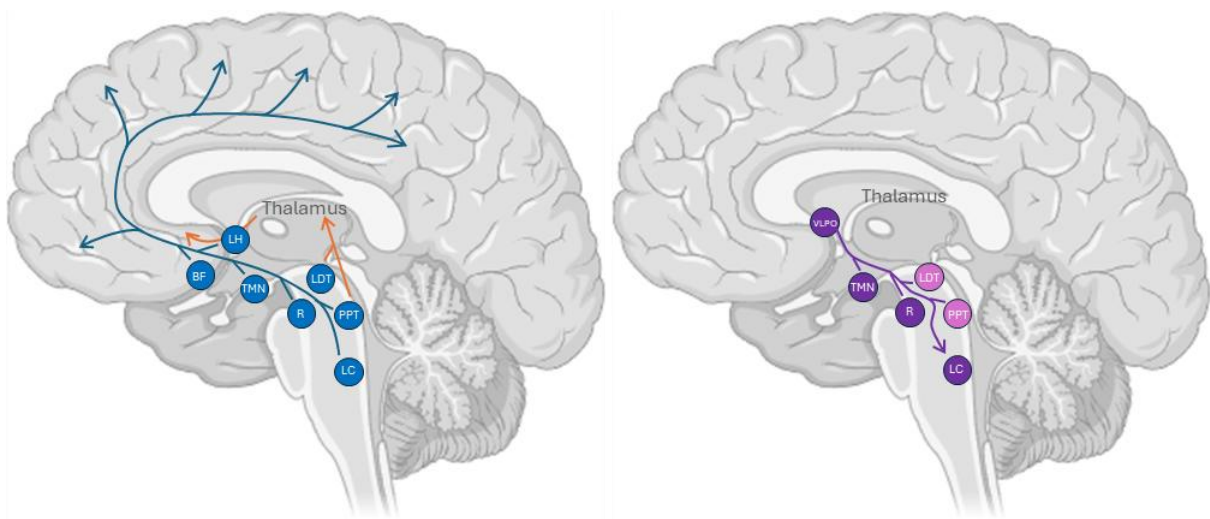


Figure 12. Illustration of the main neural circuits promoting wakefulness (left) and sleep (right). On the left, one of the primary wake-promoting pathways (in blue) originates from monoaminergic cell groups, including the locus coeruleus (LC), releasing noradrenaline, the dorsal and median raphe nuclei (R) which produce serotonin, and the tuberomammillary nucleus (TMN) which releases histamine. This arousal system receives additional input from peptidergic neurons in the lateral hypothalamus (LH), which produce orexin, and from GABAergic neurons in the basal forebrain (BF). The orange lines represent inputs to the thalamus from cholinergic cell groups located in the upper pons and the pedunculopontine and laterodorsal tegmental nuclei (PPT-LDT). On the right, the sleep-promoting pathways are primarily composed of GABAergic neurons in the ventrolateral preoptic area (VLPO) of the hypothalamus, whose role is to inhibit the arousal systems. Adapted from Saper & Fuller (2017).

While the SCN is the primary circadian pacemaker, secondary circadian clocks are also distributed in the brain and in peripheral organs of the human body (Buijs et al., 2016). They show tissue-specific rhythmicity and contribute to the local regulation of some processes such as metabolism, endocrine function, and sleep-wake regulation (Buijs et al., 2016; Lamia et al., 2008; C. J. Morris et al., 2012). They also modulate behaviour and cognition (Cajochen & Schmidt, 2025). The SCN sends

timing signals using neuronal and hormonal pathways, to allow the synchronisation of these multiple and widespread clocks. At the cellular level, circadian rhythmicity is driven by a feedback loop involving core clock genes, which coordinate cellular and systemic physiological rhythms (Cajochen & Schmidt, 2025). Between 43% and 82% of protein-coding genes display rhythmic expression in at least one tissue (Meyer et al., 2022), depending on the organ.

The regulation of sleep propensity and wakefulness stability depends on the interaction between the circadian wake-promoting signal and homeostatic sleep pressure (Dijk & Czeisler, 1994). As wakefulness extends during the day, sleep pressure (Process S) progressively increases and reaches its peak around habitual bedtime. In parallel, the circadian system (Process C) creates a wake-promoting signal that goes against this rising sleep pressure, preserving alertness and cognitive performance. This circadian arousal signal reaches its peak approximately two hours before habitual bedtime, during a time window called *wake maintenance zone* (WMZ) (Shekleton et al., 2013; Strogatz et al., 1987). At this time of day, despite high levels of homeostatic sleep pressure, the circadian drive for wakefulness supports sustained alertness and delays sleep onset (Dijk & Czeisler, 1994; Shekleton et al., 2013). This phenomenon perfectly illustrates the counterbalancing effect of the circadian system against homeostatic sleep drive, helping to maintain wakefulness and cognitive performance during the late evening hours. Following its peak, the circadian wake signal rapidly declines, corresponding with the onset of melatonin secretion and a drop in core body temperature, both factors known to promote the transition to sleep (Refinetti, 2020; Waterhouse et al., 2012). During sleep, homeostatic pressure is progressively dissipated with time spent asleep. In the later part of the night, even though sleep pressure is low, sleep can be maintained thanks to the circadian system entering the *sleep-promoting zone*, a phase of reduced arousal (Waterhouse et al., 2012). This period is associated with the lowest core body temperature and the peak in cortisol secretion (Refinetti, 2020). The coordinated action of both processes

ensures a consolidated nocturnal sleep episode and sustained wakefulness during the day when entrained.

It is important to underline that the interaction between Processes S and C is not simply additive, but is rather dynamic and bidirectional (Borbély et al., 2016). Findings from protocols that enable the decoupling of circadian and homeostatic rhythms (detailed in Chapter 2, 1.3) revealed that the level of sleep pressure influences the amplitude of circadian modulation: it tends to be diminished under high homeostatic load and enhanced when sleep pressure is low (Deboer, 2018; Dijk & Czeisler, 1995). Additionally, the homeostatic marker of SWA is modulated by circadian phase (Lazar et al., 2015). Similarly, prolonged wakefulness also alters SWA patterns through circadian mechanisms (Cajochen, 2024; Hubbard et al., 2020). This further highlights the mutual regulation between these two core processes. Misalignment, such as in shift work or jet lag, disrupts this interaction, impairing performance and increasing health risks (Boivin et al., 2022; Walker et al., 2020).

Finally, the inter-individual variability in the expression of the circadian rhythm is well established (Adan et al., 2012). These inter-individual differences often lead to categorising individuals as being either “morning” or “evening types” (Roenneberg et al., 2007). These manifests in everyday behaviours, including habitual bedtimes and the preferred period of the day to do complex cognitive tasks. This morning or evening preference is known as *chronotype* (Müller & Haag, 2018). Its origins are multifactorial, from genetic, to occupational and environmental factors (Schmidt, Peigneux, Cajochen, et al., 2012; Schmidt & Collette, 2016). Furthermore, circadian and homeostatic sleep-wake processes are modulated by the chronotype. Individuals with a morning preference tend to accumulate sleep pressure more rapidly during the day, while evening types exhibit a slower build-up of sleep pressure (Gaggioni et al., 2014; Schmidt, Peigneux, Cajochen, et al., 2012; Schmidt & Collette, 2016). Physiologically, circadian markers such as core body temperature or melatonin secretion are also dependant of chronotype: morning types display these markers earlier (phase advance),

whereas evening types show a later shift (phase delay) (Adan et al., 2012; Lack et al., 2009; Papatsimpa et al., 2021). Research indicates that chronotype changes with age, with older adults generally shifting towards earlier sleep-wake patterns (Druiven et al., 2021; Münch, 2014), and therefore a “morning” profile. This age-related shift is also associated with more superficial and less consolidated sleep in healthy older adults (Münch, 2014; Taillard et al., 2021). On another level, the shift towards morningness is associated with higher levels of positive affect and subjective health in older adults (Biss & Hasher, 2012). Evening-type preferences in older individuals have however been linked to increased mortality risk and poorer health outcomes, including higher rates of depression (Didikoglu et al., 2019).

1.2.1. Age-related modifications of circadian and homeostatic sleep-wake regulation

Apart from a shift in chronotype, age-related modifications in sleep-wake regulation also include reduced homeostatic buildup and weakened circadian in older adults, leading to changes in sleep timing, maintenance, as well as changes in macro- and microstructure characteristics (Taillard et al., 2021).

When it comes to age-related changes in homeostatic sleep regulation, they are complex and not fully understood yet. While many age-related sleep changes have been credited to weakened circadian regulation (Cajochen et al., 2006), empirical evidence also points to modifications in homeostatic pressure, such as reduced need for sleep, with ageing. For instance, an age-related decrease has been reported for both daytime sleep propensity and nocturnal slow-wave sleep (Dijk et al., 2010), alongside a reduced maximal capacity for sleep (Klerman & Dijk, 2008). This aligns with previous reports which highlighted the importance of both circadian and homeostatic changes in shaping age-related sleep architecture (Dijk et al., 1999). Computational modelling further suggests that a combination of reduced circadian amplitude and reduced homeostatic build-up of sleep pressure could underlie the observed changes across the lifespan (Skeldon et al., 2016). A reduced

homeostatic drive with age would potentially explain the lower vulnerability to sleep deprivation in older adults (Taillard et al., 2021). Despite these modifications, some studies report that older adults exhibit unaffected daytime sleepiness, and that they display smaller cognitive impairments during acute sleep deprivation compared to younger adults, suggesting lower vulnerability to extended wakefulness (Taillard et al., 2021). However, findings using the Multiple Sleep Latency Test indicate that ageing is associated with a reduced daytime sleep propensity (Dijk et al., 2010), which may actually reflect a lower physiological capacity or drive for sleep rather than genuine resilience to prolonged wakefulness. Independently, such changes may result from a combination of reduced homeostatic sleep pressure, attenuated circadian influence, and structural or functional alterations in subcortical regions regulating sleep-wake cycles (Dijk et al., 2010; Taillard et al., 2021).

The age-related dampening of the circadian alerting signal and weakened homeostatic buildup of sleep pressure, as well as their functional consequences on nocturnal sleep (i.e., reduced slow-wave duration and amplitude, diminished sleep quality, higher fragmentation), cause a blunted day-night fluctuation in alertness, which mainly manifests as an increased subjective daytime sleepiness and a higher propensity for unplanned naps (Van Someren, 2000). Moreover, the reduced restorative quality of sleep contributes to elevated daytime fatigue in older populations (Hawker et al., 2010). Functionally, these combined circadian and homeostatic alterations impair vigilance and cognitive performance : older adults demonstrate increased reaction time variability during sustained attention tasks, accounting for a greater predisposition to fatigue-induced lapses (Carvalho-Bos et al., 2007). On one hand, the regulatory changes observed with ageing also exacerbate mental fatigue: the amplitude reduction of the circadian wake-promoting signal leads to persistent subjective effort to sustain cognitive engagement (Mairesse et al., 2014). On the other hand, weakened homeostatic process manifests as a steeper rise in frontal theta power during cognitive tasks, signalling faster accumulation of fatigue (Neu et al., 2015). Similarly, experimental

fragmentation mimicking age-related SWA loss induces increased subjective fatigue (Benkirane et al., 2022). There is a non-additive interplay between circadian and homeostatic influences, in which declines in either process disproportionately amplify perceived cognitive effort in older adults (Mairesse et al., 2010).

All in all, it's the sleep-wake cycle circadian regulation that appear to be the more affected. In fact, ageing goes along with changes in circadian processes at both behavioural and molecular levels (Popa-Wagner et al., 2017). These alterations can in turn contribute to sleep disturbances, dementia, and depression (Van Someren, 2000). Age-related changes in circadian rhythms of healthy older adults include a phase advance of the overall circadian rhythm (Dijk et al., 2000; Monk, 2005), which is also evident in core body temperature, melatonin, and cortisol secretion patterns (Duffy et al., 2015). Phase angle is defined as the interval between an internal circadian marker such as dim-light melatonin onset (DLMO_n) or core-body temperature minimum, and habitual bedtime. It also shifts with age: older adults go to bed earlier by clock time, but also earlier according to their endogenous circadian cycle (Duffy & Dijk, 2002). Moreover, older adults show increased vulnerability to circadian desynchronization and insufficient daytime light exposure (Münch, 2014). While some studies suggest that ageing is accompanied by reductions in the amplitude of key circadian markers, such as the nocturnal melatonin secretion rhythm (Carrier et al., 1996) and the core-body temperature cycle (Dijk & Duffy, 1999), the evidence is mixed (Monk, 2005). This possible amplitude reduction would however lead to attenuated signals during the critical interaction window that is the WMZ (Cajochen et al., 2006; Münch et al., 2005) and the sleep-promoting zone (Dijk et al., 1999, 2000). These age-related alterations in both homeostatic and circadian components prompt the need for precise measurement techniques to capture sleep-wake and circadian regulation processes underlying sleep phenotypes in older adults.

1.3. Assessment of the sleep-wake cycle and circadian rhythms

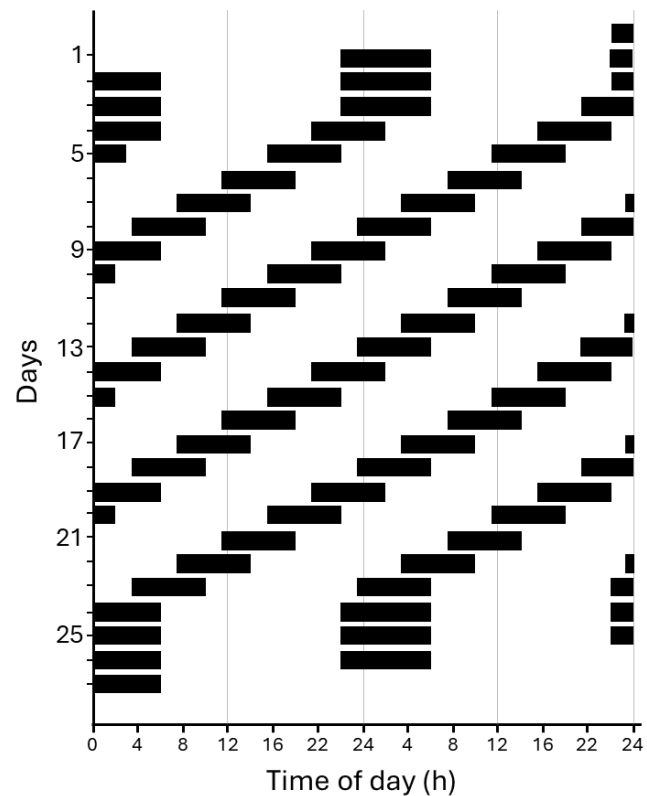
1.3.1. *Experimental protocols*

The assessment of circadian rhythms, sleep-wake cycles, and homeostatic sleep pressure in human sleep research relies on specific protocols, as well as on physiological and behavioural markers. Controlled laboratory settings such as the Constant Routine and Forced Desynchrony protocols are particularly helpful in this context. The Constant Routine is considered one of the gold standard for circadian research (Yousefzadehfard et al., 2022), because it brings external influences to a minimum accurately measure intrinsic circadian rhythms, primarily through markers such as melatonin, core body temperature, and cortisol (Hofstra & Weerd, 2008; Yousefzadehfard et al., 2022). The Forced Desynchrony protocol is used to dissociate circadian from homeostatic processes (Cajochen & Schmidt, 2025). The use of actigraphy, sleep diaries, questionnaires, and cognitive performance tasks, provide additional approaches for more naturalistic and comprehensive assessments (Blatter & Cajochen, 2007; Hofstra & Weerd, 2008). Additionally, new methods using machine learning, amongst others, hold promise for future perspectives, although they still need validation across multiple populations and conditions to be trustworthy (Dijk & Duffy, 2020). Nevertheless, standardised protocols and coherent theoretical frameworks remain crucial for the continued progression and practical application of circadian research in fields such as chronobiology (Dijk & Duffy, 2020).

The **Forced Desynchrony (FD) protocol** is used to isolate participants from external time cues, such as environmental light and temperature, or social behaviours such as meal timings. During FD, participants are exposed to a sleep-wake cycle significantly shorter (e.g., 19 hours) or longer (e.g., 28 hours) than the typical near 24-hour cycle, and for periods ranging from several days to weeks (Czeisler et al., 1999). Because the internal circadian clock cannot adapt to these artificial cycles, it progressively desynchronises from the induced sleep-wake schedule, adopting its intrinsic ("*free-running*") period of approximately 23.9 to

24.5 hours (Kleitman, 1987). This misalignment allows the investigation of endogenous circadian rhythmicity separately from homeostatic sleep pressure, as well as enabling detailed analysis of sleep pressure at various circadian phases. Consequently, FD protocols demonstrate that neurobehavioral performance, such as sustained attention, exhibits a circadian modulation independent of the timing of prior sleep, typically peaking in the evening and declining toward the early morning (Cajochen & Schmidt, 2025). However, the amplitude of this circadian effect is not fixed and can be modulated by the level of sleep pressure, with higher pressure generally amplifying the performance decline during adverse circadian phases (Wyatt et al., 1999).

Figure 13. A 27-day forced-desynchrony protocol, including 3 adaptation days, 24 repetitions of a 20-hour sleep-wake and dark-light schedule, and 3 re-adaptation days. Adapted from (Wyatt et al., 2006).



In contrast, the **Constant Routine (CR) protocol** consists of maintaining participants under tightly controlled conditions : constant posture (usually semi-recumbent), continuous dim light, and evenly spaced, standardised meals, while preventing sleep for a prolonged period (typically ≥ 24 hours, see Figure 14 upper panel) (Duffy & Dijk, 2002; Minors & and Waterhouse, 1984; Yousefzadehfard et al., 2022). By eliminating external time cues and standardizing behavioural

routines across all circadian phases, CR unmasks the endogenous circadian pacemaker's contribution to physiological and cognitive rhythms (Duffy & Dijk, 2002). Under these conditions, researchers can precisely measure intrinsic circadian markers and track subjective alertness, and neurobehavioral performance, without masking by sleep or external zeitgebers (Dijk et al., 1992). Such measurements have shown that, even as homeostatic sleep pressure accumulates, the circadian system counteracts declining alertness during usual waking hours (Dijk et al., 1992). A variant, the **multiple-nap CR** (Figure 14, bottom panel), replaces continuous wakefulness with brief sleep opportunities at regular intervals, allowing direct assessment of sleep propensity across circadian phases (Cajochen et al., 2001; Dijk et al., 1999; J. K. Wyatt et al., 1999). Mostly, they are used to unmask the circadian rhythm by keeping the homeostatic sleep pressure at a minimum (Duffy & Dijk, 2002; Minors & and Waterhouse, 1984). Although CR protocols are demanding to implement due to their duration and need for strict environmental control, they are very powerful for characterizing circadian rhythm properties and assessing their contributions alongside homeostatic influences, despite some remaining interplay between the two processes (Duffy & Dijk, 2002; Minors & and Waterhouse, 1984).

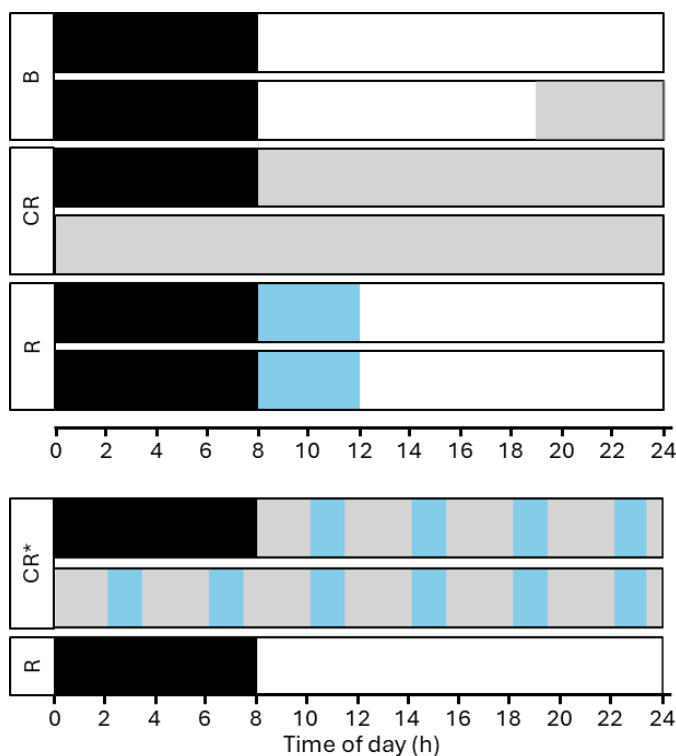


Figure 14. **Top panel:** Raster plot of a 6-day protocol including two baseline days (B), 40-hour of CR protocol (CR), and two recovery days (R). **Bottom panel:** Raster plot of a 40-hour multiple nap CR protocol (CR*), including a 40-hour of 10 cycles of 160-min wakefulness and 80-min sleep opportunities. Black represents nighttime sleep, white represents wakefulness in normal light levels (>10 lux), grey represents wakefulness in dim light condition (<10 lux), blue represents sleep opportunities. Adapted from (Collet et al., 2020).

1.3.2. Measures

1.3.2.1. Rest-Activity cycle (Actimetry)

Actimetry is a non-invasive, wrist-worn technique that provides a practical way to monitor daily rest-activity cycles and therefore estimate sleep-wake patterns in real-life settings, including in clinical populations (Chevalier et al., 2003; Ortiz-Tudela et al., 2010). Each actimeter contains a piezoelectric accelerometer (typically triaxial), measuring movement in the vertical (x), antero-posterior (y), and medio-lateral (z) planes (Ancoli-Israel et al., 2003). It continuously records and stores acceleration data, for as long as multiple months. A band-pass filter (0.25-3 Hz) is then applied to remove gravitational artifacts, and the resulting movements are expressed as “activity units” at sampling intervals ranging from one second up to several minutes, depending on the user’s set-up (Ancoli-Israel et al., 2003). By capturing rest-activity cycles on a large scale and in an ecological context, actimetry allows detailed evaluation of rhythmic patterns including circadian, without disrupting participants’ routines. It is, to date, the only measure that allows such rest-activity assessment to such a scale.

When compared with polysomnography in healthy individuals, actimetry demonstrates excellent sensitivity for nocturnal sleep detection, often higher than 90% (Sadeh, 2011). This sensitivity is however typically accompanied by lower specificity, meaning that periods of quiet wakefulness are frequently misclassified as sleep. This is particularly relevant in populations with poor and/or fragmented sleep, such as older adults. Recent algorithms have been developed to enhance specificity by incorporating contextual information such as consolidated rest periods intervals and circadian patterns (Crespo et al., 2013; Roenneberg et al., 2015). This approach standardizes sleep detection irrespective of the specific actimeter model used and facilitates broader application across different commercial devices.

Because human rest spans are shorter than active periods, and represent only about a third of the 24-hour cycle, standard sinusoidal models fit poorly. Therefore,

to evaluate temporal organisation of the sleep-wake cycle, a nonparametric approach is often employed in human studies, including metrics such as M10 (sum of activity during the 10 most active hours) and L5 (sum during the 5 least active hours), with the relative amplitude defined as : $(M10-L5)/(M10+L5)$ (Gonçalves et al., 2015). Additionally, inter-daily stability quantifies the consistency of the 24-hour activity pattern across multiple days, while intra-daily variability measures fragmentation by assessing how frequently transitions occur between rest and activity within a single day (Witting et al., 1990). High stability indicates a reproducible day-to-day pattern, whereas high variability reflects frequent rest-activity transitions within a day. Nonparametric analysis of actimetry data quantifies rhythm stability, fragmentation, and amplitude (Gonçalves et al., 2015), while combined measures such as TAP (temperature, activity, and body position) enhance accuracy by integrating skin temperature and posture information (Ortiz-Tudela et al., 2010), although complicated to implement in everyday life settings. In situ approaches frequently pair actimetry with tools like chronotype questionnaires to investigate human rest-activity patterns in naturalistic environments (Roenneberg et al., 2015). These methods correlate well with rest-activity logs and improve sensitivity for distinguishing periods of rest and activity compared to single-measure approaches.

Age-related changes derived from actigraphy studies that align with findings from polysomnography and laboratory protocols. Particularly, they coincide on ageing being associated with reduced estimated total sleep time, lower sleep efficiency, increased sleep onset latency, and a higher number of nocturnal awakenings (Huang et al., 2002; Park et al., 2021; Yoon et al., 2003). Furthermore, it confirms that older adults exhibit earlier activity onset and offset (Park et al., 2021; Robillard et al., 2014; Yoon et al., 2003), indicating earlier circadian timing. As a result, older adults' activity peaks occur earlier in the day, with more robust rest-activity rhythms and increased morning activity levels (Park et al., 2021). Although older adults exhibit greater day-to-day stability compared to younger individuals (Luik et al., 2013; Musiek et al., 2018; Park et al., 2021), their 24-hour cycle appears more

fragmented, with more frequent transitions between wakefulness and sleep during ageing, independently of various medical comorbidities (A. S. P. Lim et al., 2011; Musiek et al., 2018). This fragmentation is partly due to increased transitions from rest to activity at night, as well as the intrusion of rest periods during the day (A. S. P. Lim et al., 2011), for example, a higher number of naps among older adults (Yoon et al., 2003).

1.3.2.2. Endocrine markers

Melatonin, one of the primary biological markers of circadian rhythmicity in humans, is an endogenous hormone secreted by the pineal gland under the control of the SCN (C. J. Morris et al., 2012). Its secretion begins to rise in the early night, approximately 12-14 hours after wake-up time (Figure 15). It then peaks around 03h00 as core body temperature reaches its nadir (Heyde et al., 2018; Refinetti & Manaker, 1992). Its secretion is limited to nighttime, as it is suppressed by light input transmitted by photosensitive retinal ganglion cells to the SCN (Cipolla-Neto & Amaral, 2018). Because of the seasonal variability in photoperiod, melatonin secretion duration lengthens in winter and shortens during summer (Cipolla-Neto & Amaral, 2018). The dim light melatonin onset (DLMO_n) usually occurs 2-3 hours before habitual bedtime, and is a widely used circadian phase marker (Burgess et al., 2003). DLMO_n also enables calculation of the phase angle, quantifying alignment between the circadian rhythm and environmental time (Duffy & Wright, 2005), since the interval between bedtime (from PSG or actimetry) and DLMO_n indicates circadian phase relative to sleep timing.

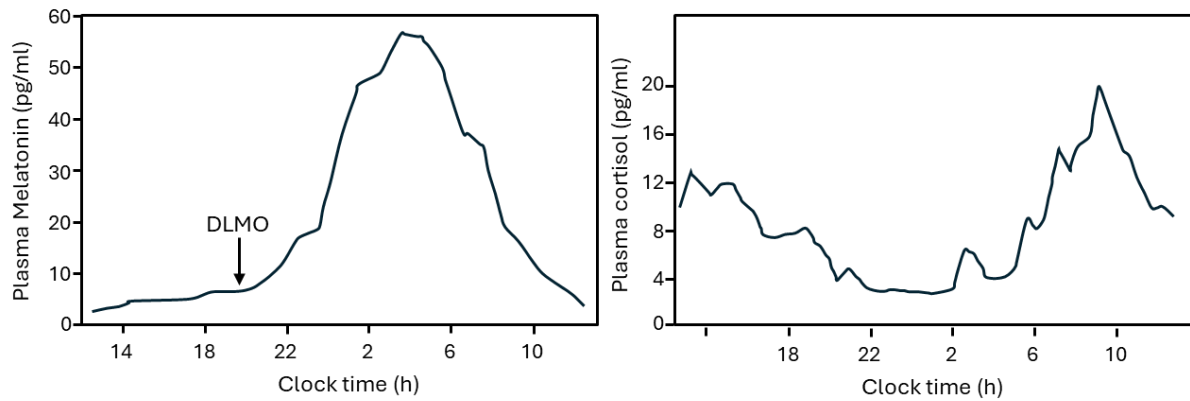


Figure 15. Human circadian rhythms of (left) plasma melatonin level, with dim light melatonin onset (DLMO) indicated in the evening, and (right) plasma cortisol level, adapted from (Hofstra & Weerd, 2008).

Cortisol levels, another biological marker for circadian rhythms, rise in the early morning before awakening. It provides an arousing signal that helps the transition from sleep to wakefulness, and modulates cortical excitability (Gaggioni et al., 2014; Ly et al., 2016). Salivary-derived cortisol levels collected particularly just after awakening and right before bedtime offer valuable insights into diurnal cortisol patterns (Edwards et al., 2001; Kudielka et al., 2007). Actigraphy-derived rest-activity rhythms have been associated with cortisol patterns: more nocturnal restfulness is linked to lower cortisol levels, but daytime sedentary behaviour is linked to higher cortisol (Cash et al., 2017; Kudielka et al., 2007). In the same line, moderate correlations have been found between actigraphy-estimated sleep onset and DLMO timing (Burgess & Eastman, 2005). Cortisol measures complements melatonin profiling, alongside other markers such as body temperature, actigraphy, and chronotype questionnaires to form a comprehensive toolkit for evaluating circadian function under both laboratory conditions (Arendt, 2005; Chung, 2009; Hofstra & Weerd, 2008).

Both melatonin and cortisol rhythms are associated with age-related changes in the context of healthy ageing. However, findings on age-related modifications of melatonin show mixed results: the circadian modulation of melatonin secretion may not change significantly (Godfrey et al., 2022), but the nocturnal peak concentration might decline with advancing age (Godfrey et al., 2022; Scholtens et al., 2016). This decline begins around 60 years old, and becomes more pronounced

in individuals over 70 (Zhao et al., 2002). Notably, older individuals living in care facilities tend to have lower nocturnal melatonin peaks and higher daytime levels compared to independently living elderly (Godfrey et al., 2022). In general, healthy and community-dwelling older adults exhibit earlier melatonin phase and lower amplitude compared to younger individuals (Kim et al., 2014; Rahman et al., 2023). Interestingly, the acute response to light remains unaffected by age (Kim et al., 2014). The age-related cortisol changes are more defined, with older adults exhibiting an increase in mean cortisol levels (Van Cauter et al., 1996). The circadian rhythm of cortisol also undergoes a phase advance, with earlier peak in secretion (Sherman et al., 1985; Van Cauter et al., 1996). Additionally, the cortisol amplitude is dampened in older adults (Copinschi & Van Cauter, 2008; Van Cauter et al., 1996). These changes are linked to well-known alterations in sleep patterns, including earlier sleep onset and awakening times (Copinschi & Van Cauter, 2008).

1.3.3.3. Body temperature

Core body temperature (CBT) exhibits a strong circadian oscillation, following a sinusoidal pattern with peaks in the late afternoon and troughs in the early morning (Figure 16)(Refinetti & Manaker, 1992; Słomko & Zalewski, 2016; Weinert & Waterhouse, 2007). This modulation is driven by the circadian clock : the SCN modulates hypothalamic thermoregulatory centres to adjust vasodilation and sweating, resetting the body's temperature set point (Refinetti & Manaker, 1992; Weinert & Waterhouse, 2007). Evening light exposure acutely influences CBT by suppressing its normal nighttime decline (Dijk, 2012), while physical activity produces a masking effect through heat generation. Yet, the intrinsic circadian rhythm of CBT persists even when activity-driven heat is controlled (Refinetti & Manaker, 1992; Weinert & Waterhouse, 2007).

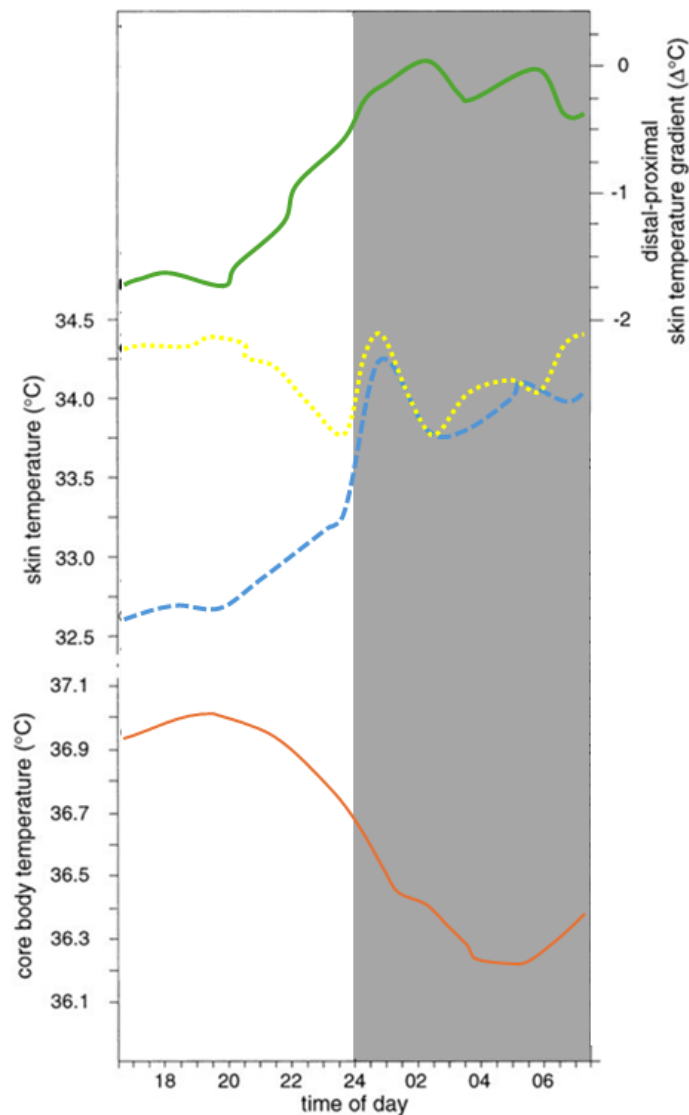


Figure 16. Time course of core body temperature (CBT) in orange, distal (blue dashed) and proximal (yellow dashed) skin temperatures, and the resulting distal-to-proximal skin temperature gradient (DPG, green) in a baseline 7.5-h constant routine (CR) followed by a 7.5-h sleep period. Adapted from (Kräuchi et al., 2000).

To measure CBT, rectal temperature remains the gold standard but its invasiveness limits ambulatory or large-scale use. Therefore, skin temperature recording has emerged as a valuable, non-intrusive method for assessing thermoregulatory circadian and rest-activity rhythms (Batinga et al., 2015). In this context, the wireless iButton device has been validated as a reliable tool for measuring skin temperature in both laboratory and real-world settings (Hasselberg et al., 2013; Longato et al., 2017). They are little data loggers (17 mm diameter, 6 mm thick) that record skin temperature at pre-set epochs, via an integrated thermistor, with a maximum of 0.0625°C sensitivity (Hasselberg et al., 2013).

Proximal skin temperatures (e.g., trunk or clavicular area) mirror the CBT daily modulation, whilst distal skin temperatures (e.g., hands and feet) exhibit an inverse

pattern, and rather rising during the biological night (Figure 16)(Kräuchi, 2010). The distal-proximal gradient of temperature (DPG) is calculated as the mean distal skin temperature minus the mean proximal skin temperature (Kräuchi, Knoblauch, et al., 2006). This gradient captures the dynamic of peripheral vasodilation and heat redistribution from core to periphery, faithfully reflecting thermoregulatory modulations during the 24-hour cycle (Ballell et al., 2023; Kräuchi et al., 1999; Kräuchi & Wirz-Justice, 1994; Longato et al., 2017). DPG, like the distal skin temperature, shows the inverse pattern of CBT modulation : it peaks in the early morning hours, around 02h00-03h00, and reaches its lowest point in the late afternoon, marking maximal heat loss at night and minimal during the day (Ballell et al., 2023; Gradisar & Lack, 2004; Van Someren, 2000). Under CR conditions, distal skin temperature continues to exhibit an inverse circadian pattern relative to CBT, while proximal temperature parallels CBT with similar amplitude (Kräuchi et al., 2000; Raymann et al., 2007; Van Someren et al., 1999).

Nocturnal sleep is usually initiated during the declining portion of the CBT curve (Campbell et al., 1993; Dijk & Czeisler, 1994), and the concomitant increase in heat loss (measured by DPG) signals readiness for sleep (Kräuchi, 2007a; Raymann et al., 2007). Elevated DPG correlates with faster sleep onset and greater subjective sleepiness, and therefore serves as a sensitive, non-invasive marker of sleep propensity and circadian phase (Kräuchi, 2007a; Lushington et al., 2004; Raymann et al., 2005). Moreover, and regardless of timing, sleep is associated with changes in thermophysiology (Kräuchi, 2010). When sleep is initiated even outside of the usual nocturnal period, for example by taking an afternoon nap, similar thermophysiological changes occur as seen before and during nocturnal sleep (Kräuchi, 2010). Notably, sleep also contributes to the body's ability to regulate temperature, such that robust thermoregulatory effects can be induced by the relaxing aspect of sleep (Kräuchi, 2010).

It is worth noting however, that thermophysiological effects occurring during sleep initiation can also be observed without falling asleep. Thermophysiological changes start directly after lights-off and even before sleep initiation (Kräuchi,

2010). Relaxation techniques induce a withdrawal in muscular and cutaneous sympathetic nerve activity leading to increased distal skin blood flow and temperature (Lushington et al., 2004; Recordati, 2003). Thus, distal vasodilatation, followed by a drop in CBT, appears to be a thermophysiological event, which is in part related to relaxing behaviour (Kräuchi, 2010). Body posture is also a powerful modulator of the thermophysiological changes. Moving from sitting or standing to a supine position rapidly increases distal skin blood flow, raises the DPG, and accelerates the fall in CBT, thereby heightening sleepiness (Kräuchi et al., 1997; Kräuchi & Wirz-Justice, 2001). The reverse shift to an upright posture produces opposite effects, so posture must be controlled when evaluating circadian or sleep-related temperature metrics. Gravitational redistribution of blood also cools the extremities when limbs are elevated or the body is tilted, further illustrating how positional changes reshape peripheral temperatures (Azemachi et al., 2023; Mayerson & Toth, 1938). During passive heating, CBT predominantly influences neuromuscular performance in force tasks, whereas skin temperature has greater impact on position-related tasks, underscoring function-specific thermal sensitivities (Coletta et al., 2018). To capture these intertwined effects, using an approach that combines distal temperature, actimetry, and body posture, markedly improves rest-activity classification and circadian phase estimation in ambulatory studies compared with actimetry alone (Ortiz-Tudela et al., 2010).

Healthy ageing has been reported to be associated with a phase advance, but also with reduced circadian amplitude of CBT in some (e.g., Czeisler et al., 1992; Dijk et al., 2000; Duffy et al., 1998), but not all (e.g., Buysse et al., 2005; Monk et al., 2000) studies. This blunted rhythm is partly due to weakened signals from the SCN and diminished melatonin production (Czeisler et al., 1992). On the contrary, pathological ageing (e.g., patients suffering from Alzheimer's disease) is linked to a delayed phase and a stronger, but highly variable, amplitude (Van Someren, 2002; Van Someren et al., 1999).

To be more specific, healthy ageing is accompanied by lower metabolic heat production and retention, impaired heat loss mechanisms, as well as reduced

thermal sensitivity (Degroot & Kenney, 2007; Martinez-Nicolas et al., 2018; Van Someren, 2007). Consequently, proximal skin temperatures, tightly regulated by CBT, tend to be more stable but slightly elevated at night, reflecting impaired thermolysis (Van Someren, 2002, 2007). In contrast, distal skin temperatures, which facilitate heat loss and are usually higher at night to promote sleep onset, rise less markedly in older adults, indicating impaired vasodilation (Van Someren, 2002). It should also be noted that older individuals exhibit overall higher distal skin temperatures (Batinga et al., 2015; Martinez-Nicolas et al., 2018), especially during daytime (Martinez-Nicolas et al., 2017). The subsequent DPG therefore shows a blunted increase in the evening in elderly individuals (Kräuchi et al., 2000). This reduced evening DPG elevation may contribute to common age-related sleep difficulties such as delayed sleep onset and fragmented sleep. The relationship between pre-sleep heat-loss activation and sleep latency has been suggested to be weaker in older compared to younger individuals (Raymann et al., 2007), and the sensitivity of sleep propensity to enhanced distal skin temperature has also been shown to change with age (Raymann et al., 2007).

2. Association between sleep-wake cycle and cognitive ageing

Far from being isolated physiological processes, both sleep architecture and circadian rhythmicity exert profound and dynamic influences on key domains of cognition, including attention, memory, executive function, and emotional regulation (Diekelmann & Born, 2010; Lim & Dinges, 2008; Mander et al., 2017). These effects have been associated with specific neurobiological mechanisms such as SWA-dependent memory consolidation (Rasch & Born, 2013) and circadian modulation of cortical excitability and synaptic plasticity (Gaggioni et al., 2014; Ly et al., 2016). For example, cortical responses to a sustained-attention task follow robust regional circadian rhythms while simultaneously declining with accumulated sleep debt, underscoring the powerful, combined modulation of wake-related cognitive function by both the circadian clock and sleep homeostasis (Muto et al., 2016). They are moreover particularly relevant in ageing, where

altered sleep-wake regulation may accelerate cognitive decline (Mander et al., 2017; Scullin & Bliwise, 2015). Disruption of either the homeostatic or circadian systems, through sleep deprivation, circadian misalignment, or age-related dampening, has been consistently linked to impairments in neurocognitive performance and increased risk for neurodegenerative diseases such as Alzheimer's disease (Harper et al., 2005; Ju et al., 2014; Musiek et al., 2018).

2.1. Sleep and cognition

Although objective measures of sleep duration using actigraphy-estimated sleep report either no significant relationship with cognitive functioning (Blackwell et al., 2006), or a negative association with either short (Miyata et al., 2013) or long sleep duration (Spira et al., 2017), meta-analyses focusing on subjective sleep duration reveal that self-reported extreme sleep durations (short and long) are consistently associated with reduced cognitive performance (Devore et al., 2016; J. C. Lo, Groeger, et al., 2016). Sleep loss impairs cognition, and especially long-term and short-term memory (Heyde et al., 2018). In addition, subjective evaluation of sleep duration is positively associated with the incidence of Alzheimer's disease, especially when duration is extremely long or short (J.-C. Chen et al., 2016). More than only quantity, quality also seems to be important. Low self-reported sleep quality is associated with impaired cognitive performances, particularly in episodic memory, sustained attention, processing speed, inhibition and cognitive flexibility (Kim et al., 2021; Potvin et al., 2012). This is further confirmed by objective measures, with lower actimetry-derived sleep efficiency being linked to lower cognitive performance (Owusu et al., 2023; West et al., 2021). Longer sleep onset latencies, time awake during nighttime sleep, and higher nocturnal sleep fragmentation are also linked to poorer cognitive outcomes (Blackwell et al., 2006; Luik et al., 2015; Owusu et al., 2023; West et al., 2021).

Objective changes in both the macrostructure and microstructure of sleep have been linked to cognitive functioning in the context of ageing (Djonlagic et al., 2021). Older adults with altered sleep architecture show measurable changes in cognitive

performance (Song et al., 2015). Indeed, a higher percentage of light sleep (N1) increases the odds of decline in processing speed, executive function, and global cognition, while reduced REM sleep associates with greater global decline (Song et al., 2015). Moreover, alterations in sleep spindles and slow waves are among the most implicated, particularly due to their role in memory consolidation (Hoedlmoser et al., 2022). Greater SWA predicts improved overnight memory change (Mander et al., 2013), yet Scullin (2013) indicates that SWS correlates positively with memory in young adults but not in older adults. Changes in the coupling between sleep spindles and slow waves have been associated with reduced memory consolidation (Hahn et al., 2020; Helfrich et al., 2018; Muehlroth et al., 2019) and have also been shown to predict cognitive decline in the older population (Chylinski et al., 2022; Djonlagic et al., 2021).

2.2. Rest-activity cycles and cognition

Both the 24-h activity rhythm and sleep are related to global cognitive functioning. Possibly, the ageing process creates a vulnerability to the impact of sleep and circadian rhythms disturbances on cognitive performance (Luik et al., 2015). Such disturbances in the 24-h activity rhythm seem to be mostly related to tasks that draw on perceptual speed and executive functioning (Luik et al., 2015).

Of note, more stable 24-hour activity rhythms and less fragmented cycles have been linked to better cognitive performance, reflected by better executive function, processing speed, visuospatial performance, episodic memory and sustained attention (Luik et al., 2015; Oosterman et al., 2009). On the opposite, increased fragmentation of activity during the day has been associated with poorer performance across multiple cognitive domains, including episodic memory, working memory, processing speed, executive performance and visuospatial abilities (A. S. P. Lim et al., 2012; Oosterman et al., 2009). Reduced daytime activity, in particular, has been shown to predict decreased sleep efficiency and increased wake time after sleep onset, both of which contribute to lower executive functioning (J. M. Zeitzer et al., 2018). In home-dwelling individuals with AD

dementia, a more fragmented activity rhythm has also been linked to diminished well-being, including impaired cognitive functioning, decreased social interaction, and increased depressive symptoms (Carvalho-Bos et al., 2007).

In addition to rhythm fragmentation, lower amplitude of the circadian rest-activity rhythm has been associated with cognitive decline (Rogers-Soeder et al., 2018; J. H. Roh et al., 2014), and may predict such decline up to five years in advance (Walsh et al., 2014). Furthermore, individuals with cognitive impairment tend to exhibit a delayed peak in circadian activity, indicating phase shifts (Cochrane et al., 2012). More recent findings also highlight the negative impact of circadian misalignment: when the rest-activity cycle is not synchronised with the external light-dark cycle, executive functioning is further impaired (Blackwell et al., 2023).

Beyond behavioural rest-activity patterns, circadian-regulated physiological processes also influence cognition. The circadian amplitude, phase and rate of rise and fall of CBT has been repeatedly linked to cognitive functioning (Heyde et al., 2018): higher CBT amplitude predicts better working memory and attentional performance. Performance of such cognitive domains tend to fluctuate in parallel with CBT, peaking during the biological day when CBT is highest, and declining at night when CBT reaches its nadir (Burke et al., 2015; Lewandowska et al., 2018; J. C. Lo et al., 2012; Schmidt, Peigneux, & Cajochen, 2012). Even a small increase in CBT ($\sim 0.15^{\circ}\text{C}$) has been associated with improved cognitive performance and alertness (Van Someren, 2007; Wright et al., 2002). The DPG, which inversely mirrors CBT, also correlates with fluctuations in alertness and executive functioning (Heyde et al., 2018; Santhi et al., 2016).

Circadian fluctuations in cognitive performance are not uniform across all domains. A summary of age-related effects on cognitive domains is depicted in Table 1. Higher-order functions such as working memory, executive control, and sustained attention are more sensitive to time-of-day effects, particularly under conditions of sleep deprivation or high cognitive load (Lewandowska et al., 2018; Wright et al., 2002). This vulnerability is further modulated by chronotype: the so-called

"synchrony effect" highlights the benefit of alignment between an individual's chronotype and the timing of cognitive assessment (Puttaert et al., 2019; Schmidt et al., 2007).

These findings highlight the complex interplay between circadian regulation, rest-activity rhythms, and cognitive functioning, particularly in the context of ageing. Building on this, the next section will examine the role of daytime napping, being a potential marker and modulator of sleep-wake cycle fragmentation, and its implications for cognitive health in older adults.

	Cognitive function		Effect	Reference (reviews)
Attention	Selective		↓	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
	Divided		↓	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
	Sustained		↔	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
	Processing Speed		↓	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
Memory	Working	Verbal	↓	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
		Visuospatial	↓	Angel & Isingrini (2015); Prince et al. (2024)
	Episodic	Encoding	↓	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
		Storage	↔	Glisky (2007); Prince et al. (2024)
		Retrieval	↓	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
	Semantic		↔ or ↑	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
	Autobiographical		↔	Glisky (2007)
	Procedural		↔	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
	Prospective		↔	Angel & Isingrini (2015); Glisky (2007)
Executive	Inhibition		↓	Angel & Isingrini (2015); Glisky (2007); Prince et al. (2024)
	Shifting		↓	Angel & Isingrini (2015); Prince et al. (2024)
	Update		↓	Angel & Isingrini (2015); Prince et al. (2024)
	Planification		↓	Prince et al. (2024)

Table 1. **Summary of age-related cognitive evolution in healthy ageing, on attentional, memory and executive processes. Specific cognitive functions are depicted separately.** Arrows denote the direction of effect of each nap condition on specific cognitive domains: ↑ = positive (enhanced performance), ↔ = mixed or no clear effect, ↓ = negative (impaired performance).

Chapter 3. Napping

1. Napping and the sleep-wake cycle

Napping is a complex behaviour, shaped by culture and evolving throughout the lifespan. In Mediterranean countries such as Spain or Greece, the habitual “siesta” is the norm with up to 60-70% of adults who nap regularly. On the contrary, in the United States or Northern Europe, fewer than 20% of adults report regular daytime napping (Willoughby et al., 2023). Napping is often assumed to have deep evolutionary roots, but evidence from pre-industrial equatorial societies suggests that it was actually relatively uncommon, implying that early humans may have been predominantly monophasic sleepers (Yetish et al., 2015). In the modern era, however, napping plays various, multi-faceted, roles within the broader regulation of the sleep-wake cycle, particularly in older adults.

Ageing is accompanied by marked alterations in both homeostatic and circadian components of sleep regulation, which together predispose older adults to daytime napping (Mander et al., 2017). Nocturnal melatonin secretion in seniors shows a reduced amplitude and an earlier offset (Godfrey et al., 2022), weakening the circadian anchor that normally sustains daytime alertness and thereby permitting an earlier rise in sleepiness during the late morning and early afternoon (Zisapel, 2001). In the same line, an age-related attenuation of the evening circadian arousal was evidenced using a multiple-nap protocol (Münch et al., 2005). Circadian rhythm of CBT in older individuals is also blunted, with a diminished nocturnal nadir and a delayed, attenuated morning temperature rise. This creates a prolonged “thermal window” of reduced vigilance in the post-lunchtime period (Kräuchi, Cajochen, et al., 2006). Moreover, homeostatic sleep-pressure driven by adenosine accumulation appear amplified with age, as both slower clearance and heightened A_1 receptor sensitivity intensify the drive for sleep by midday despite unchanged nocturnal sleep duration (Landolt, 2008). Older adults also display an earlier onset as well as a greater prevalence of SWA in the afternoon, which indicates a lowered cortical threshold for sleep initiation and a stronger

homeostatic burden even in brief nap attempts (Van Dongen et al., 2004). However, some authors found physiological daytime sleep propensity can actually be reduced in healthy ageing, even in the presence of nocturnal slow-wave sleep decline (Dijk et al., 2010). This suggests that while subjective sleepiness and the tendency to take unplanned naps may increase with age, the underlying capacity to initiate sleep during the day may be attenuated, potentially reflecting changes in homeostatic regulation.

More than half of older adults aged above 70 years old nap at least twice a week, and the incidence of napping tends to increase with advancing age (Foley et al., 2007). This rise in napping incidence is accompanied by notable inter- and intra-individual variability in its characteristics, including timing, frequency, and duration (Cross et al., 2015). The reasons for napping are multifactorial and can include : compensation for sleep loss, circadian-driven dips in alertness, hedonic factors (e.g., napping for pleasure), or habitual behaviours embedded in cultural or personal routines (Duggan et al., 2018; Mednick, 2024).

The timing of naps is however closely intertwined with the circadian process. Older adults are more likely than younger individuals to engage in naps that occur later in the day (Yoon et al., 2003), often aligning with or intruding upon the so-called WMZ (i.e., wake maintenance zone), a circadian window in the late afternoon to early evening when sleep propensity is lowest and wakefulness strongly promoted (Dijk & Czeisler, 1995). This WMZ is subject to age-related impairment, with older adults experiencing a lower drive for arousal during this time window (Münch et al., 2005). Napping during or near the WMZ may result in a delay in subsequent nocturnal sleep onset and an increase in night-time awakenings, contributing to circadian misalignment (Deantoni et al., 2024). This misalignment is not only a matter of timing but may reflect or cause underlying biological changes. Indeed, older habitual nappers exhibit a significantly greater reduction in the amplitude of circadian rhythms in melatonin secretion and REM sleep propensity than is typically observed with ageing, indicating an exacerbated weakening of their circadian drive (Deantoni et al., 2024). Furthermore, Reyt et al. (2022) reported

that more frequent and later-in-the-day habitual napping in healthy older adults is associated with a disrupted 24-hour rest-activity rhythm, which in turn predicts poorer episodic memory performance. From a sleep physiology perspective, naps taken later in the day are associated with a higher homeostatic sleep pressure and, consequently, show increased amounts of SWS and SWA (Cross et al., 2015; Milner & Cote, 2009). This is in contrast to early afternoon or morning naps, which may contain more REM sleep due to circadian phase effects (Cross et al., 2015). While these properties may confer restorative benefits, such as enhanced memory consolidation (Lo et al., 2021) and reduced sleepiness (Milner & Cote, 2009), they may also negatively impact the architecture of subsequent nocturnal sleep. Daytime napping has been shown for example to reduce SWA in the following nighttime sleep (Werth et al., 1996), indicating a redistribution of homeostatic sleep pressure. Napping behaviour has also been linked with a greater nocturnal sleep fragmentation (Goldman et al., 2008), lower sleep efficiency (Monk et al., 2001; Owens et al., 2010), shorter sleep duration (Foley et al., 2007; Most et al., 2012), earlier morning awakenings (Cross et al., 2015; Foley et al., 2007; Yoon et al., 2003) and later/longer sleep onset latencies (Campbell et al., 2005; Cross et al., 2015; J. Li, Vitiello, et al., 2018), although not all studies find associations between napping and nighttime sleep parameters (Aber & Webb, 1986; Buysse et al., 1992; Campbell et al., 2005; Jean-Louis et al., 2000). There seems to be no association between the duration and/or frequency of napping and self-reported nocturnal sleep quality, for instance (Goldman et al., 2008; Most et al., 2012). Finally, nap intention is known to play a mediating role : prophylactic, intentioned naps tend to alleviate homeostatic sleep pressure without significantly delaying nocturnal sleep onset or altering circadian phase, thereby supporting stable 24-h rhythms (Ficca et al., 2010). In contrast, opportunistic or recuperative naps taken in direct response to high sleepiness often occur later in the day, fragment the rest-activity rhythm, and can blunt evening circadian alerting signals (Monk et al., 2001), as discussed above. Recreative or “appetitive” naps, being those taken purely for enjoyment or out of boredom rather than to compensate for sleep loss, tend to be brief, self-

initiated rests occurring in periods of low sleep pressure (Ficca et al., 2010). In older adults, appetitive napping often mirrors lifestyle and leisure patterns more than physiological need, and is associated with higher intradaily activity fragmentation without robust improvements in restorative sleep markers or sustained cognitive function (Milner & Cote, 2009).

These chronic alterations in sleep regulation extend beyond nocturnal architecture to systemic health: long and frequent naps in older adults have been linked to increased cardiovascular morbidity (Sun et al., 2022) and a higher all-cause mortality (Ancoli-Israel & Martin, 2006; Dhand & Sohal, 2007; Zhong et al., 2015). Importantly, greater irregularity in nap timing and variability in nap frequency have been linked to adverse neurobiological markers. Specifically, higher cortical amyloid- β burden in memory-related regions such as the precuneus and posterior cingulate (Winer et al., 2020) and elevated pro-inflammatory protein (Lo, Groeger, et al., 2016).

2. Napping and Cognition

In the same cohort who contributed this thesis, it was observed that more frequent and later-in-the-day naps are correlated with a disrupted 24-hour rest-activity rhythm (Reyt et al., 2022). More specifically, older adults who napped more frequently and later in the day showed lower interdaily stability of their rest-activity rhythm indicating less consistent day-to-day patterns, while also showing a higher intradaily variability, reflecting more fragmented activity-rest transitions within each day. Frequent and delayed napping, in turn, predicts poorer episodic memory performance, a domain particularly sensitive to ageing and early AD (Reyt et al., 2022). Gao et al. (2025) found that greater day-to-day variability in daytime napping was linked to increased amyloid- β burden and neurofibrillary tangle density, although this variability was not directly predictive of incident AD. These findings align with evidence that excessive daytime sleepiness (Epworth Sleepiness Scale (ESS) score ≥ 10 ; Johns, 1991), and frequent or prolonged napping in the aged, are associated with a higher risk of cognitive decline and risk of

developing AD over time (Leng et al., 2019; J. Li et al., 2022; Overton et al., 2024). Excessive daytime napping² is linked to poorer cognitive performance in people with mild cognitive impairment, with increased dementia risk and accelerated cognitive decline, including episodic memory, executive function, and perceptual speed (Overton et al., 2024). Longer naps are linked to slower processing speed, poorer verbal fluency and memory, as well as higher depressive symptoms (Cross et al., 2015). Individuals who nap frequently tend to present a steeper decline in overall cognition over time, with longitudinal evidence supporting these associations, particularly in verbal fluency and executive functioning (Overton et al., 2024). Overall, this excessive napping behaviour is partly independent of nighttime sleep (Leng et al., 2019; J. Li et al., 2022; Most et al., 2012; Pilcher et al., 2001), and could reflect a change in the 24-hour circadian control of the sleep-wake cycle (J. Li et al., 2022). Habitual napping may therefore reflect underlying sleep-wake fragmentation and circadian dysregulation, even hypersomnolence phenotypes, but also potentially contribute (or at least be associated) to cognitive decline through sleep inertia, disrupted nocturnal sleep, and circadian misalignment (Leng et al., 2019; L. Zhang et al., 2023). This line of thought is further strengthened by the fact that unplanned (Owusu et al., 2019) and long naps despite appropriate sleep duration the previous night (J. Li, Vitiello, et al., 2018; Xin et al., 2020) are linked to negative cognitive outcomes. In this context, napping could be seen as an early risk factor for cognitive decline or clinically significant cognitive impairment (Leng et al., 2019; Owusu et al., 2019).

As it is the case for most age-related human behaviours, napping is not completely vilified. If well-timed, planned and brief (< 30 min), naps can improve alertness, mood and various aspects of cognitive performance, including memory consolidation (Cai et al., 2021; Leong et al., 2022; Milner & Cote, 2009). Furthermore, not all studies report an association between cognition, including memory, and napping (Álvarez-Bueno et al., 2022; Paz et al., 2023). Several studies

² Long (>60 min) and frequent napping behaviour

showed that older adults who engage in moderate nap durations (30-90 minutes) experience cognitive benefits, and particularly when naps occur earlier in the afternoon and intra-daily variability is low (Keage et al., 2012; Zhang et al., 2023). Yet, these positive outcomes may depend on nighttime sleep quality and circadian alignment, as the interaction between daytime and nocturnal sleep remains critical in determining net cognitive outcomes (Dautovich et al., 2008; Leng et al., 2019). A summary of nap characteristics effects on cognitive domains is depicted in Table 2. For example, early naps are associated with better nocturnal sleep efficiency and reduced wake after sleep onset in older adults, compared to naps later during the day (Dautovich et al., 2008). This suggests that nap timing and individual circadian phase should be carefully considered in research and clinical settings.

		Type of nap	Effect	Reference
Attention	Vigilance	Occasional, moderate	↑	Li et al. (2022)
		Frequent	↔	Leong et al. (2022), Milner et al. (2006)
	Processing Speed	Long	↓	Brooks & Lack (2006), Chang et al. (2022), Cross et al. (2015), Leong et al. (2022), Overton et al. (2024), Souabni et al. (2022), Tietzel & Lack (2002)
	Sustained attention	Short	↑	Li et al. (2022)
		Moderate	↑	Li et al. (2022)
	Divided attention	Short	↔	Li et al. (2022)
Memory	Verbal working memory	Occasional, short	↑	Li et al. (2022)
		Frequent, moderate	↓	Owusu et al. (2019)
		Long	↔	Leong et al. (2022)
	Visuospatial working memory	Occasional, short	↑	Li et al. (2022)
	Episodic memory	Occasional, short	↑	Cai et al. (2021), Kitamura et al. (2021), McDevitt et al. (2018), Souabni et al. (2022), Wang et al. (2021)
		Moderate	↑	Álvarez-Bueno et al. (2022), Li et al. (2022), McDevitt et al. (2018), Zhang et al. (2023)
		Long	↓	Álvarez-Bueno et al. (2022), Cross et al. (2015), Gao et al. (2025), Kitamura et al. (2021), Leng et al. (2019), Li et al. (2022), Overton et al. (2024), Zhang et al. (2023)
		Frequent	↓	Leong et al. (2022), Owusu et al. (2019), Rey et al. (2022)
Executive	Verbal fluency	Frequent, long	↓	Álvarez-Bueno et al. (2022), Cross et al. (2015), Overton et al. (2024), Souabni et al., 2022)
	Inhibition	Short	↑	Souabni et al. (2022)
		Long, irregular	↓	Overton et al. (2024), Souabni et al. (2022)
Global	MMSE, MOCA,...	Short	↑	Álvarez-Bueno et al. (2022)
		Moderate	↔	Álvarez-Bueno et al. (2022), Auyeung et al. (2013), Keage et al. (2012), Li et al. (2022)
		Long	↓	Álvarez-Bueno et al. (2022), Li et al. (2018, 2022), Overton et al. (2024), Xin et al. (2020)

Table 2. **Summary of cognitive outcomes of daytime napping in healthy older adults, on attentional, memory and executive processes. Specific cognitive functions are depicted separately.** Nap durations are defined as short (<30 min), moderate (30-60 min) and long (>60 min). Frequency categories as occasional (<2 naps/week) and frequent (≥2 naps/week). Arrows denote the direction of effect of each nap condition on specific cognitive domains: ↑ = positive (enhanced performance), ↓ = negative (impaired performance), ↔ = mixed or no clear effect. Abbreviations: MMSE = Mini-Mental State Examination; MoCA = Montreal Cognitive Assessment.

2.1. Underlying cerebral correlates

Recent findings from the CogNap study highlighted the association between frequent napping in older adults and poorer episodic performance (Reyt et al., 2022). In addition, and using the Sternberg paradigm, we³ have also showed that habitual napping in older people is associated with lower working memory performance, especially at the highest task difficulty (Reyt et al., 2025). As this task was realised during a fMRI acquisition, brain correlates underlying this nap-related difference could be investigated. In this context, it was evidenced that habitual nappers presented a reduced hemispheric asymmetry in older adults who regularly nap, driven by a higher right-DLPFC activation across increasing task difficulty (Reyt et al., 2025). In a compensational framework, this finding suggests that habitual napping is associated with a more ‘old age-like’ profile of brain function, as posited by the CRUNCH or HAROLD models (Cabeza, 2002; Cappell et al., 2010; Schneider-Garces et al., 2010). They also proved to rely more heavily on parietal regions relative to frontal ones, and their thalamic activation, particularly in the right hemisphere, was consistently higher than people from the same age who do not regularly nap (Reyt et al., 2025). Recruitment of additional resources associated with maintenance of performance are characteristics of compensatory process described in the context of successful ageing (Cabeza & Dennis, 2013). However, the contralateral activation observed in WM task in regular nappers is not linked to WM performance. This absence of efficient prefrontal-behaviour coupling, combined with more diffuse activation patterns, may also point to a dedifferentiation process in ageing brains that habitually nap.

In summary, napping in older adults is a multifaceted behaviour that come from, and potentially influences, the interplay between homeostatic sleep pressure, circadian regulation, lifestyle routines, and neurobiological changes. Short and well-timed naps may support cognitive functioning and compensate for age-related changes in nocturnal sleep. In contrast, chronic, long, or irregular naps especially

³ See Appendix 2, co-first authorship of cross-sectional fMRI results

when occurring later in the day may reflect or exacerbate circadian misalignment, sleep-wake fragmentation, and pathological brain ageing. Some authors have suggested that the effects of daytime rest depend as much on the habit itself as on nap characteristics, with habitual nappers differing from non-nappers in domains such as memory. Although it is unclear whether napping is beneficial or harmful, little is known about the correlates of napping in healthy older adults (Leng et al., 2019). Because napping habits are so heterogeneous, most studies to date have treated naps as a measurement tool or a secondary variable, often using actigraphy or sleep diaries primarily to validate nocturnal sleep metrics, rather than as the central focus of investigation. Only in the past decade have a handful of dedicated studies begun to explore napping per se and its direct implications for physical and cognitive health in older adults (Leng et al., 2019; Paz et al., 2023). These studies often combine subjective reports, such as sleep diaries or the Epworth Sleepiness Scale, with objective recordings from actigraphy or polysomnography to capture nap timing, frequency, duration, and fragmentation. While subjective methods are accessible but prone to recall bias, objective measures allow precise and continuous assessment of rest–activity rhythms and sleep propensity (Most et al., 2012; Vitiello, 2009). Employing these tools is crucial to distinguish adaptive nap strategies from early markers of pathology and to establish a more robust evidence base regarding the true costs and benefits of daytime sleep in ageing (Most et al., 2012; Vitiello, 2009).

Chapter 4. Objectives and Hypotheses

In the preceding sections, we outlined how ageing alters the sleep-wake cycle, brain function and cognition, and how these domains interact in later life. Age-related disruption of the sleep-wake cycle seems to be linked to cognitive decline and an increased need for functional compensation at the brain level. Nevertheless, the specific impact of wakefulness fragmentation, such as that introduced by daytime napping, has been only sparsely examined.

The overarching aim of this thesis is to characterise the association between sleep-wake cycle fragmentation and age-related trajectories of cognition and brain function, with a particular focus on the contribution of the circadian timing system. Using habitual napping as an operational marker of circadian sleep-wake disruption and fragmentation of wakefulness continuity in ageing, we aim at testing two primary hypotheses. First, habitual napping in older adults is associated with circadian dysregulation, evidenced by a reduced amplitude in the 24-hour modulation of the temperature circadian marker and altered pre-sleep thermoregulatory dynamics. Second, a long-term nap-suppression intervention would stabilise circadian rhythms, leading to maintained or improved cognition, principally in the episodic and working memory domains, accompanied by modulation of their cerebral correlates, over a one-year period.

To address these aims, Study 1 examines age-related changes in thermoregulation and their association with working memory. Study 2 investigates the relationship between habitual napping in healthy older adults, circadian modulation of temperature, and interactions with sleep initiation processes. Studies 3 and 4 test whether re-stabilising circadian sleep-wake organisation via a one-year nap-suppression intervention mitigates age-related cognitive decline: Study 3 evaluates effects on episodic memory, whereas Study 4 focuses on working memory performance and associated functional compensation. More precisely:

Study 1 aims to characterise age-related differences in circadian thermoregulation estimates in the field, indexed by the 24-hour distal-proximal skin temperature gradient (DPG), and in visuospatial working-memory (WM) binding. As WM performance has been shown to follow temperature rhythm (Burke et al., 2015; Lewandowska et al., 2018; R. West et al., 2002), we further tested whether thermoregulatory markers predict performance across the day. We hypothesised that older adults would exhibit a reduced DPG amplitude and poorer binding accuracy than young adults. We further expected that lower (i.e., more “wake-like”) DPG values at testing times would be associated with better working-memory performance irrespective of age, and that time-of-day would modulate these effects, such that shifts in performance between morning and evening co-vary with concomitant changes in DPG.

Study 2 aims to determine how habitual napping shapes thermoregulatory heat-loss dynamics, indexed by the DPG, and their link with sleep initiation across a 40-h multiple-nap protocol in healthy older adults. We hypothesised that, relative to self-reported non-nappers, regular nappers would show a generally higher daytime DPG during scheduled wake bouts, reflecting greater sleep readiness, and a reduced 24-h DPG amplitude, consistent with dampened circadian temperature modulation. We further predicted that pre-sleep heat-loss dynamics would differ with respect to habitual napping: specifically, habitual older nappers would exhibit altered (and possibly attenuated) increases in DPG from before sleep onset and consequently shorter sleep-onset latencies during sleep opportunities.

Study 3 investigates whether a 12-month behavioural intervention to suppress daytime napping in habitual older nappers can stabilise circadian sleep-wake organisation, as assessed by actimetry. As previous work from the team highlighted a negative correlation between nap frequency and episodic memory performance (Reyt et al., 2022), we further wanted to assess whether this nap-suppression would attenuate age-related decline in episodic memory, relative to non-nappers and to habitual nappers who continued napping over the same period. We hypothesised that participants coached to reduce their nap habit would show

sustained decreases in daytime nap frequency and duration, as verified by actimetry. Those same participants would be expected to exhibit smaller decline in episodic performance, more specifically a maintained autonomic retrieval strategy, as compared to habitual nappers who continued napping over one year.

In the same vein, we build on cross-sectional findings from our team showing a decreased WM performance at highest task level and underlying dedifferentiation in activation profile (Reyt et al., 2025). In this context, **Study 4** evaluates whether the same one-year nap-suppression intervention in habitual older nappers mitigate WM decline and normalises task-related brain activity. We hypothesised that continued nappers would show a steeper drop in accuracy, particularly at higher working memory loads. alongside dorsolateral prefrontal cortex (DLPFC) fMRI-derived BOLD overactivation with reduced hemispheric asymmetry. As we previously observed that regular napping is associated with a heightened parietal activation relative to frontal regions, we further expected that increased and more bilateral recruitment across an extended set of working-memory regions would also be associated with continued napping, as well heightened thalamic engagement indexing wake-state instability. In contrast, nappers who substantially reduced daytime rest would exhibit behavioural trajectories comparable to non-nappers and retain (or regain) a positive association between left-DLPFC activation and working memory performance, indicating preserved compensatory efficiency.

Experimental part

Experimental protocol

We present here the experimental protocol and participants' pool used in studies 2 to 4, as those were based on the same bigger project. This thesis and the results presented herein derive from data collected within the framework of the study entitled "COGNAP: to nap or not to nap? - Why napping habits interfere with cognitive fitness in ageing" (ERC: COGNAP project-GA 757763). The aim of this project was to identify factors related to the sleep-wake cycle that protect against cognitive decline. More specifically, it sought to explore inter-individual variability in the temporal organisation of wakefulness and sleep during healthy ageing, through different nap phenotypes. The central hypothesis of this project was that habitual napping was both a cause and consequence of disrupted sleep-wake cycle regulation processes, including the circadian rhythm, and ultimately has negative repercussions on cognitive functioning as well as on brain structure. Following the cross-sectional characterization of circadian, cognitive and brain processes, the project also included an interventional component aimed at restoring a consolidated sleep-wake cycle via an intervention consisting of the reduction of habitual naps. Finally, a longitudinal component was also added, to assess the age-related trajectories in terms of cognition and brain function. Study 1 explored another cohort with ambulatory data: all details regarding the participant sample and protocols will be detailed in the study presentation itself.

A total of seven hundred and seventy-three community-dwelling adults aged above 60 years old were initially contacted for the COGNAP Project. Recruitment spanned diverse socio-economic backgrounds and was conducted via newspaper and radio advertisements, university channels, and GDPR-compliant databases available within the research unit. All volunteers were retired and living at home. Following eligibility screening and classification based on self-reported napping behaviour, 94 participants (59 to 81 years old, mean age = 68.8 years, SD = 5.5) were prospectively enrolled. Our sample size (and group allocation) were determined through a priori power calculations based on previously reported effect sizes for

circadian (Münch et al., 2005), cognitive (Donohue et al., 2014; Oosterman et al., 2009; Rönnlund et al., 2005; Sperling et al., 2014), and brain measures (Raz et al., 2005) in ageing, indicating that 87 participants (29 per group) would provide 80% power after accounting for attrition.

General exclusion criteria comprised a current or past history of neurological, psychiatric, or other medical conditions known to affect cognition or sleep-wake regulation, chronic medication use and substance dependency, and a Body Mass Index (BMI) > 29. Cognitive impairment was screened using the Mini-Mental State Examination (MMSE; cut-off < 27; Folstein et al., 1975) and the Mattis Dementia Rating scale (MDR; cut-off < 130; Lucas et al., 1998): participants scoring below these thresholds were excluded. Sleep disorders were assessed during a screening polysomnography (PSG) night. Individuals with an apnoea-hypopnoea index > 10 events/hour or periodic limb movements of sleep with associated arousals > 10/hour were also excluded. Additional exclusion criteria included moderate-to-severe depression (Beck Depression Inventory [BDI-II] > 19; Beck & Steer, 1984), severe anxiety (Beck Anxiety Inventory [BAI] > 30; Beck et al., 1988), history of diabetes, smoking, excessive caffeine intake (> 4 cups/day), excessive alcohol consumption (> 14 units/week), other drug use, and travel across more than one time zone within the three months preceding study entry. Participants receiving stable treatment (> 6 months) for hypertension and/or hypothyroidism were eligible.

From this eligible pool of 94 participants, 32 participants reported to not or only occasionally nap (non-nap group), and 64 individuals reported to nap regularly ($\geq$ 3 naps/week, each > 30 minutes, for at least one year). Groups were matched for age, sex, BMI, perceived night-time sleep quality (Pittsburgh Sleep Quality Index (PSQI); Buysse et al., 1989), Morningness-eveningness type questionnaire (MEQ; Horne & Ostberg, 1976) and season of assessment. The study covered all seasons of the year and took place from August 2018 to November 2021.

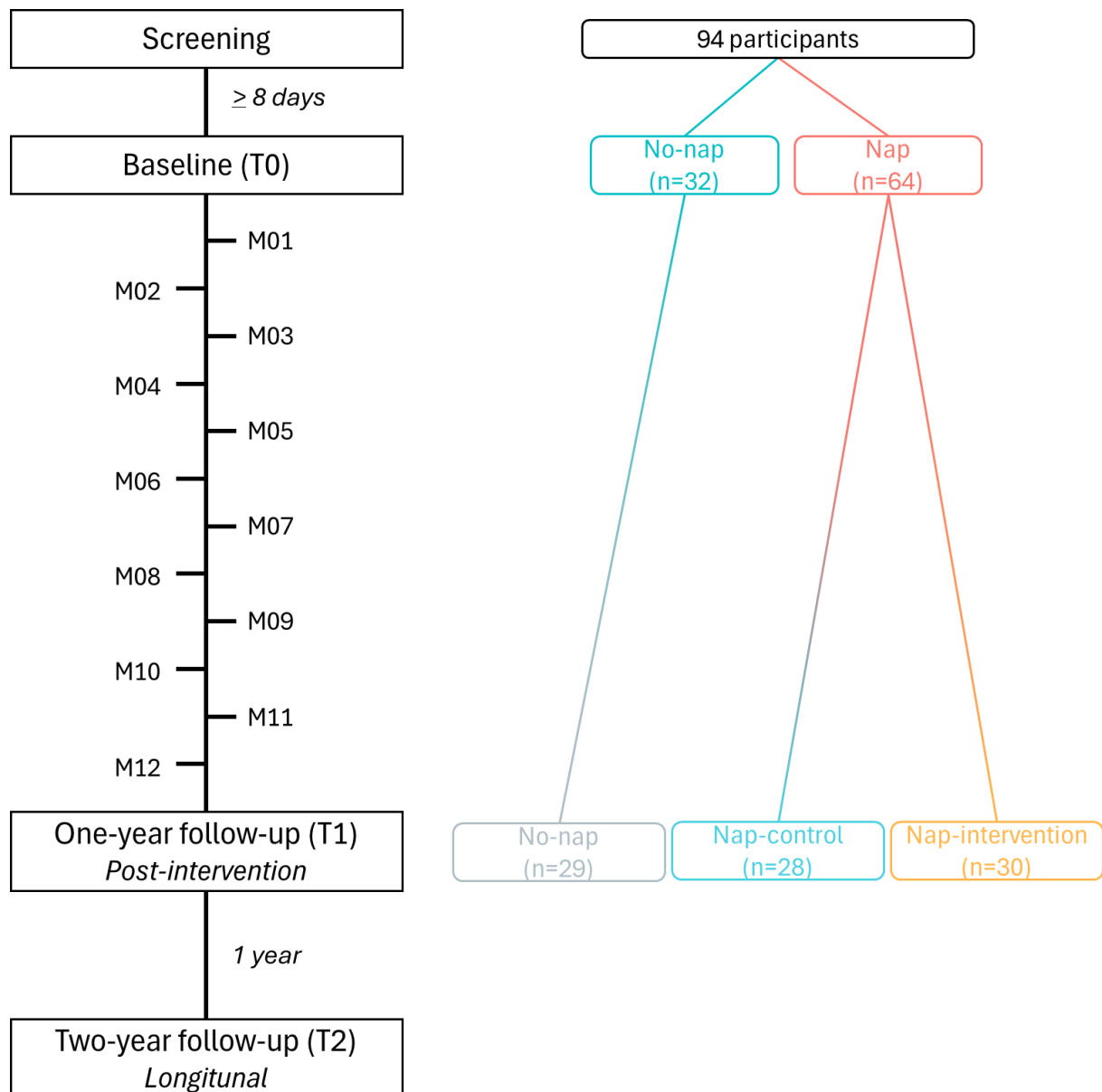


Figure 17. COGNAP study protocol.

During the first **screening** visit (Figure 17), the study procedures were explained, eligibility questionnaires were completed, and written informed consent was obtained (local Ethics Committee of the University Hospital and of the Faculty of Psychology, Speech Therapy and Educational Sciences at the University of Liège; n° B707201733554, ref 2017/211). Participants were then provided with a wrist-worn actigraph and instructed to follow their usual routines without any constraints on bed- or wake-times (“free-living” actigraphy) to characterise their rest-activity rhythm. After a minimum of eight days of actigraphy, participants

came to the laboratory for a habituation night, serving two purposes: first, to exclude individuals with undiagnosed sleep disorders, and secondly to familiarise participants with the sleep environment so that subsequent sleep measurements would be less affected by the “first-night effect”.

The following morning, participants entered the **baseline** part of the protocol, also called T0. A 3T structural MRI scan (Magnetom Prisma, Siemens Medical Solutions, Erlangen, Germany) was acquired, including sequences enabling diffusion imaging and the assessment of hippocampal integrity, as well as white- and grey-matter integrity. Participants were then asked to wear the actigraph for an additional week (7-15 days, mean : 13.58 days, SD: 1.81) while adhering to fixed and self-selected bed- and wake-times, to ensure adequate sleep duration and stable circadian entrainment. Night-time sleep timing was individually adapted and centred on an 8-h sleep opportunity. No specific instruction was given with respect to napping. Compliance with the night-time sleep schedule was verified by actigraphy and sleep diary recordings. Alcohol and caffeine consumption during this week was prohibited to prevent any withdrawal effects during the stay. Upon their return to the laboratory, participants completed a comprehensive cognitive test battery and underwent a 3T functional MRI session. This comprised a resting-state acquisition followed by BOLD activity recording during a working-memory task (Sternberg paradigm). Participants were subsequently prepared for the baseline night, which preceded circadian assessment.

A 40-hour multiple-nap protocol conducted under constant-routine conditions (Figure 18) was used to examine each participant’s circadian rhythm modulation. Ambient light was maintained between 4.5 and 5 lux during wakefulness (0 lux during sleep opportunities), room temperature at 19 °C, and posture was controlled (semi-recumbent during wakefulness except for scheduled bathroom visits). Isocaloric meals were provided at regular intervals, all external time cues were removed (no windows, clocks, phones or watches), and social interactions were kept to a minimum. Circadian assessment comprised ten alternating cycles, each consisting of 80 minutes of scheduled sleep opportunities followed by 160

minutes of wakefulness. The first sleep opportunity started 130 minutes after the scheduled wake-up time from the baseline night. Wakefulness in the last cycle was limited to 40 min to allow the 8-hour recovery night to start at habitual bedtime. Continuous polysomnography was recorded to quantify sleep propensity across the 24-hour cycle, including electroencephalography (EEG, seven sets : Fz, Cz, C3, C4, Pz, Oz, O2), electrooculograms (EOG), electromyograms (EMG) and electrocardiograms (ECG). Actigraphy and skin temperature were also continuously monitored. During wake periods, participants completed hourly subjective ratings of sleepiness (KSS) and mood (VAS) and performed cognitive tasks targeting working memory (N-Back task) and vigilance (PVT) around the midpoint of each wake period. Salivary melatonin samples were also collected hourly during wakefulness. Quiet activities such as reading, listening to music, or watching films were permitted to help maintain wakefulness. In addition, continuous video monitoring enabled experimenters to detect signs of drowsiness and prevent unintended sleep, as well as physical exercise or standing up.

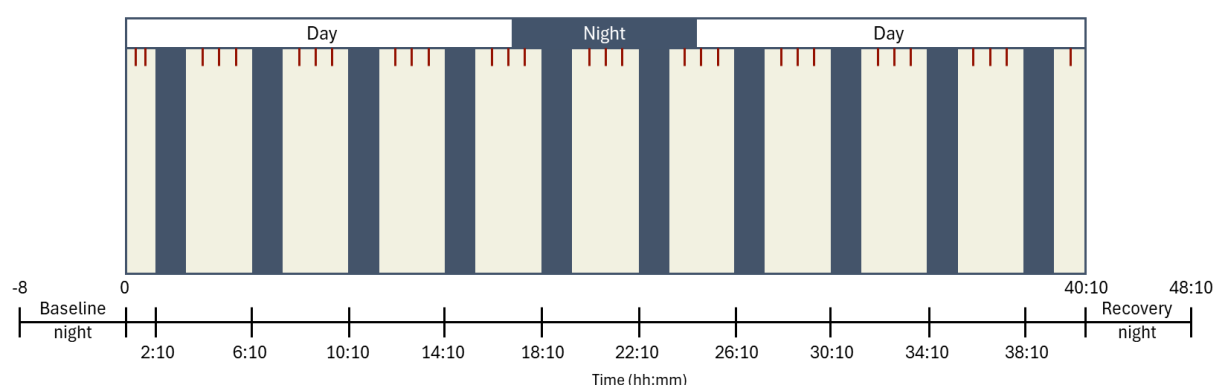


Figure 18. Graphical representation of the multiple-nap protocol, with dark blue panels representing the scheduled sleep opportunities of 80 minutes, and the yellow panels representing the scheduled 160 minutes wakefulness periods. Red vertical lines represent time-points at which subjective sleepiness and mood ratings, as well as salivary melatonin, were collected. Time elapsed since start of the protocol (end of baseline night) is depicted on the x-axis.

After the multiple-nap protocol, a minimum of a 4-day washout period was imposed to permit re-stabilisation of the sleep-wake cycle prior to subsequent assessments. A second visit within the baseline assessment part of the study was then organised to administer a second cognitive test battery. The full set of cognitive assessments enabled the computation of composite scores indexing

attentional capacity, memory, and executive functions. To minimise confounding effects of time of day on cognitive performance, the cognitive evaluations were predominantly scheduled between 13:30 and 17:00.

This last baseline session was followed by a sleep-education intervention, which both provided guidance on improving sleep hygiene and served to allocate participants to the interventional phase of the study. Indeed, during the screening phase, approximately twice as many habitual nappers as non-nappers were recruited to permit a subsequent random allocation of nappers into two interventional arms. At this point in time, regular nappers were randomly assigned to either a nap-control group or a nap-intervention group (Figure 18). All participants, including non-nappers, received a structured sleep-education session grounded in cognitive-behavioural therapy principles for insomnia (Heyde et al., 2018). For the intervention group, this session additionally introduced the requirement to discontinue napping: participants in this group were instructed to markedly reduce (frequency and/or duration) and ultimately eliminate naps, using a progressive decrease over the first four weeks.

Following this somno-education session, all individuals were followed for one year (M01 to M12, Figure 18). Throughout this period, wrist actigraphy was worn continuously under free-living conditions to track the stability or change in sleep-wake cycles, daytime rest behaviour, and compliance with recommendations. Experimenters contacted participants weekly during the initial month and monthly thereafter to download actimetric data, support behavioural adjustments, and reinforce compliance. Lifestyle factors (timing/amount of physical activity, caffeine and alcohol intake) were also reviewed monthly to document concomitant changes. Participants in the nap-control and non-nap groups were similarly monitored with actigraphy and contacted regularly to report lifestyle changes and complete questionnaires, but no behavioural manipulation was imposed.

At the end of the **one-year follow-up (T1)**, all participants returned to the laboratory. They completed, over 2 visits again, the same neuropsychological

battery targeting episodic memory, attention, and executive functions, underwent an anatomical and functional MRI scan, and repeated the baseline questionnaires. Participants in the nap-intervention arm were additionally invited to repeat the multiple-nap constant-routine protocol to examine potential changes in markers of circadian sleep regulation pre- versus post-intervention.

Finally, all participants were seen again at the **two-year follow-up (T2)**, equating to two years after the baseline phase. During the year post-interventional phase, participants were not contacted nor monitored in any way before the two visits. During this follow-up, they repeated the full cognitive battery, questionnaires, structural and functional MRI acquisitions, as well as a 2-week-long actigraphy recording to assess the sleep-wake cycle evolution and daytime napping characteristics.

Study 1. Uncorrelated age-related changes in visuo-spatial working memory binding and thermoregulation

Marine Dourte ^{1,2,3}, Gregory Hammad ¹,
Christina Schmidt^{1,2}, Philippe Peigneux ^{1,3}

¹ Sleep and Chronobiology Laboratory, GIGA-CRC Human Imaging Unit, University of Liège, Liège, Belgium.

² Psychology and Neuroscience of Cognition Research Unit (PsyNCog), Faculty of Psychology and Educational Sciences, University of Liège, Liège, Belgium.

³ UR2NF, Neuropsychology and Functional Neuroimaging Research Unit, affiliated at Center for Research in Cognition and Neurosciences and ULB Neurosciences Institute, Université Libre de Bruxelles (ULB), Brussels, Belgium.

Published in *Clocks & Sleep*, 2025, 7(2), 17;
<https://doi.org/10.3390/clockssleep7020017>

Abstract: Ageing is associated with alterations in circadian rhythms and thermoregulation, contributing to a fragmentation of the sleep-wake cycle and possibly age-related changes in cognitive performance. In this study, we investigated the relationship between visuo-spatial working memory (vsWM) performance and thermoregulation in young (18-34 years) and old (64-84 years) healthy human adults. Variations in the distal-proximal skin temperature gradient (DPG) were continuously monitored over the 24-hour cycle in a field setting. vsWM was assessed during morning (09:00) and evening sessions (17:00) using an object-location binding task. As expected, a reduced circadian DPG amplitude was observed in old as compared to young participants. Likewise, old participants produced more errors than the young ones in object identification and location, suggesting reduced vsWM ability. Notwithstanding, no significant association was found between circadian DPG modulation and vsWM performance, nor between testing time-of-day and cognitive performance. Further research is needed to explore environmental factors and the timing of peak circadian rhythms to better understand the interplay between circadian biology and cognitive ageing.

Keywords: circadian rhythms; visuo-spatial working memory; ageing; thermoregulation; distal-proximal gradient (DPG); cognitive performance

1. Introduction

Circadian rhythms evolve across the human lifespan (Cajochen et al., 2006; Duffy et al., 2015; Hofman & Swaab, 2006). Amongst other changes, ageing has been associated with lower heat production and conservation, impaired heat loss, and reduced thermal sensitivity (Degroot & Kenney, 2007; Martinez-Nicolas et al., 2018; Van Someren, 2007). These alterations have been suggested to contribute to the classically observed phase advance and reduced circadian amplitude of the core body temperature (CBT), but also to overall increased daytime distal skin temperature (Martinez-Nicolas et al., 2018). The distal-proximal gradient (DPG; computed as the subtraction of the mean proximal skin temperature from the mean distal skin temperature) that indirectly accounts for heat redistribution from the core to the periphery and daily dynamics in thermoregulation is viewed as a sensitive marker for circadian phase and amplitude in humans (Hasselberg et al., 2013; Kräuchi et al., 1999; Longato et al., 2017; van Marken Lichtenbelt et al., 2006). Indeed, circadian modulation of proximal skin temperature was positively linked to that of CBT, while the circadian rhythms of distal skin temperature was inversely correlated to the CBT circadian modulation (Gradisar & Lack, 2004; Kräuchi, Knoblauch, et al., 2006). DPG therefore exhibits a circadian modulation throughout the sleep-wake cycle. While an increase in skin temperature is associated with faster sleep onset and heightened sleepiness (Gradisar & Lack, 2004; Kräuchi, Knoblauch, et al., 2006; Raymann et al., 2007), some studies show that its circadian modulation is partially unaffected by the homeostatic build-up of sleep pressure (Fronczek et al., 2006; Kräuchi, Knoblauch, et al., 2006). Instead, it serves as a signal to the brain, indicating readiness for sleep (Gradisar & Lack, 2004; Martinez-Nicolas et al., 2017). This makes DPG a convenient, non-invasive way to explore circadian organisation in individuals (Hasselberg et al., 2013; Longato et al., 2017; Martinez-Nicolas et al., 2018).

Ageing is characterised by changes in physiological and behavioural parameters that can in turn exert a detrimental effect on cognitive performance (Schmidt & Collette, 2016; Weinert & Waterhouse, 2007). In the memory domain, visuo-spatial

working memory (vsWM; that allows temporary maintenance of visual information while the direct input is lacking) was shown to be affected by age (Babcock & Salthouse, 1990; Gazzaley et al., 2005; W. Johnson et al., 2010; Jost et al., 2011; Reuter-Lorenz & Sylvester, 2005). Furthermore, time of day, i.e. a circadian effect, was found to modulate these age-related changes (Murman, 2015). It is assumed that the identity and the location of a target stimulus are separately stored for short amounts of time in vsWM, and that the final visual representation is achieved by the process of binding these two different elements (Sala & Courtney, 2009; Wood, 2011). While some studies found the binding process to be unaffected by age in healthy individuals (Della Sala et al., 2012; Parra et al., 2009; Parra et al., 2010), others reported an age-related decline (Della Sala et al., 2012; Martinez-Nicolas et al., 2017; Schmidt & Collette, 2016; Weinert & Waterhouse, 2007). Binding was even proposed as one of the first processes to decline in the early stages of pathological ageing such as in Alzheimer's disease (Parra et al., 2009).

Associations have been reported between global working memory performance and daily CBT oscillations (Burke et al., 2015; M. P. Johnson et al., 1992; Lewandowska et al., 2018; J. C. Lo et al., 2012; Schmidt, Peigneux, & Cajochen, 2012; R. West et al., 2002) as well as the homeostatic buildup and dissipation of sleep pressure (Burke et al., 2015). Daily modulation of performance was found to parallel the CBT curve and inversely mirror DPG (Burke et al., 2015; Heyde et al., 2018; M. P. Johnson et al., 1992; Reichert et al., 2017; Santhi et al., 2016). Indeed, performance on cognitive tasks is positively correlated with body temperature, being highest during the biological day when CBT is at its peak and DPG at its trough. An increase of just $\sim 0.15^{\circ}\text{C}$ has been associated with significant improvements in cognitive performance and alertness, indicating that even small changes in temperature may be associated with cognitive benefits (Van Someren, 2007; Wright et al., 2002). Furthermore, tasks with a high cognitive load, such as those requiring sustained attention or working memory, seem to be more affected by body temperature changes than simpler reaction-time tasks (Wright et al., 2002).

In this study, we investigated the association between visuo-spatial binding performance in working memory, circadian DPG modulation and time of day in groups of healthy old and young individuals. We hypothesised a reduced amplitude of the 24-hour modulation of DPG in healthy old participants, concomitantly with a poorer performance in the visuo-spatial binding task, as compared to young participants. We further assumed that vsWM performance would be linked to DPG measures during testing times, with a higher DPG being linked to better performance. Furthermore, we speculated that differences in vsWM performance between morning and evening assessments would correlate with DPG differences.

2. Results

2.1. vsWM task

2.1.1. Identification performance

The proportion of correctly identified targets in each group is depicted Figure 1A. The analysis highlighted main effects of maintenance Delay ($F=26.55$, $p<.001$, $\eta^2=.019$) and number of Items ($F=156.63$, $p<.001$, $\eta^2=.198$), identification accuracy being poorer with a longer maintenance delay and a higher number of items. The Delay*number of Items interaction effect was significant ($F=34.58$, $p<.001$, $\eta^2=.039$); post-hoc tests showed that long delays and more items lead to poorest performance ($t_{279}=-10.84$, $p<.001$). Additionally, there was a main Group effect ($F=64.28$, $p<.001$, $\eta^2=.075$) with overall poorer accuracy in old than young participants. Finally, the Group*number of Items interaction was significant ($F=36.58$, $p<.001$, $\eta^2=.028$); post-hoc tests indicate that keeping more items in vsWS impact more old than young participants ($t=-5.68$, $p<.001$). Main Time-of-Testing ($F=.033$, $p=.57$, $\eta^2<.01$) and Group*Time-of-Testing ($F=3.32$, $p=.07$, $\eta^2<.01$) effects were non-significant. Identification performance by Time-of-Testing and Group is depicted Figure 1E.

2.1.2. Absolute location error

Absolute location errors per group are depicted Figure 1B. Main effects of maintenance Delay ($F=66.53$, $p<.001$, $\eta^2=.040$) and number of Items ($F=339.81$, $p<.001$, $\eta^2=.321$), and their interaction ($F=43.74$, $p<.001$, $\eta^2=.019$), were significant. Post-hoc tests showed poorer performance at longer delays ($t=8.25$, $p<.001$) and with a higher number of items displayed ($t=-18.40$, $p<.001$), as well as the combination of the two ($t=17.20$, $p<.001$). Old participants produced more location errors than young participants (main Group effect, $F=295.90$, $p<.001$, $\eta^2=.250$). Significant interactions were observed between Group and Delay ($F=12.887$, $p<.001$, $\eta^2=.008$), as well as Group and Number of Items ($F=98.444$, $p<.001$, $\eta^2=.057$). Old participants did more errors than young participants at both increased Delay ($t=12.97$, $p<.001$) and Number of Items ($t=12.38$, $p<.001$). There was no main Time-of-Testing ($F=.089$, $p=.77$, $\eta^2<.01$) nor Group*Time-of-Testing interaction ($F=.036$, $p=.85$, $\eta^2<.01$) effects. Absolute location error by Time-of-Testing and Group is depicted Figure 1F.

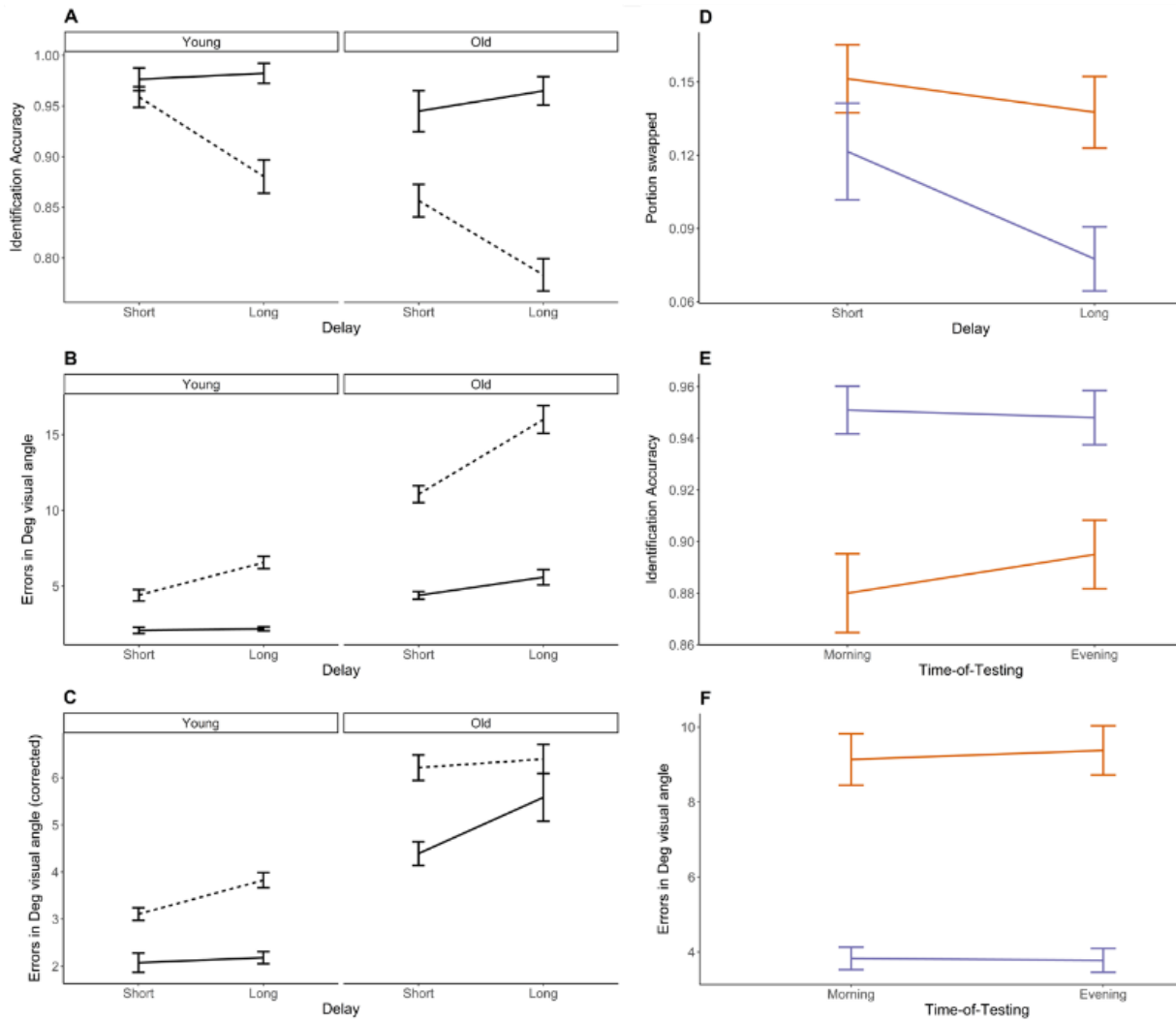


Figure 1. Performance at the Visuospatial object-binding task in old and young participants. (A,E) Identification accuracy (percentage); (B,F) Location errors (visual angle degree); (C) NIC, i.e., location error controlled for object-location swapping; (D) proportion of swap errors. Left panel: number of items are depicted in full lines for 1 item, and in dashed lines for 3 items. Right panel: old participants are depicted in orange, and young participants in purple. Individual datapoints are depicted for the older group in Figure S1 of Supplementals.

2.1.3. Location error controlling for swap errors

A main Group effect was observed for the number of swap errors ($F=11.97$, $p<.001$, $\eta^2=.054$), but the interaction with maintenance Delay (Group*Delay, $F=.64$, $p=.43$, $\eta^2=.006$) or Time-of-Testing (Group*Time-of-Testing, $F=2.72$, $p=.10$, $\eta^2=.009$) were non-significant. Old individuals committed more swap errors than young participants. Time-of-Testing ($F=.001$, $p=.97$, $\eta^2=.001$) and Delay ($F=2.96$, $p=.09$, $\eta^2=.020$) did not significantly affect swap errors. Location errors controlled for object-location swaps (NIC) are depicted Figure 1C, and the number of swap errors per group and maintenance delay are shown Figure 1D.

When location errors were controlled for swap errors, the analysis disclosed main effects of Delay ($F=7.68$, $p=.006$, $\eta^2=.014$), Number of Items ($F=91.29$, $p<.001$, $\eta^2=.079$) and Group ($F=346.86$, $p<.001$, $\eta^2=.363$). Whereas old participants exhibited an overall higher error rate than the young participants, performance was not modulated by longer maintenance delay (Group*Delay interaction, $F=.20$, $p=.66$, $\eta^2<.01$) nor by a higher number of items (Group*Number of Item interaction, $F=.07$, $p=.79$, $\eta^2<.01$). Time-of-Testing ($F=.10$, $p=.75$, $\eta^2<.01$) and the interaction with the Group factor ($F=1.81$, $p=.18$, $\eta^2<.01$) were non-significant.

2.2. 24-hour time course of DPG levels

The 24-hour time course of the DPG by group is depicted in Figure 2. Analyses disclosed a main Time effect ($F=18.00$, $p<.001$, $\eta^2=.02$), indicating a DPG modulation over the 24-hour cycle. The main Group effect was not significant ($F=.14$, $p=.71$, $\eta^2<.01$) but there was a Group * Time interaction effect ($F=2.07$, $p<.001$, $\eta^2=.50$) indicating a differential DPG modulation throughout the 24-hour cycle between the two age groups. Both the Group*cosine function interaction ($t=4.719$, $p<.001$, $\beta=.339$) and the Group*sine function ($t=2.623$, $p=.009$, $\beta=.297$) were significant, substantiating a difference in DPG amplitude and phase over the course of the biological day, with old participants exhibiting a lower amplitude variation (1.03°C) than their young counterparts (1.73°C), as well as a 2° ($=8\text{min}$) phase advance (old participants: 37° ; young participants: 39°).

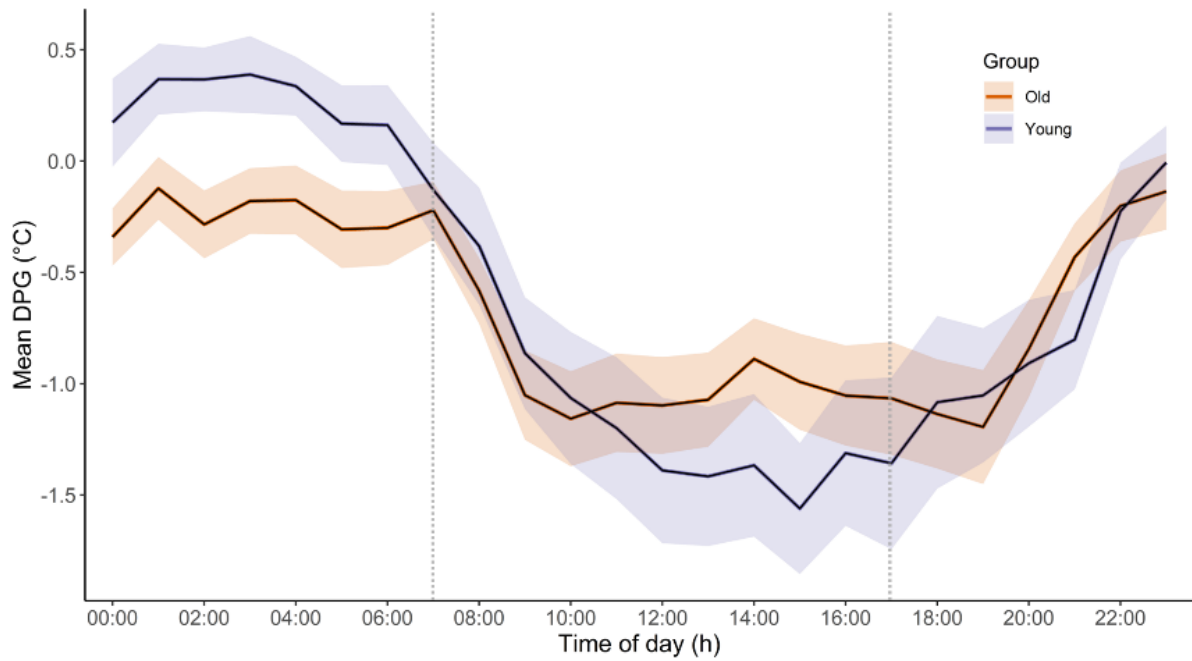


Figure 2. Time course of distal-proximal gradient (DPG) per Group (Old: orange; Young; purple) across the 24-hour cycle. SEM are displayed in shaded colour. Testing times are indicated by grey dotted vertical lines.

2.3. Link between DPG levels and working memory performance

Models investigating the influence of DPG measures during testing times on vsWM performance showed a significant Group effect for all vsWM parameters: identification performance ($t=2.439$; $p=.018$, $\eta^2=.003$), absolute location error ($t=-7.912$; $p<.001$, $\eta^2=.130$), number of swap errors ($t=-2.061$, $p=.044$, $\eta^2=.067$), and NIC ($t=-6.282$, $p<.001$, $\eta^2=.101$). However, when looking at the link regardless of testing times, we found no significant associations between DPG levels and identification performance ($t=.984$; $p=.33$, $\eta^2<.01$), absolute location error ($t=-.738$, $p=.46$, $\eta^2<.01$), number of swap errors ($t=-1.504$, $p=.14$, $\eta^2=.002$) and NIC ($t=-.738$, $p=.46$, $\eta^2<.01$). Moreover, no interaction was found between DPG and Group for identification performance ($t=-0.59$, $p=.55$, $\eta^2<.01$), absolute location error ($t=-.48$, $p=.64$, $\eta^2<.01$), number of swap errors ($t=-.46$, $p=.65$, $\eta^2<.01$), and NIC ($t=1.03$, $p=.31$, $\eta^2<.01$).

In a second step, Kendall's tau correlations were computed for each score between the morning-evening difference of vsWM performance and the morning-evening difference between DPG measures. No significant correlation emerged between

morning-evening differences of DPG and identification performance ($\tau=-.05$, $z=-.09$, $p=.39$), absolute location error ($\tau=.06$, $z=1.15$, $p=.25$), proportion of swap errors ($\tau=.02$, $z=.24$, $p=.81$) and NIC performance ($\tau=.09$, $z=1.65$, $p=.10$). Of note, when looking at evening and morning evaluations separately, we found that the DPG level during evening assessments was significantly correlated with absolute location error ($\tau=.129$, $z=2.26$, $p=.024$) and NIC ($\tau=.113$, $z=1.98$, $p=.048$). There was also a trend towards a correlation between DPG level and absolute location error during morning assessment ($\tau=-.11$, $z=-1.87$, $p=.06$). All other vsWM measures were not significantly correlated with DPG levels, whatever the time of assessment (all $p_s > .10$).

3. Discussion

Our study aimed at investigating whether an age-related decline in spatial working memory (vsWM) and binding performance is linked to DPG levels assessed over the 24-h cycle. To do so, we continuously monitored proximal and distal body skin temperature using ambulatory thermal sensors and assessed vsWM performance using an object-location binding task at two different time points of the day (morning vs. evening).

First, we observed a circadian modulation of the DPG over the 24-hour cycle, in line with previous literature (Batinga et al., 2015; Harper et al., 2005; Kräuchi, 2010; Kräuchi & Wirz-Justice, 1994). We also found age-related differences in the amplitude of the DPG modulation, with old participants exhibiting a lower amplitude than their young counterparts. Although focusing on an indirect index of heat redistribution and not CBT itself, this reduction in amplitude aligns with existing evidence for age-associated alterations in circadian rhythm parameters, such as a phase advance and a reduced amplitude (Batinga et al., 2015; Cajochen et al., 2006; Harper et al., 2005; Hofman & Swaab, 2006; Van Someren et al., 1999). Additionally, our results indicate a satisfying reliability of temperature distal-proximal recordings obtained in home-based ecological conditions to assess the circadian modulation of skin temperature. Indeed, we observed a clear circadian

rhythmicity even though participants wore the device at home, with no constraints regarding heating or thermal exposure like in well-controlled laboratory conditions, confirming that skin temperature displays a strong endogenous component, despite the existence of multiple external influences (Kräuchi, Knoblauch, et al., 2006; Martinez-Nicolas et al., 2013).

Second, we found age-related differences in performance in the vsWM object-location binding task. Old participants exhibited poorer identification accuracy and an increased rate of absolute location errors. These findings are in line with prior research highlighting an age-related decline in vsWM (Babcock & Salthouse, 1990; Gazzaley et al., 2005; W. Johnson et al., 2010; Pertzov et al., 2015) (but see (Della Sala et al., 2012; M. Parra et al., 2009; M. A. Parra et al., 2010) for null results). We also found that the impact of factors such as a maintenance delay and number of items to process is more pronounced in old than young individuals, as previously reported (Pertzov et al., 2015). Aging is known to be associated with increasing inter-individual differences (Lupien & Wan, 2004; Rowe & Kahn, 1987), raising the question whether some of our old participants would exhibit more profound deficits either in thermoregulatory and/or working memory terms, with potential outliers skewing data distribution and the means. To address this concern, we display the data points of old participants for all cognitive factors in Supplementary Material Figure S1. Inspection of Figure S1 data shows that no subset of old individuals skewed the mean or were potential outliers, which might be explained by the fact that our old participants were carefully recruited and exhibited good parameters for their age (see Table 1), which may to some extent qualify them as successful ageing persons (Lupien & Wan, 2004; Rowe & Kahn, 1987) and reduce the inherent age-related variability. Therefore, these results emphasize the vulnerability of vsWM processes to age-related changes and task demands.

Despite the presence of age-related differences both at the cognitive and thermoregulatory levels, we did not observe significant associations between DPG modulation and cognitive performance suggesting that, at least within the constraints of our study, daily modulation of DPG levels does not translate into

variations in cognitive (vsWM) performance. Moreover, no performance difference between young and old participants was found between evening and morning evaluations. These results do not support previous literature showing that young adults tend to show better cognitive performance in the evening while old adults typically perform better in the morning due to their respective chronotype and higher alertness levels during those hours (Hicks et al., 2023; Schmidt et al., 2007; R. West et al., 2002). However, our old participants displayed a moderately morning chronotype, whereas our young group had a neutral chronotype, which might have diluted such effects, potentially shifting performance evenly across the circadian cycle. Additionally, and though it was not within the scope of this paper, it should be noted that sleep pressure affects cognitive performance differently in young and old adults. The latter exhibit a relative resilience to the effects of sleep buildup (Silva et al., 2010) whereas young adults proportionally exhibit greater cognitive impairments with higher sleep pressure (Blatter et al., 2006; Harrison & Horne, 1998). Hence, although it remains speculative, old adults may compensate performance during the evening, eventually not reducing much as compared to their morning evaluation, and young participants may suffer more from a higher sleep buildup in the evening, eventually counteracting their chronotype-driven preference for evening evaluations. It must also be mentioned that while circadian timing influences cognition, especially working memory and executive control, aligning testing times with individual sleep-wake schedules helps reducing chronotype-induced performance enhancement (Schmidt, Peigneux, Cajochen, et al., 2012). Following this line of reasoning, and knowing that even a small 0.15°C increase can be associated with improved cognitive performance (Wright et al., 2002), it might be that an absence of differences in the present study can be explained by the morning assessment: whereas young people would “suffer” from the testing moment not being aligned with their chronotype, performance would be compensated by the apparent higher DPG at this moment, favouring better performance. However, this could not be demonstrated with our current results.

A limitation of the current protocol is that the so-called morning and evening testing times were chosen to accommodate for acceptable hours to visit participants at home, leading to fixed hours (9am and 5pm) for the morning and evening testing schedules. Consequently, vsWM tests were performed according to time of day and not according to circadian phase. Additionally, this study relied solely on the distal-proximal skin temperature gradient, taking proximal temperature at the subclavicular level that cannot be equated to core body temperature (Boon et al., 2014; Kräuchi & Wirz-Justice, 1994). Still, proximal skin areas mainly contain capillaries with nutritive functions, with circadian time course of blood flow through these capillaries following the time course of core body temperature (Kräuchi, Knoblauch, et al., 2006); while distal skin temperature, mainly containing arterio-venous anastomoses, shows an inverse pattern (Kräuchi, 2007b). Although DPG can be used as an indirect index of heart redistribution from the core (Hasselberg et al., 2013; Longato et al., 2017), our results should be regarded with circumspection as they rely on proximal skin to distal skin temperature gradients. Moreover, we could not monitor the environmental temperature exposure of our participants during the 5-days recording. It may be speculated that old participants would tend to stay home more than young participants or seek warmer environments (Hoof & Hensen, 2006). Future ambulatory studies should investigate potential differences in thermal comfort behaviour in relation to DPG recordings, for such variables could impact thermoregulation processes. Indeed, a lower contrast in activity in daily life and less time spent outside, and thus a lower contrast of environmental temperature, may lead to lower thermoregulation differences and partly explain differences in the modulation of DPG amplitude between young and old people in our study (Martinez-Nicolas et al., 2014). However, given the correlative nature of this study, we can't generalize our results or draw any strong conclusions. Future research may benefit from a more comprehensive examination of these factors to elucidate the nuanced interplay between circadian rhythms, thermoregulation, and vsWM in ageing.

4. Materials & Methods

4.1. Sample

18 young (18-34 years) and 23 old (64-84 years) participants gave their written informed consent to participate in this study approved by the Psychology faculty advisory ethics committee of the Universite Libre de Bruxelles (agreement number #155/2020). Exclusion criteria were the presence or history of circadian, sleep or related disorders, insufficient uncorrected vision, extreme chronotype (MEQ < 31 or > 69, Horne & Ostberg, 1976) and poor self-reported quality of sleep on the past month (PSQI > 7, Buysse et al., 1989). Too short (<6 hours) or excessive (>11 hours for young, >9 hours for old participants) nocturnal sleep duration was also an exclusion criterion (Hirshkowitz et al., 2015). Young female participants were only tested during their follicular phase, and old women had to be out of the acute stage of menopause, to account for the impact that hormonal changes can have on both cognition and temperature regulation (F. C. Baker et al., 2019; F. C. Baker & Driver, 2007; Santhi et al., 2016). Demographic information and between-group differences are depicted Table 1.

	Young (n=18)	Old (n=23)	Statistics
Age	23.9 ± 3.96	72.5 ± 6.14	$W=418, p<.001$
Sex	13 women, 6 men	13 women, 9 men	$X^2=0.086, p=.769$
BMI	21.3 ± 5.63	26.6 ± 3.19	$W=357, p<.001$
Sleep quality (PSQI)	4.37 ± 1.64	3.96 ± 1.73	$W=184.5, p=.523$
Chronotype (MEQ)	51.5 ± 9.32	63 ± 7.13	$W=348, p<.001$
Wake-up time	07h53 ± 01h05	07h44 ± 01h01	$W=176, p=.817$
Sleep onset time	23h47 ± 01h47	22h43 ± 00h26	$W=47.5, p<.001$
Total sleep time	08h06 ± 01h27	09h01 ± 01h06	$W=258, p=.006$

Table 1. Demographic and questionnaire data by group (mean + standard deviation). BMI: body mass index; PSQI: Pittsburgh Sleep Quality Index; MEQ: Morningness-Eveningness Questionnaire.

4.2. Object-location binding task

The object-location binding task, created by Pertzov and colleagues (Pertzov et al., 2012, 2015), aims at investigating the binding process linking the identification and spatial components of presented items in visual working memory. As illustrated Figure 3, one or three abstract geometric stimuli (fractals) are presented at specific locations over the screen for one or three seconds, respectively. Then, after a short (1 sec) or a long (4 sec) delay, one of the presented fractals is shown again in the centre of the screen, together with a new, never presented fractal. Participants are instructed (a) to identify the previously presented fractal by selecting it with the mouse pointer, and then (b) to determine its original location by dragging it on its estimated position. When the choice is confirmed by pressing the spacebar, the next trial is initiated (Pertzov et al., 2015). After having completed a 10-trials practice block to ensure a correct understanding of the procedure, participants perform 100 trials in a row. To differentiate object identification from spatial location, 3 measures of performance are computed: (1) object identification, i.e., the number of correctly identified items divided by the total number of trials; (2) absolute location errors, i.e., the pixel distance between the reported location of the correctly identified object and its true, original location; and (3) nearest item control (NIC), i.e., a measure of precision in location that considers the possibility of "swap errors", where individuals correctly identify the fractal but mistakenly report it as being at the location of another item in the memory array. NIC is thus calculated as the distance between the chosen location and the location of the nearest fractal in the original memory array, regardless of whether it was the target item. NIC helps to assess how precisely people remember locations without being concerned about the identity of the items and can help understand location performance irrespective of item identity (Pertzov et al., 2015).

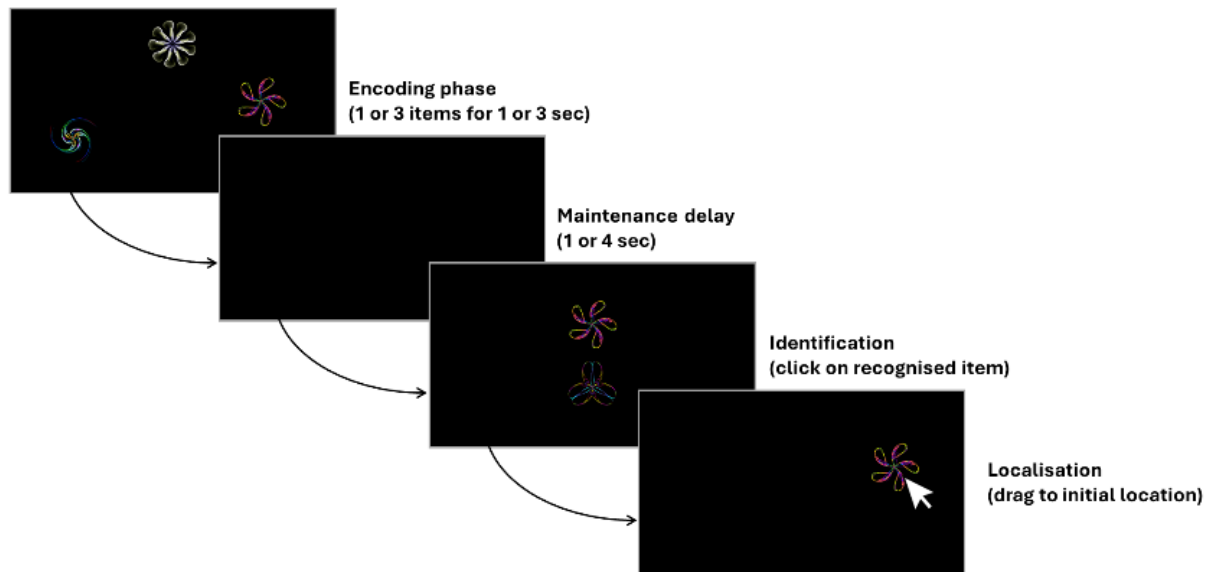


Figure 3. Sample procedure for a 3-item trial, adapted from Pertzov et al., 2015.

4.3. Thermometry

Small, flat thermal device probes (iButtons, Maxim/Dallas Semiconductor Corp., USA) were applied both to the subclavicular area (proximal skin temperature measurement) and to the wrist of the non-dominant hand (distal skin temperature measurement) using air-permeable plasters (Mefix®). Recording was obtained at a 0.0625°C resolution, averaged over each 300-second epoch. Individual raw recordings were visually inspected, and segments where captors were removed or malfunctioning were excluded from the analysis. The DPG value was obtained by subtracting proximal from distal skin temperature at each epoch, then averaged over 1-hour bins, resulting in 24 DPG points per day reflecting the heat redistribution from proximal skin, an indirect index of CBT (not obtained in this study), to periphery. These 24 points were then averaged across the 5 recording days to create a 24-hour profile per participant.

4.4. Experimental procedure

The experiment took place at the participants' home. They were instructed to wear the proximal and distal iButtons for 5 consecutive days (except for periods of extended water immersion, e.g., bath, or high physical impact activities).

Participants were given precise instructions on how to replace the probes in case of removal. They were also instructed to stick to a regular sleep-wake schedule with no major variations (± 1 hour from pre-selected schedule) and avoid naps. In addition, they were instructed not to consume alcohol, and energy drinks/food during the assessment. To facilitate data cleaning and monitoring, they were also asked to fill in a sleep calendar with their approximate wake-up and bedtimes, as well as the time and reasons for removing the sensors. On the last 2 days of the protocol, participants were administered the computerized object-location binding task (Pertzov et al., 2012). Testing was conducted at two different times of the day (9am and 5pm), the administration order being counterbalanced between participants. A schematic representation of the study protocol is depicted Figure 4.

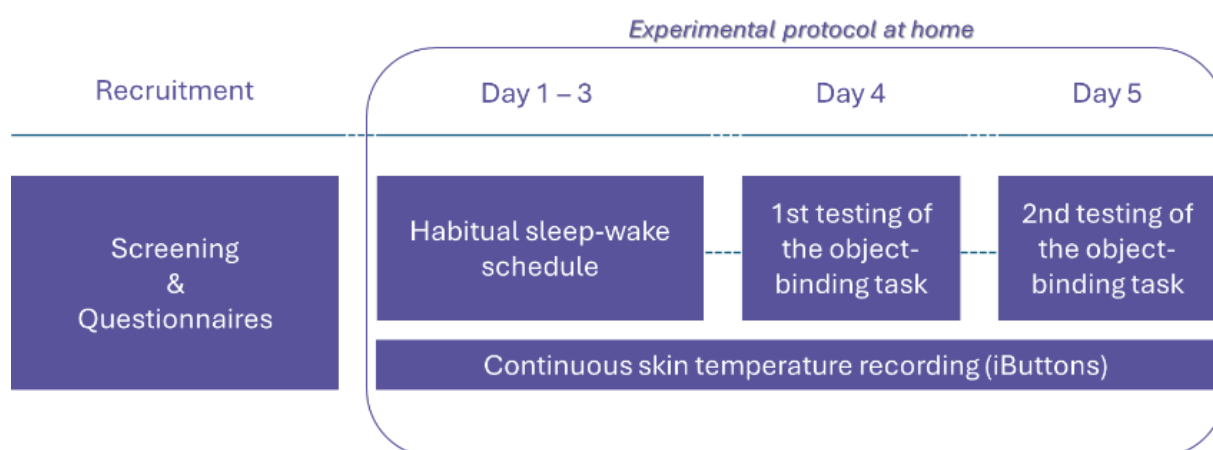


Figure 4. Summary of the study protocol taking place at the participants' home. Testing times for the object-binding task were either 9am or 5pm on two different days, counterbalanced.

4.5. Statistical Analysis

Analyses were conducted using the statistical software R-Studio (R Core Team, 2020), version 4.2.2. Regarding the object-location binding task, identification accuracy and absolute location errors were first analysed separately with the same statistical model, using an Aligned Rank Transform (ART) Anova (ART package, Wobbrock et al., 2011), to correct for the non-normal distribution of the data (all $p < .001$) and heteroscedasticity (all $p < .001$). Both models aimed at investigating the effects of the within-subject factors maintenance Delay (2-level factor, short vs

long), number of Items (2-level factor, 1 vs 3), and Time-of-Testing (2-level factor, morning vs evening), and the between-subject factors Group (2-level factor, young vs old), as well as their interactions. A similar ART Anova was conducted on swap errors with within-subjects factors maintenance Delay and Time-of-Testing, and the between-subject factors Group, and their interactions. Finally, the location error rate controlling for swap errors, or NIC (that can only be computed in the 3-items conditions), was analysed with the same model as for the swap errors. Post-hoc pairwise comparisons were conducted with contrasts adjusted using the Holm correction to account for multiple comparisons.

Concerning thermoregulation, we focused on the time course of skin temperature over the 24-hour cycle. DPG analysis was performed using a mixed-design Anova with between-subject factor Group (2-level, young vs. old), and within-subject factor Time (24 time bins). Group and time were defined as fixed effects and subject as random intercept. Body mass index (BMI) was added as a covariate as it was different between groups (see Table 1). Harmonic regressions were used to compare phase and amplitude of the 24-hour DPG modulation by group, based on the following model:

$$Y = \beta_0 + (\beta_1 + \beta_{\text{Group}1} * (\text{Group} == 1)) * \cos(2 * \pi * T / 24) + (\beta_2 + \beta_{\text{Group}2} * (\text{Group} == 1)) * \sin(2 * \pi * T / 24) + \beta_3 (t),$$

where Y is the dependent variable (DPG), β_0 is the mean response, β_1 and β_2 are the coefficient of the cosine and sine harmonics, $\beta_{\text{Group}1}$ and $\beta_{\text{Group}2}$ are the coefficients of the categorical variable Group, β_3 is the coefficient of the linear trend, T is the circadian period, set to 24h. The categorical variable Group is equal to 1 for old participants and 0 otherwise. From the model parameter estimates, we derived for each both amplitude ($A = \sqrt{[(\beta_1 + \beta_{\text{Group}1} * (\text{Group} == 1))]^2 + [(\beta_2 + \beta_{\text{Group}2} * (\text{Group} == 1))]^2}$) and phase ($\Phi = \text{atan2}(\beta_2, \beta_1) / (2 * \pi) * 360$), where atan2 is the 2-argument arctangent function, for each group.

To investigate the hypothesis that vsWM performance is linked to the DPG level at the time of testing, a linear model assessed the impact of Group (2-level, young vs

old) and DPG (continuous variable, as measured during computer testing, mean DPG level between start and end of the task) on performance (4 models: identification, location, swap errors, NIC). Finally, difference scores were computed for DPG and performance metrics to assess the correlation between DPG and performance changes between sessions. To do so, we computed a differential DPG between testing times by subtracting DPG during the morning test from the DPG during the evening test for each subject. The same calculation was applied to obtain the difference between evening and morning tests performance for identification accuracy, absolute location error and NIC. Kendall's correlations were used to assess the correlation between the two difference scores. Finally, Kendall's correlations were also applied to assess the link between DPG levels and cognitive performance (4 measures) during morning and evening sessions separately.

Study 2. The Impact of Napping Habits on the Relationship Between Thermoregulation and Sleep in Healthy Older Adults: a cross-sectional study

Marine Dourte^{1,2,3}, Gregory Hammad¹, Stella de Haan¹, Michele Deantoni¹, Mathilde Reyt^{1,2,4}, Marion Baillet⁵, Alexia Lesoinne¹, Vincenzo Muto¹, Philippe Peigneux³, Christian Cajochen⁶ Christina Schmidt^{1,2}

¹ GIGA-CRC Human Imaging Unit, Sleep and Chronobiology Laboratory , University of Liège, Liège, Belgium.

² Psychology and Neuroscience of Cognition Research Unit (PsyNCog), Faculty of Psychology and Educational Sciences, University of Liège, Liège, Belgium.

³ UR2NF, Neuropsychology and Functional Neuroimaging Research Unit, Center for Research in Cognition and Neurosciences, ULB Neurosciences Institute, Université Libre de Bruxelles (ULB), Brussels, Belgium.

⁴ Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal (CRIUGM) & Concordia University

⁵ Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA

⁶ Centre for Chronobiology, Psychiatric Hospital of the University of Basel, Basel, Switzerland.

Submitted and Under Review

Abstract : Thermoregulatory processes are closely linked to sleep initiation and maintenance throughout the circadian cycle. As such, these processes may facilitate, or protect, against the initiation of daytime napping, which increases with age. We aimed at exploring the association between napping habits on skin temperature-derived heat loss modulation and its association with sleep onset over the circadian cycle in healthy older adults. To do so, polysomnography-derived sleep onset latency and the distal-proximal skin temperature gradient (DPG) were recorded during a 40-h multiple-nap protocol in two groups of healthy older adults who self-reported as either regular nappers or non-nappers (30 regular nappers vs 28 non-nappers: age range 59-82 years, 30 female). We observed that nappers presented a significantly lower DPG in the wake periods surrounding the afternoon nap window (14:45 - 17:30). Furthermore, the classically observed evening rise in DPG occurred significantly earlier in nappers than in non-nappers. Finally, shorter sleep onset latencies over nap opportunities were associated with a faster DPG increase at lights-off in both groups, but the association was significantly stronger in non-nappers compared to nappers. The findings of our cross-sectional study indicate that napping in older adults is associated with altered thermoregulatory processes and, possibly, weakened associations between heat loss and sleep initiation processes. Our results may offer insights into which thermoregulatory processes contribute to sleep initiation over the circadian cycle with potential implications for managing sleep in older adults.

Keywords: Temperature; Distal proximal temperature gradient (DPG); Sleep onset latency; napping ; Ageing ; Circadian rhythms

1. Introduction

Thermoregulation is essential for facilitating sleep initiation, and the circadian distribution of sleep-wake states is tightly coupled to circadian body temperature modulation. Human sleep is typically initiated during the declining portion of the core body temperature (CBT) curve (Campbell et al., 1993; Czeisler et al., 1980; Dijk & Czeisler, 1994; Zulley & Campbell, 1984) and the concomitant increase in heat loss at the end of the day has been associated with increased ease to fall asleep (Kräuchi, 2007a; Kräuchi et al., 1999; Raymann et al., 2007).

Notably, regardless of timing, sleep is associated with changes in thermophysiology (Kräuchi, 2010). Indeed, when sleep is initiated outside of the usual nocturnal period by taking an afternoon nap, similar thermophysiological changes occur as seen before and during nocturnal sleep (Kräuchi, 2010). Conversely, sleep also contributes to the body's ability to regulate temperature, such that robust thermoregulatory effects can be induced by the relaxing aspect of sleep (Kräuchi, 2010). It is worth noting however, that thermophysiological effects occurring during sleep initiation can also be observed without falling asleep. Thermophysiological changes start directly after lights-off and even before sleep initiation (Kräuchi, 2010). Relaxation techniques induce a withdrawal in muscular and cutaneous sympathetic nerve activity leading to increased distal skin blood flow and temperature (Lushington et al., 2004; Recordati, 2003). Thus, distal vasodilatation, followed by a drop in CBT, appears to be a thermophysiological event, which is in part related to relaxing behaviour (Kräuchi, 2010).

In studies carried out under the constant routine protocol, distal skin temperatures of hands and feet exhibit an inverse circadian rhythm in comparison with CBT (Kräuchi, 2010). In contrast, proximal skin temperatures (e.g. clavicular area and/or trunk) follow CBT with similar amplitude (Kräuchi, 2010). The distal-proximal skin temperature gradient (DPG) provides a selective measure of distal skin blood flow, and of body heat loss via the extremities (Kräuchi et al., 1999). Notably, the dynamics of the DPG have previously been associated with sleep onset latency, sleep efficiency (Kräuchi, 2007a; Kräuchi et al., 1999; Raymann et al., 2007)

and sleepiness modulation (Kräuchi, Cajochen, et al., 2006). While the circadian CBT rhythm reaches its maximum in the early evening and its minimum in the early morning, DPG shows the reverse pattern, increasing during the subsequent declining phase of CBT (Gradisar & Lack, 2004; Kräuchi, 2002; Van Someren, 2000). As such, the DPG has been proposed as a reliable estimate for assessing circadian temperature modulation and its relationship with sleep-wake behaviour, reflecting body heat redistribution and the daily dynamics of thermoregulation (Hasselberg et al., 2013; Longato et al., 2017).

Ageing is known to be accompanied by lower metabolic heat production and retention, impaired heat loss mechanisms, as well as reduced thermal sensitivity (Degroot & Kenney, 2007; Martinez-Nicolas et al., 2018; Van Someren, 2007). Concomitantly, healthy ageing has been reported to go along with a phase advance, but also with reduced circadian amplitude, with CBT serving as one of its markers, in some (e.g., Czeisler et al., 1992; Dijk et al., 2000; Duffy et al., 1998), but not all (e.g., Buysse et al., 2005; Monk et al., 2000) studies. Notably, a delayed phase and a stronger, but highly variable, amplitude has been reported in patients suffering from Alzheimer's disease (Van Someren, 2002; Van Someren et al., 1999). This reflects the opposite of the advanced phase and flattened amplitude associated with normal ageing (Van Someren, 2002). Moreover, a phase advance (Batinga et al., 2015; Dittmar et al., 2024; Weiss et al., 1992) has been observed in older compared to younger individuals, together with an overall higher distal skin temperature (Batinga et al., 2015; Martinez-Nicolas et al., 2018), especially during daytime (also related to sleepiness levels (Martinez-Nicolas et al., 2017). Finally, older adults show an attenuated increase in distal skin temperature after lights-off. This relationship between pre-sleep heat-loss activation and sleep latency has been suggested to be weaker, compared to their younger counterparts (Raymann et al., 2007). The sensitivity of sleep propensity to enhanced distal skin temperature (e.g., through foot warming) has also been shown to change with age (Raymann et al., 2007).

Ageing is generally accompanied by changes in sleep. Advanced sleep timing, shortened nocturnal sleep duration, and an increase in frequency/duration of daytime naps, together with an increased number of nocturnal awakenings and time spent awake during the night, have been rather consistently reported with increasing age (J. Li, Vitiello, et al., 2018). From a circadian or thermophysiological perspective, daytime napping can be considered as “sleeping outside the temporal niche” or as an intrusion of sleep in the active daytime period. Regular daytime napping may then reflect a visible manifestation of altered circadian sleep regulation. Accordingly, we recently reported that, compared to self-reported non-nappers, healthy older regular nappers displayed reduced day-night differences in sleep efficiency (SE), Rapid Eye Movement (REM) sleep, and a reduced amplitude in the circadian modulation of melatonin secretion (Deantoni et al., 2024). These results provide first evidence of altered circadian sleep-wake regulation in older regular nappers. However, potential differences in thermophysiological dynamics and their association with day- and night-time sleep initiating processes has not yet been explored. The goal of this study was to examine how thermophysiological modulation across the 24-hour cycle differs between self-reported regular nappers and non-nappers, and how these differences relate to sleep initiation during scheduled sleep opportunities. To do so, the mean DPG was extracted over scheduled wake episodes of a 40-hour multiple nap protocol in healthy older self-reported nappers and non-nappers. We hypothesised that regular nappers would display an overall higher DPG over daytime wake episodes - as an index of increased readiness for sleep. Furthermore, in line with the previously observed reduced amplitude in melatonin expression, we expected to observe an overall reduced amplitude in DPG modulation over the 40-hour protocol in self-reported nappers compared to non-nappers. We further aimed at assessing overall daily dynamics of pre-sleep changes in the DPG dynamics by exploring the association between DPG changes from lights-off to sleep onset latency across sleep opportunities. We hypothesized that nappers would show altered pre-sleep heat

loss dynamics and/or facilitated sleep initiation during daytime sleep opportunities.

2. Methods

The manuscript was written in compliance with the use of the STROBE cross sectional reporting guidelines (von Elm et al., 2008).

2.1. Participants

Seven hundred and seventy-three individuals aged ≥ 60 years old were initially contacted. Recruitment covered a wide range of socio-economic classes and was performed via advertisement in newspapers, radio and university and by taking advantage of already existing GDPR-compliant databases at the research unit. Volunteers were retired and lived at home. Out of this sample, 94 individuals (mean : 68.8 years, std: 5.5 years) were prospectively included according to their self-reported nap habit behaviour and after an eligibility check. General exclusion criteria consisted of presence or history of neurological, psychiatric or other medical diseases affecting cognition or sleep-wake rhythms, chronic medication and addiction, and Body Mass Index (BMI) >29 . All participants were screened for cognitive impairment and excluded if scores were below the cut-off score for suspected dementia/mild cognitive impairment symptoms (Mini-Mental State Examination <27 , MMSE, (Folstein et al., 1975); and Mattis Dementia Rating scale <130 , MDR, (Lucas et al., 1998). Sleep disorders were assessed during a screening polysomnography (PSG) night. Volunteers with apnoea/hypopnoea index >10 /h or periodic limb movements of sleep associated with an arousal >10 /h were excluded. Additionally, other exclusion criteria were indicative of moderate or severe depression (Beck Depression Inventory [BDI-II] > 19 , Beck & Steer, 1984) or severe anxiety (Beck Anxiety Inventory [BAI] > 30 , Beck et al., 1988); history of diabetes, smoking, excessive caffeine intake (> 4 cups/day), excessive alcohol (> 14 units/week) or other drug consumption, and travelling more than one time zone in

the 3 months before the beginning of the study. Participants with stable treatment (> 6 months) for hypertension and/or hypothyroidism were included.

Out of the participant pool, a sample of 30 self-reported regular nappers (reporting to nap at least 3 times a week for more than 30 minutes and since at least one year, according to a nap-specific questionnaire, see supplemental Table S1) and 28 self-reported non-nappers, for whom thermometry and PSG-derived sleep variables were available. Differences in daytime rest characteristics were also verified using actimetry (see below). Groups were matched for age, sex, BMI, perceived nighttime sleep quality (Pittsburgh Sleep Quality Index (PSQI), (Buysse et al., 1989), Morningness-eveningness type questionnaire (MEQ, (Horne & Ostberg, 1976) and season of assessment. Demographic characteristics of the two groups are summarized in Table 1.

Sample size estimation ($n = 30$ per group) was based on previous literature reports on age-related effects in the circadian regulation of sleep and behavioural outcomes like those assessed here (Münch et al., 2005).

2.2. Study procedure

The study covered all seasons and took place from August 2018 to November 2021. After an eligibility check (questionnaires and interview), participants underwent a PSG night in the laboratory to screen for apnoea/hypopnea and periodic limb movements. They were then asked to wear a MotionWatch 8® actigraph (Cambridge Neurotechnology, Cambridge, UK) and to complete a sleep diary for a minimum of eight days (mean = 15 days 21:47, std = 4 days 03:24, max=21 days) while maintaining their usual routines at home, to assess daytime rest habits. These recordings were used to confirm the individual's nap phenotype according to the aforementioned predefined criteria.

The week preceding laboratory stay, participants were asked to adhere to a predefined sleep-wake schedule (8-h $\pm$ 30-min time in bed) to warrant adequate sleep and stable circadian entrainment upon participation. Night-time sleep timing was

individually adapted and centred on an 8-h sleep opportunity. No specific instruction was given with respect to napping. Compliance with the night-time sleep schedule was verified by actigraphy and sleep diary recordings. Alcohol and caffeine consumption during this week was prohibited to prevent any withdrawal effects during the stay. The experimental protocol in the laboratory began with a baseline night (8-hours, at habitual bedtime), followed by a 40-hour multiple nap protocol encompassing 10 short sleep-wake cycles of 80 min of sleep opportunity (i.e., nap) alternating with 160 min of wakefulness (Figure 1).

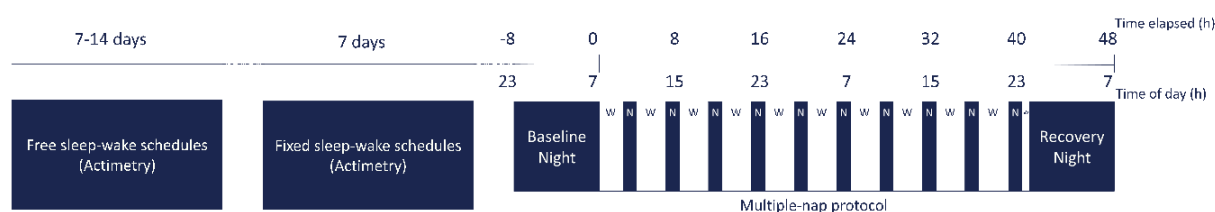


Figure 1. Schematic representation of the study protocol. The first blue box represents the 7-14 days of free sleep-wake schedules (mean:15days, std:4 days) recorded by actimetry, done at screening to verify participants' self-reported nap phenotype. The second blue box represents the fixed sleep-wake schedules, verified by actimetry, to ensure adequate sleep and stable circadian entrainment upon participation. The third box represents the multiple-nap protocol, with blue panels labelled "N" representing the scheduled sleep opportunities of 60 minutes, and the white panels labelled "W" representing the scheduled 165 minutes wakefulness periods. Time elapsed since start of the protocol (end of baseline night) is depicted in the upper x-axis, while average time of day is depicted in the lower x-axis.

The first nap opportunity started 130 minutes after the scheduled wake-up time from the baseline night. Wakefulness in the last cycle was limited to 40 min to allow the 8-hour recovery night to start at habitual bedtime. During the 56-hour stay in the laboratory, a series of environmental factors were controlled: light intensity (< 5 lux during scheduled wakefulness; <1 lux during scheduled sleep opportunities), isocaloric food intake (standardized meals every 4 h), ambient temperature (~19°C) and body posture (semi-recumbent position during scheduled wakefulness and recumbent position during nap opportunities, except for scheduled bathroom visits). Throughout the protocol, participants were unaware of the time of day and social interactions were kept to a minimum. Further details regarding other measurements of the study procedure can be found in (Reyt et al., 2022) and (Deantoni et al., 2024).

2.3. Actimetry

Rest bouts were identified from actimetry recordings as consolidated periods of low activity lasting between 15 minutes and 4-hours, occurring during the biological daytime, as defined in (Reyt et al., 2022). Daytime rest duration (overall mean duration of daytime rest bouts) and frequency (mean number of daytime rest bouts per day) were assessed based on actigraphy (Motionwatch 8, CamNtech, UK) monitoring at screening. Participants wore the device at the non-dominant wrist. Locomotor activity was downloaded using the Motionware software (Motionware 1.2.5, CamNtech, UK), reconstructed on the 3 axes, aggregated into 30-sec epochs and processed using the open-source software pyActigraphy (v1.0; (Hammad et al., 2021). The Munich Actimetry Sleep Detection Algorithm (MASDA; (Loock et al., 2021; Roenneberg et al., 2015) was used to automatically detect consolidated rest periods over daytime as defined in (Reyt et al., 2022).

2.4. Thermometry

Skin temperature was continuously recorded during the laboratory stay using iButtons® (Maxim/Dallas Semiconductor Corp., USA) sensors, with 300-s intervals and a 0.0625°C sensitivity. Sensors were fixed to bilateral distal (inner wrists and ankles) and proximal (subclavicular area) areas with thin air-permeable surgical tape (Hypafix®). Distal temperature was defined by the weighted mean of both locations, whereas proximal temperature was averaged between the two subclavicular probes. Raw recordings from every subject were visually inspected. Segments where captors were detached or malfunctioning were removed for analysis. The DPG was calculated from skin temperature values for each 5 minutes bins as the difference between mean distal temperature (4 probes) minus mean proximal skin temperature (2 probes).

Since napping can affect the amount and structure of sleep over the 24-hour cycle (Deantoni et al., 2024), and body temperature is affected by sleep propensity and structure (Dijk et al., 1999), we prioritized the extraction and analysis of skin temperature data from scheduled wake bouts over the protocol to test the first

hypothesis, that regular nappers would display an overall higher DPG than self-reported non-nappers while also showing altered daily modulation. The first 30 minutes of every wake episode were removed before computing the bins to account for the known confounding effects of sleep inertia on temperature modulation (Kräuchi et al., 2005). Similarly, data from the first 130-min wake-bout, following the baseline night, were removed from the analysis to account for possible temperature-related carry-over effects from night-time (baseline) sleep. Moreover, results from the same cohort indicate that participants enter the laboratory with cumulative sleep debt, despite adhering to a self-selected fixed sleep-wake schedule, which appears to dissipate after the first scheduled sleep-opportunities of the protocol (de Haan et al., 2025). This further justifies the exclusion of the first wake episode, as it likely reflects a transitional state influenced by both prior sleep pressure and residual nocturnal physiology.

Harmonic regressions were however computed on continuous DPG measures over wake bouts to assess the impact of napping on amplitude and phase (see statistical analysis section for further details).

Finally, to assess the link between DPG dynamics before sleep initiation, DPG slopes were extracted as the difference between DPG at lights-off to the last DPG measurement before the first epoch of any sleep stage, divided by time from lights-off to sleep onset.

2.5. Sleep parameters over nap sleep opportunities

PSG recordings were conducted during sleep opportunities over the protocol, using N7000 amplifiers (EMBLA, Natus Medical Incorporated, Planegg, Germany) with Ag/AgCl ring electrodes. The sampling rate was set at 500 Hz and signals were filtered online by applying a notch filter (50Hz). The montage consisted of seven EEG sets (Fz, Cz, C3, C4, Pz, Oz, O2), two electrooculograms, two electrocardiograms and two chin electromyograms. Sleep stages were automatically scored on 30-s epochs according to the American Academy of Sleep Medicine criteria (AASM, (Iber, 2007)) using a validated (Berthomier et al., 2020) sleep scoring algorithm ASEEGA

(ASEEGA, PHYSIP, Paris, France, (Berthomier et al., 2007)) that has been validated in healthy older adults (Chylinski et al., 2022) and used to score nap sleep (Deantoni et al., 2024). During each sleep opportunity, sleep onset latency (SOL) was computed as the duration from lights-off to the first epoch of any sleep stage. SE was extracted for each sleep opportunity (SE: sum of sleep stages 1,2,3 and REM sleep divided by total sleep opportunity, see supplemental Figure S1). Sleep data have been partly published in (Deantoni, Baillet, Hammad, et al., 2023; Deantoni, Reyt, Berthomier, et al., 2023; Deantoni et al., 2024).

2.6. Statistical analyses

All statistics were computed using the R-Studio software environment (4.2.2 version, R Core Team, 2020). Effect sizes were reported alongside p-values to provide an estimate of the magnitude of observed effects. For Wilcoxon rank-sum tests, effect sizes were expressed as rank-biserial correlations, calculated using the *rstatix* package (Kassambara, 2023). For analyses based on other models, partial eta squared (η^2) values were computed using type II sums of squares with the *effectsize* package (Ben-Shachar et al., 2020). Effect sizes were interpreted according to conventional benchmarks: small ($\eta^2 \approx 0.1$), medium ($\eta^2 \approx 0.06$), and large ($\eta^2 \geq 0.14$) (J. Cohen, 2013; Lakens, 2013).

Demographics (age, sex, BMI, season of assessment), sleep (chronotype, perceived sleep quality, periodic limb movement, sleep apnoea), sleepiness and daytime rest characteristics (duration and frequency) were compared between group using a Wilcoxon rank test or Chi-squared test.

To test the hypothesis of the nap group having an effect on DPG during scheduled wakefulness and its modulation over the protocol, we first computed a repeated measures analysis of variance using the DPG as dependent variable and by including the between-subject factor group (regular nappers vs. non-nappers) and the within-subject factor session (10 levels). The model included a random intercept for each subject to account for inter-individual variability. Separate models were also run for proximal and distal temperature measurements.

Furthermore, for all three models, SE from the preceding nap opportunity was added as a covariate. Post-hoc analyses were computed using Tukey tests.

Circadian phase and amplitude of DPG were compared between groups by using a harmonic regression model, including a linear trend and a random intercept (u_i) for each participant i as follows:

$$t_{ij} = (\beta_0 + u_i) + (\beta_1 + \beta^{\text{Nap}_1}(\text{Nap}==1)) * \cos(2\pi/T * (j/6*T)) + (\beta_2 + \beta^{\text{Nap}_2}(\text{Nap}==1)) * \sin(2\pi/T * (j/6*T)) + \beta_3 * j$$

where β_0 is the mean response, β_1 and β_2 are the coefficient of the cosine and sine harmonics, β^{Nap_1} and β^{Nap_2} are the coefficients of the categorical variable Nap, β_3 is the coefficient of the linear trend, T is the circadian period, set to 24h and j , an index running over the 10 sessions. The categorical variable Nap is equal to 1 for self-reported napping participants and 0 otherwise. Amplitude A and phase Φ were then derived from the model parameter estimates as: $A = \sqrt{(\beta_1 + \beta^{\text{Nap}_1} * (\text{Nap} == 1))^2 + (\beta_2 + \beta^{\text{Nap}_2} * (\text{Nap} == 1))^2}$ and $\Phi = \text{atan2}(\beta_2, \beta_1)$, where atan2 is the 2-argument arctangent function.

In a final step, to explore association between the DPG dynamics and sleep onset latency across nap sleep opportunities, linear models (*lmerTest* package, (Kuznetsova et al., 2017)) were used to test the association between SOL (dependent variable), DPG slope (continuous predictor), as well as group and session (categorical predictors). Subject was considered as a random factor in the model. As SOL can only be computed if one did sleep during a sleep opportunity, instances in which the participant did not sleep were not included in the analyses (Table S3).

3. Results

3.1. Demographics, sleep quality, sleepiness and actimetry-derived daytime rest characteristics

Self-reported nappers and non-nappers did not significantly differ with respect to age, biological sex, PSQI, MEQ, season of assessment, BMI scores, sleep apnoea and Periodic Limb Movement (PLMS) indices (all $p_s > .09$, see Table 1). However, daytime sleepiness prior to the protocol as assessed with the Epworth sleepiness scale (ESS, (Johns, 1991)) disclosed a statistical trend towards enhanced sleepiness in regular nappers compared to non-nappers (Wilcoxon rank sum test, $W = 286$, $p = .055$, $r = .25$). As expected, groups also differed in actimetry-derived daytime rest characteristics, such that self-reported regular nappers exhibited significantly higher daytime rest frequency (Wilcoxon rank sum test, $W = 117$, $p < .001$, $r = .62$) and duration ($W = 224$, $p = .002$, $r = .40$) than self-reported non-nappers.

3.2. Modulation of skin temperature and the distal-proximal gradient over wake bouts

The time course of DPG data over the 40-hours multiple nap protocol is depicted in Figure 2 (averaged over 15-min bins to improve visual clarity, see also supplemental Table S2 for mean values and standard deviations of the DPG over binned wake bouts and nap opportunities, according to session and group).

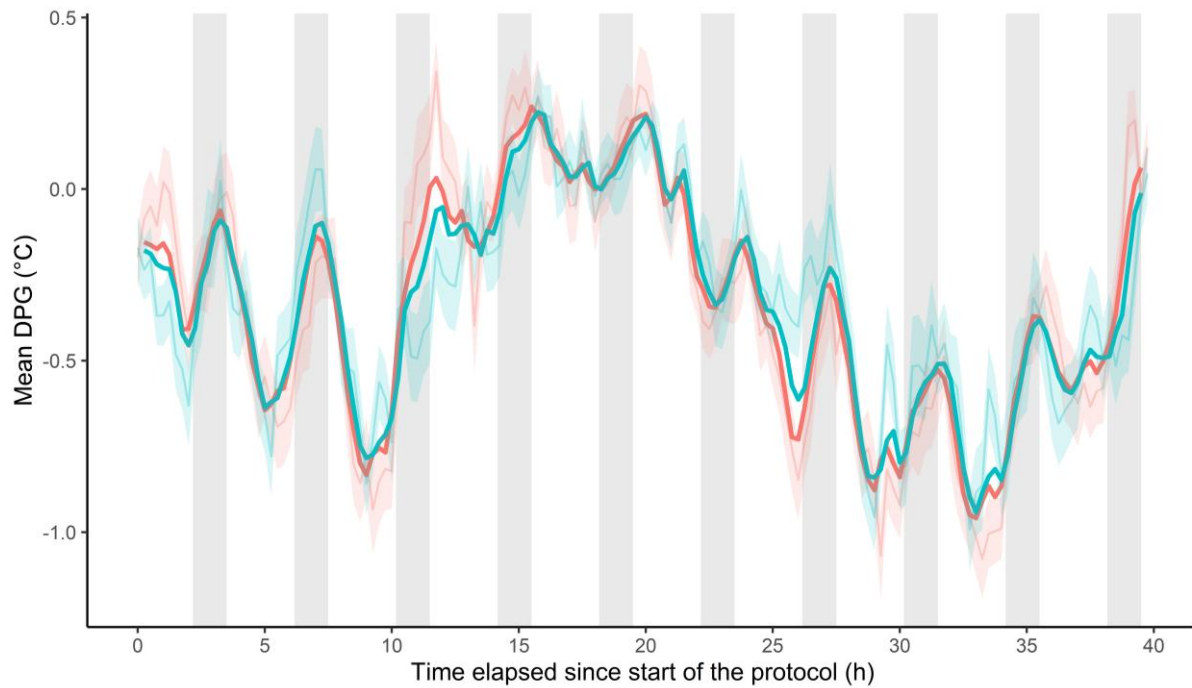


Figure 2. Temporal profile of DPG across the 40-hour protocol, per group (red = nappers; blue = non-nappers). Thin, semi-transparent lines represent DPG values averaged over 15-minute time bins. To enhance visual clarity while preserving data resolution, a running average was overlaid as bold solid lines. Shaded areas indicate the standard error of the mean (SEM), calculated across individual participant means within each time bin. Nap opportunities (N) are shown in grey, scheduled wake episodes (W) in white. Mean clock time is averaged across all participants.

For statistical analyses, the mean DPG was extracted over scheduled wake sessions of the nap protocol (wake bouts S2-S11, Figure 3). A main effect of session was detected ($F(9,556)=114.18, p<.001, \eta^2=.068$): a daily modulation as highlighted in previous studies under similar experimental conditions (Kräuchi, Knoblauch, et al., 2006) was observed (Figure 3). A main effect of group ($F(1,556)=7.576, p=.006, \eta^2<.01$) was also observed, with an overall lower wake DPG in self-reported regular nappers compared to non-nappers. Finally, a significant session*group interaction was observed ($F(9,556)=6.521, p<.001, \eta^2<.01$). Session-by-session comparisons indicated that nappers exhibited a significantly lower DPG than non-nappers during session 3 ($p_{adj}=.019$) and 9 ($p_{adj}=.003$), which occurred on average between 14:45 and 17:30 in the afternoon of the first and second protocol day, respectively (see Figure 2). Furthermore, the groups exhibited divergent patterns at the transition from day (session 4, 18:45-21:30) to the night-time (session 5, 22:45-01:30; see Figure 3) sessions: while the DPG during wake bouts significantly

increased in non-nappers from session 4 to 5 ($p_{adj} < .001$), this was not observed in nappers ($p_{adj} = .919$). In the nap group, the DPG rather significantly rose earlier in the evening during both protocol days (DPG increase from session 3 to 4, $p_{adj} < .001$, and from session 9 to 10, $p_{adj} < .001$). Note that the increase in the DPG from session 3 to session 4 was also significant for non-nappers ($p_{adj} < .001$), while this was not the case from session 9 to 10 ($p_{adj} = .56$). The post-hoc computation of the interaction term between session (3 and 4, specifically) and group revealed however that the increase was higher for nappers, compared to non-nappers ($p_{adj} < .001$). Self-reported nappers appeared thus to display a more pronounced DPG rise at earlier evening hours, compared to self-reported non-nappers.

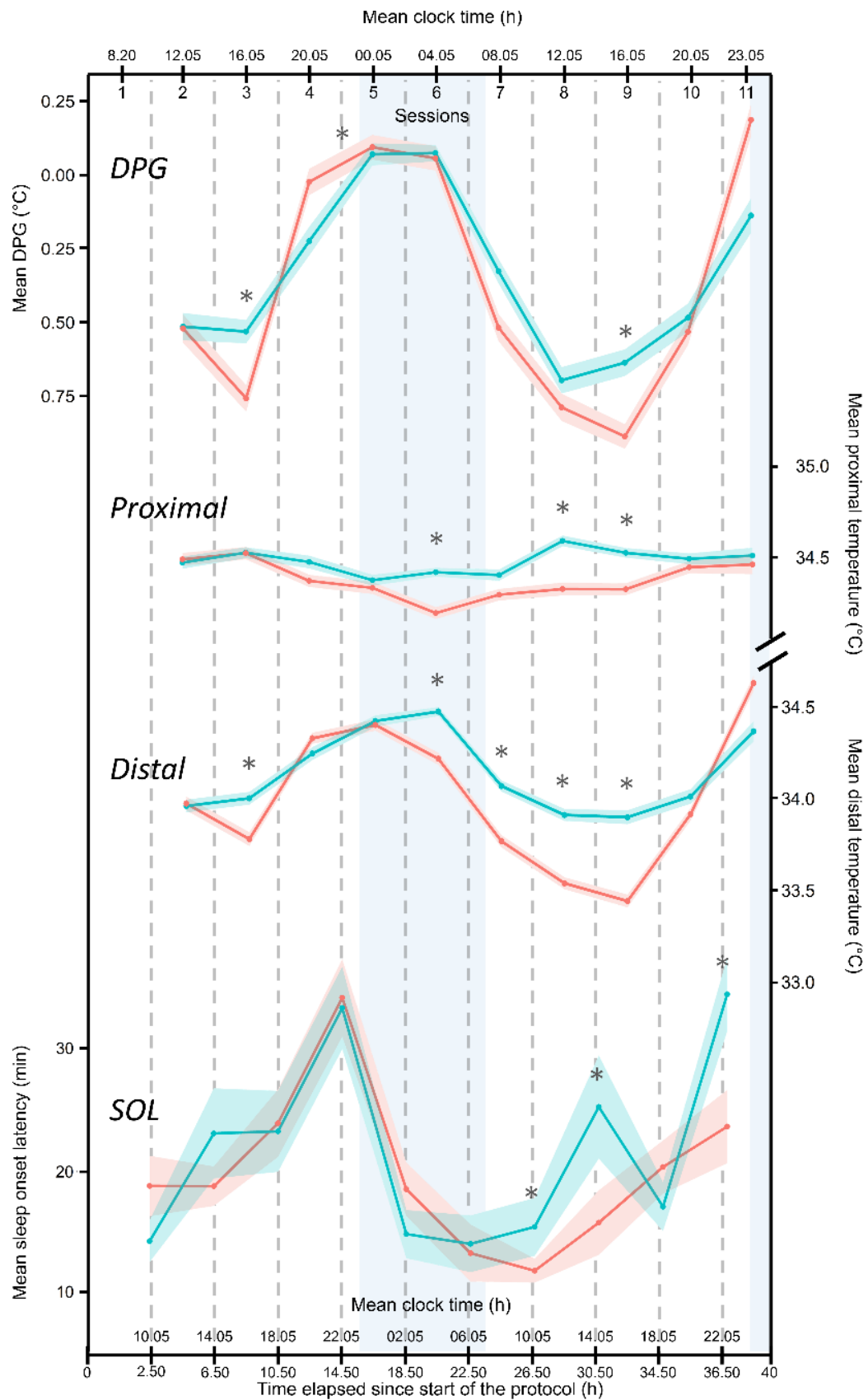


Figure 3. Averaged time course of (A) DPG, (B) proximal skin temperature, (C) distal skin temperature and (D) sleep onset latency according to session and group. Nappers are depicted in red, non-nappers are depicted in blue, with SEM displayed in shaded colour. Grey dashed lines indicate the occurrence of nap opportunities between sessions. The top x-axis depicts the midpoint of the mean clock time for each session (averaged across

individuals), while the bottom x-axis shows the mean clock time midpoint for nap opportunities (averaged across individuals) and the time elapsed since the start of the protocol. The biological night is shaded in blue. The first 130-minute session was removed from the analysis and graph to account for the potential carry-over effects of both cumulative sleep debt as well as night-time sleep (i.e. sleep inertia) on skin temperature.

Similar to the DPG, a main effect of session was observed for distal ($F(9,556)=121.94$, $p<.001$, $\eta^2=.08$) and proximal skin temperature ($F(9,556)=9.355$, $p<.001$, $\eta^2<.01$), along with a main effect of group in both measures, with self-reported nappers displaying overall lower proximal ($F(1,556)=52.329$, $p<.001$, $\eta^2<.01$) and distal temperature ($F(1,556)=114.95$, $p<.001$, $\eta^2=.01$) than non-nappers. Finally, the group*session interaction was significant for both proximal ($F(9,556)=4.7$, $p<.001$, $\eta^2<.01$) and distal measures ($F(9,556)=16.88$, $p<.001$, $\eta^2=.01$). Post-hoc tests showed that for proximal temperature, regular nappers exhibited lower temperature than self-reported non-nappers during sessions 6, 8 and 9 (all $p_{adj}<.001$), whereas for distal temperature measures, nappers exhibited significantly lower values during sessions 3, 6, 7, 8 and 9 (all $p_{adj}<.001$). Also similar to DPG measures, a significant increase in distal measures was observed from session 4 to session 5 in non-nappers ($p_{adj}=.041$), while self-reported nappers showed increasing levels earlier (from session 3 to 4 during the first protocol day ($p_{adj}<.001$) and from 9 to 10 during the second protocol day ($p_{adj}<.001$)). Distal temperature significantly increased from session 3 to 4 for self-reported non-nappers ($p_{adj}<.001$), but not from session 9 to 10 ($p_{adj}=.67$). The respective time courses of proximal and distal skin temperatures are also depicted in Figure 3.

Of note, SE of the previous nap opportunity was not significantly associated with the DPG measured during subsequent wake bouts ($F(1,556)=.036$, $p=.849$, $\eta^2<.01$). However, both distal ($F(1,556)=24.13$, $p<.001$, $\eta^2<.01$) and proximal ($F(1,556)=21.385$, $p<.001$, $\eta^2<.01$) temperature were significantly associated with prior SE such that higher preceding SE was associated with lower subsequent proximal/distal temperature values.

3.3. 24-hour amplitude and phase: Harmonic regression analysis

We observed that the parameter-derived estimates of the computed harmonic regressions on the DPG over scheduled wake bouts were significant for the cosine (β_1 ; $t=9.495$, $p<.001$) and sine (β_2 ; $t=-27.148$, $p<.001$) functions. Most importantly, a main effect of group was observed in parameter-derived estimates for both the cosine (β^{Nap}_1 ; $t=-3.229$, $p=.001$) and sine (β^{Nap}_2 ; $t=-6.941$, $p<.001$) functions. Computation of phase and amplitude by extracting parameter-derived estimates revealed that regular nappers exhibited a phase advance (-82.3° , -329.52 min) compared to non-nappers (-70.6° , -282.4 min), and they presented a higher amplitude (1.029°C) than non-nappers (0.797°C).

Given the differences in wake DPG between self-reported nappers and non-nappers, and more particularly during the classical afternoon nap window, we incorporated the 12-h component of the harmonic regression in our model. Analysis revealed that habitual nappers had a distinct 12-h component compared to non-nappers, as evidenced by a significant interaction between nap-group and the cosine function (β^{Nap}_1 ; $t=2.848$, $p=.004$). The group*sine function was non-significant (β^{Nap}_2 ; $t=1.472$, $p=.14$), indicating that groups differed with respect to amplitude of the 12-hour component (nappers: 0.143°C ; non-nappers: 0.027°C), but not their phase. Even with the addition of the 12-hour component, the results observed with the 24-hour component remained the same.

3.4. Association between DPG slope and sleep onset

In line with previous literature reports (Kräuchi, 2007a), a negative association was observed between SOL and DPG slope ($t=-7.304$, $p<.001$, $\eta^2=.23$), such that shorter SOL was associated with a faster DPG increase from lights-off. A significant main effect of session was observed ($t=-2.643$; $p=.008$, $\eta^2=.08$), indicating that SOL was generally higher during daytime compared to night-time nap opportunities. This effect was particularly evident during naps N4 and N10, which were scheduled between 21:30 and 22:50 during the first and second protocol day, respectively (Figure 3 - bottom panel). A statistical trend for a main effect of group was observed

($t=-1.930$, $p=.054$, $\eta^2<.01$), with self-reported nappers presenting overall reduced SOL and thus tending to initiate sleep faster over nap opportunities compared to non-nappers. A statistical trend toward a significant interaction between group and session was observed ($t=-1.711$; $p=.087$, $\eta^2=.02$), suggesting that SOL varied by session depending on the nap group. Nappers tended to have reduced SOL during the second protocol day, particularly during naps N7 ($p_{adj}=.008$; scheduled from 09:30-10:50), N8 ($p_{adj}=.009$; between 13:30-14:50) and N10 (between 21:30-22:50). A significant interaction between DPG slope and session ($t=2.812$; $p=.005$, $\eta^2=.05$) further indicated that the association between DPG slope and SOL varied according to the session (Figure S2). Generally, the negative association between DPG slope (lights-off to SOL) and SOL was significant for all sessions (all $p_s < 0.05$), but the association appeared strongest for nap N4 ($r=-.788$, $p<.001$) and N10 ($r=-.826$, $p<.001$) - corresponding to naps scheduled in average between 21:30 and 22:50 during the first and second protocol day, respectively. A significant interaction between DPG-slope and group was observed ($t=3.061$, $p=.002$, $\eta^2=.01$), indicating that the relationship between DPG-slope and SOL was negative for both regular nappers ($r=-0.788$, $p<.001$) and non-nappers ($r=-0.845$, $p<.001$). However, this association was stronger in non-nappers, as indicated by Cohen's q for the comparison between correlation coefficients ($q = 0.172$), reflecting a small effect (Figure 4). Finally, the triple interaction between group, session and slope of the DPG between lights-off and SOL was not statistically significant ($t=-.112$, $p=.091$).

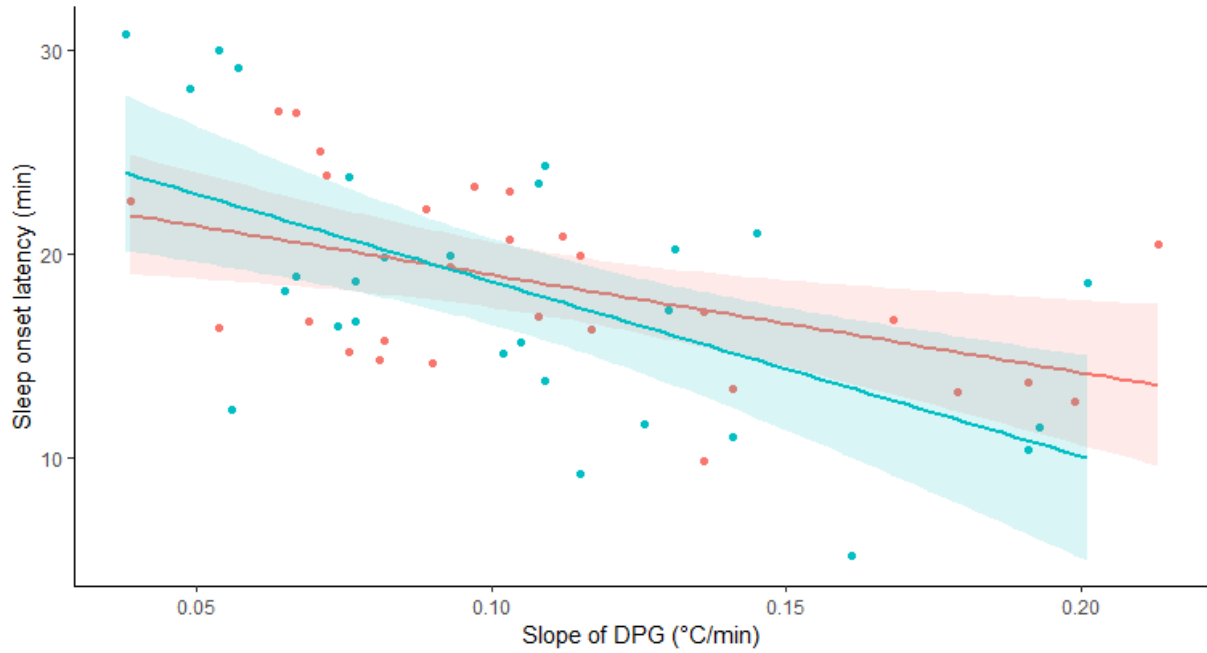


Figure 4. Association between sleep onset latency and DPG-slope from lights-off to sleep onset, averaged across all sessions plotted according to group. Each point represents the mean SOL plotted against the mean DPG slope for each participant. Lines represent linear regression fits with 95% confidence intervals shaded. Nappers are depicted in red, non-nappers are depicted in blue.

4. Discussion

Here, we aimed at exploring the impact of regular napping habits on skin temperature dynamics and its association with sleep initiating processes. We observed that, compared to self-reported older non-nappers, regular nappers (1) displayed a statistical trend towards higher daytime sleepiness and significantly more frequent/longer actimetry derived daytime rest periods, (2) an overall lower DPG during wake bouts over the 24-h cycle, especially during the sessions scheduled to the afternoon hours, contributing to an (3) apparent enhanced 24-h amplitude and (4) a concomitant stronger 12-h component in DPG-modulation. Furthermore, the results indicate (5) an advanced phase with wake-DPG increasing earlier in nappers, compared to non-nappers. Finally, (6) SOL tends to be reduced in nappers during daytime naps, especially over the second protocol day and (7) DPG slope extracted between lights-off and sleep onset is negatively associated with SOL in both groups, but stronger so in non-nappers.

Our findings indicate altered DPG-estimated heat loss dynamics in nappers, hinting towards a more polyphasic profile or stronger first harmonic rhythm component. More specifically and contrary to our initial hypothesis, we observed that regular nappers display an apparent higher 24-hour DPG amplitude than self-reported non-nappers. Notably, a higher but highly variable amplitude in CBT modulation has also been reported in patients suffering from Alzheimer's disease (Van Someren, 2002; Van Someren et al., 1999). Here, the enhanced 24-h amplitude was driven by a lower DPG during the afternoon hours of both protocol days and occurred alongside a stronger 12-h component in wake DPG modulation. Such dynamics could hint at a stronger post-lunch dip and, in turn, partially explain the napping behaviour of self-reported regular nappers. This goes with the observation that 16 out of the 30 nappers, who report sometimes napping involuntarily, eight of them report to do so after a meal (Table S2 in Supplementals). While habitual nappers presented an overall lower DPG during the wake-bouts over the afternoon, they may react by enhanced dynamics when a sleep opportunity is provided at a specific time of the day. Alternatively, nappers may initiate sleep and/or relax in the afternoon hours to “warm-up”. Note that the observed reduced wake-DPG in nappers may be partly confounded by differences in sleep duration and/or sleep characteristics of the preceding nap opportunities. However, reduced wake-DPG was also observed for the first protocol day where SOL and SE did not differ between groups.

A growing body of evidence suggests that lying down and engaging in pre-sleep relaxation behaviours elicit thermophysiological changes that closely resemble those observed during sleep onset. Upon adopting a supine position, gravitational shifts alter blood distribution, influencing skin temperature and cardiovascular parameters (Azemachi et al., 2023; Pereira Franco et al., 2025; Zaregarizi et al., 2007). These changes include increased distal skin temperature and vasodilation, driven by a withdrawal of sympathetic tone during relaxation (Kräuchi, 2007a, 2010; Lushington et al., 2004). Distal rather than proximal temperature changes appear to be the key thermophysiological correlate of relaxation-induced

sleepiness, and these shifts start even before actual sleep initiation (Kräuchi, 2007a, 2010). Although not the focus of our study, such changes are clearly visible in Figure 2, where both self-reported nappers and non-nappers show a consistent rise in DPG following lights-off, despite not all participants falling asleep rapidly, or at all. This suggests that the observed DPG increase is primarily a relaxation effect, rather than a consequence of sleep onset. Speculatively, self-reported nappers may have either trained their body to associate this DPG rise with sleep through habitual daytime rest, or they may have a lower physiological threshold for transitioning into sleep when relaxation-induced temperature shifts occur. This may partly explain their shorter sleep onset latencies compared to non-nappers, even under identical conditions.

In our study, we observed a phase advance in DPG in regular nappers as compared to self-reported non-nappers, suggesting possible earlier sleep-initiating mechanisms through vasodilated distal skin regions, and a less distinct increase of the DPG at the entrance to the biological night. A rise in heat loss during the evening is known to open the gate for sleep along with increased melatonin secretion (Kräuchi, 2007a). These two phenomena contribute to the body's ability to fall asleep during the allocated time. In regular nappers, DPG increased earlier in the evening compared to non-nappers, as aligning with the evening wake maintenance zone (WMZ). This period, occurring in the late afternoon and early evening, is when the circadian system promotes wakefulness to counteract the drive to sleep (Strogatz et al., 1987; J. Zeitzer et al., 2001). The DPG is supposed to be lower at this time of the day due to distal vasoconstriction (Kräuchi et al., 2005), suggesting that self-reported nappers display a sleep-preparation behaviour during daytime. Notably, we observed reduced SOL in regular nappers, along with increased DPG toward the end of the day. Previously, we reported that late daytime rest was associated an altered phase angle of entrainment between the rest-activity cycle and circadian phase (Reyt et al., 2022).

Consistent with previous research (Kräuchi et al., 2005), we found that SOL during nap opportunities is negatively associated with the DPG-slope between lights-off

and SOL in both groups, indicating that shorter SOL goes along with a faster increase in the DPG at lights-off. This association appeared to be stronger in non-nappers than nappers, indicating sleep initiation to be more loosely associated with thermoregulatory dynamics over the circadian cycle in habitual nappers. The sensitivity of sleep propensity to enhanced distal skin temperature has also been shown to change with age and to be further attenuated in age-related insomnia in previous studies (Raymann et al., 2007). As a result, despite being characterized by an overall lower DPG during scheduled wake periods, self-reported nappers seem more inclined to initiate sleep or relaxation behaviours when presented with a sleep opportunity. Generally, they also appear to better maintain sleep over daytime, as expressed by higher SE compared to non-nappers, at least during the second day of the protocol (Deantoni et al., 2024). These observations indicate that sleep initiation or maintenance in habitual nappers could be triggered at lower thresholds of skin temperature increase, or reduced dynamics. Knowing that changes in skin temperature reflect thermoregulatory adjustments affecting warm-sensitive neurons in the preoptic area and anterior hypothalamus, which increase their activity at sleep onset and promote sleepiness (Kräuchi, 2010; D. Kumar et al., 2011; Rothhaas & Chung, 2021), it could be speculated that thermoregulatory processes associated with napping and daytime sleep opportunities contribute to modulation of neuronal activation. This, in turn, would prompt sleepiness or sleep initiation, even with smaller increases in skin temperature.

4.1. Limitations & future perspectives

A limitation of the present study is the lack of collected core body temperature. Access to the heat producing core modulation through the protocol would have been useful to further understand the observed differences in skin temperature modulation, and their association with SOL. Given the available data, we cannot rule out whether the sleep-wake system of the participants is driving the observed thermoregulatory changes or vice-versa. While this question goes beyond the scope of the current work, a more detailed analysis of thermoregulatory changes

during sleep could help elucidate underlying sleep-dependent mechanisms while also identifying possible masking effects of sleep-wake states on DPG measures. Regarding the use of aggregated session-level skin temperature data during scheduled wake episodes across the protocol, this approach reduces temporal resolution and may obscure finer dynamics within sessions. However, the primary aim was to assess the overall modulation of wake skin temperature throughout the entire protocol rather than detailed within-session fluctuations. We consider this trade-off between temporal resolution and data aggregation appropriate to enhance the clarity and interpretability of the general temperature modulation pattern over time. In addition, our protocol does not include a comparison to continuous sleep deprivation, as done in previous research (Kräuchi, Knoblauch, et al., 2006). Such a comparison would allow for a better interpretation of the results in disentangling circadian and homeostatic contributions in the absence of masking effects of sleep. Finally, the reasons for napping are multidimensional, such that there are many different individual motivations for napping, which also depend on a range of biopsychosocial factors (Mednick, 2024). These differences should be better understood and integrated in future research. Identifying health risk and protecting factors at the interface between sleep and ageing is important, and the understanding of underlying mechanisms appears crucial. Disentangling the direction of the effects (e.g., napping as a cause or consequence of altered thermophysiological dynamics) remains to be assessed through interventional and controlled laboratory studies during which temperature or sleep can be manipulated.

4.2. Conclusions

In summary, our study demonstrates that regular self-reported napping in healthy older adults is linked to distinct thermoregulatory patterns, notably a lower distal-proximal skin temperature gradient (DPG) during wake periods surrounding the afternoon nap window and an earlier evening rise in DPG compared to self-reported non-nappers. These altered heat loss dynamics coincide with shorter

sleep onset latencies during nap opportunities, although the association between DPG increase and sleep initiation appears weaker in habitual nappers. Together, these findings highlight a modified interplay between thermoregulation and sleep propensity in self- habitual reported nappers, suggesting adaptations in their sleep-wake regulation across the circadian cycle. While limited by the absence of core body temperature and higher time-resolution data, our results offer valuable insights into how changes in thermophysiological processes may facilitate or arise from regular daytime sleep in ageing populations. Future experimental studies are needed to clarify causal mechanisms and explore how these processes can be targeted to improve sleep health and management in older adults.

Tables

	Non-nappers (n=28)	Nappers (n=30)	Statistics
Age	68.8 $\pm$ 5.85	68.7 $\pm$ 5.26	$W = 408.5, p = .86, r = .0$
PSQI	5.04 $\pm$ 2.88	4.7 $\pm$ 2.28	$W = 403.5, p = .83, r = .0$
Morningness-Eveningness	63.5 $\pm$ 7.33	62.1 $\pm$ 12.8	$W = 379, p = .95, r = .0$
BMI	24.7 $\pm$ 2.59	25.7 $\pm$ 2.65	$W = 320.5, p = .12, r = .0$
Sex	18 men, 10 women	21 men, 9 women	$X^2 = 0.03, p = .85, r = .0$
Depression index (BDI-II)	3.54 $\pm$ 3.28	4.07 $\pm$ 3.06	$W = 351, p = .53, r = .0$
Anxiety index (BAI)	3.15 $\pm$ 3.63	3.23 $\pm$ 4.28	$W = 388, p = .98, r = .0$
Season of assessment	7 fall, 8 spring, 5 summer, 8 winter	12 fall, 5 spring, 9 summer, 3 winter	$X^2 = 5.85, p = .12, r = .3$
Daytime sleepiness (ESS)	6.82 $\pm$ 3.31	8.65 $\pm$ 3.61	$W = 286, p = .055, r = .2$
Apnea (number/hour)	5.54 $\pm$ 4.69	5.6 $\pm$ 4.48	$W = 294, p = .73, r = .0$
PLMS (number/hour)	4.21 $\pm$ 5.71	2.16 $\pm$ 5.92	$W = 393.5, p = .09, r = .1$
Daytime rest duration (mins)	33.4 $\pm$ 21.6	48.4 $\pm$ 14.1	$W = 224, p = .002^*, r = .$
Daytime rest frequency (unit)	0.276 $\pm$ 0.222	0.683 $\pm$ 0.35	$W = 117, p < .001^*, r = .$

Table 1. Demographical, actigraphy-derived and questionnaire data by group (mean + standard deviation).

Supplementary Material

		Non-nappers (n=28)	Nappers (n=30)
Naps are a need	<i>Null to low</i>	24	7
	<i>Moderate to high</i>	4	23
Naps are planned		/	1 (3.33%)
Naps happen involuntarily		/	16 (53.33%)
	<i>After meal</i>		8
	<i>TV</i>		11
	<i>Other</i>		0

Table S1. Responses to the LiNap Questionnaire, asking participants whether they nap or not. If yes, follow-up questions aim at specifying the frequency, duration, type of occurrence, planification and reason for napping. Displayed here: Question 7 (Is napping a need?), Question 11 (Are naps usually planned?), and Question 13 (Do you sometimes take involuntary naps?).

		Non-nappers		Nappers	
		<i>mean</i>	<i>sd</i>	<i>mean</i>	<i>sd</i>
Session 2	<i>Wake</i>	-0,519	1,221	-0,525	1,316
	<i>Nap opportunity</i>	-0,076	1,267	-0,37	1,334
Session 3	<i>Wake</i>	-0,536	1,144	-0,764	1,25
	<i>Nap opportunity</i>	-0,375	1,346	-0,141	1,306
Session 4	<i>Wake</i>	-0,227	1,282	-0,025	1,245
	<i>Nap opportunity</i>	-0,054	1,115	0,175	0,951
Session 5	<i>Wake</i>	0,069	1,012	0,093	1,167
	<i>Nap opportunity</i>	0,053	0,999	0,028	0,913
Session 6	<i>Wake</i>	0,073	0,827	0,055	1,151
	<i>Nap opportunity</i>	-0,279	1,105	-0,382	1,069
Session 7	<i>Wake</i>	-0,33	1,094	-0,523	1,281
	<i>Nap opportunity</i>	-0,21	1,291	-0,632	1,236
Session 8	<i>Wake</i>	-0,702	1,188	-0,794	1,278
	<i>Nap opportunity</i>	-0,578	1,392	-0,74	1,173
Session 9	<i>Wake</i>	-0,642	1,336	-0,894	1,168
	<i>Nap opportunity</i>	-0,577	1,497	-0,636	1,002
Session 10	<i>Wake</i>	-0,488	1,254	-0,537	1,249
	<i>Nap opportunity</i>	-0,413	1,219	-0,176	1,081
Session 11	<i>Wake</i>	-0,14	0,945	0,186	0,931

Table S2. Mean and standard deviation of DPG during wake and nap opportunities, according to group and sessions.

	Non-Nappers (n = 28)	Nappers (n = 30)	Total included
<i>Session 1</i>	25	30	55
<i>Session 2</i>	27	30	57
<i>Session 3</i>	23	29	52
<i>Session 4</i>	26	28	54
<i>Session 5</i>	28	27	55
<i>Session 6</i>	27	30	57
<i>Session 7</i>	26	30	56
<i>Session 8</i>	24	30	54
<i>Session 9</i>	23	29	52
<i>Session 10</i>	21	25	46

Table S3. Number of participants included in the analyses of sleep onset latency, by group and the total number of participants included, by session. Some participants were removed from sessions individually if they failed to asleep during them, meaning their sleep onset latency could not be measured.

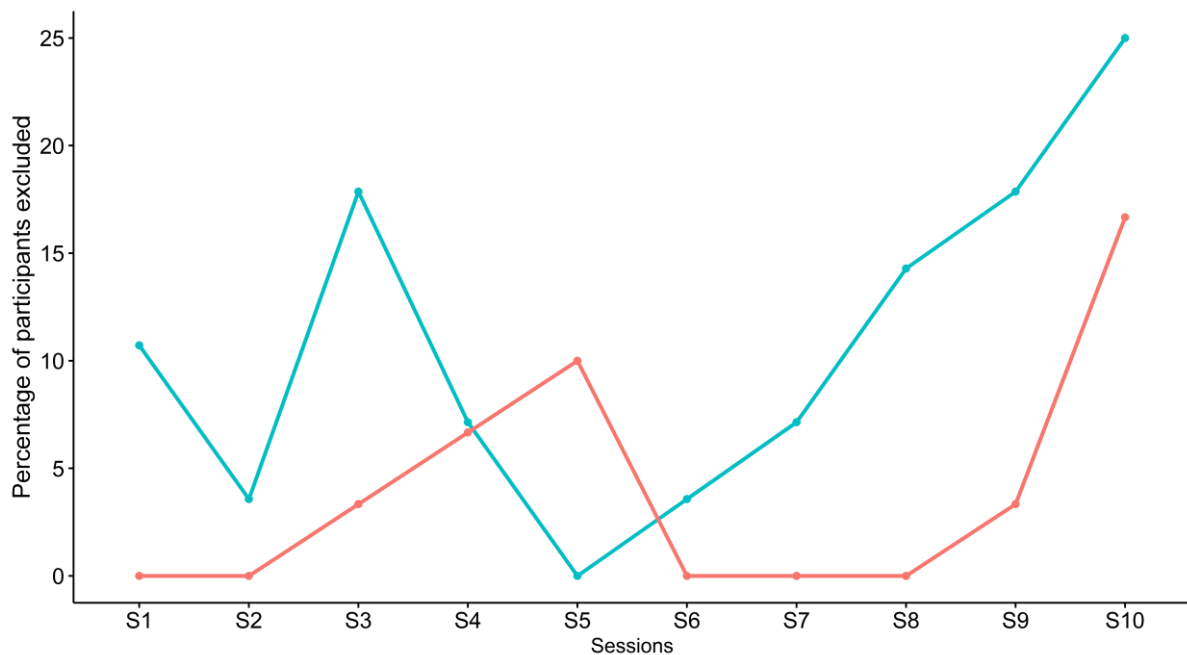


Figure S1. Time course of the percentage of participants excluded in the analyses of sleep onset latency, by group and session (blue=non-nappers, red=nappers).

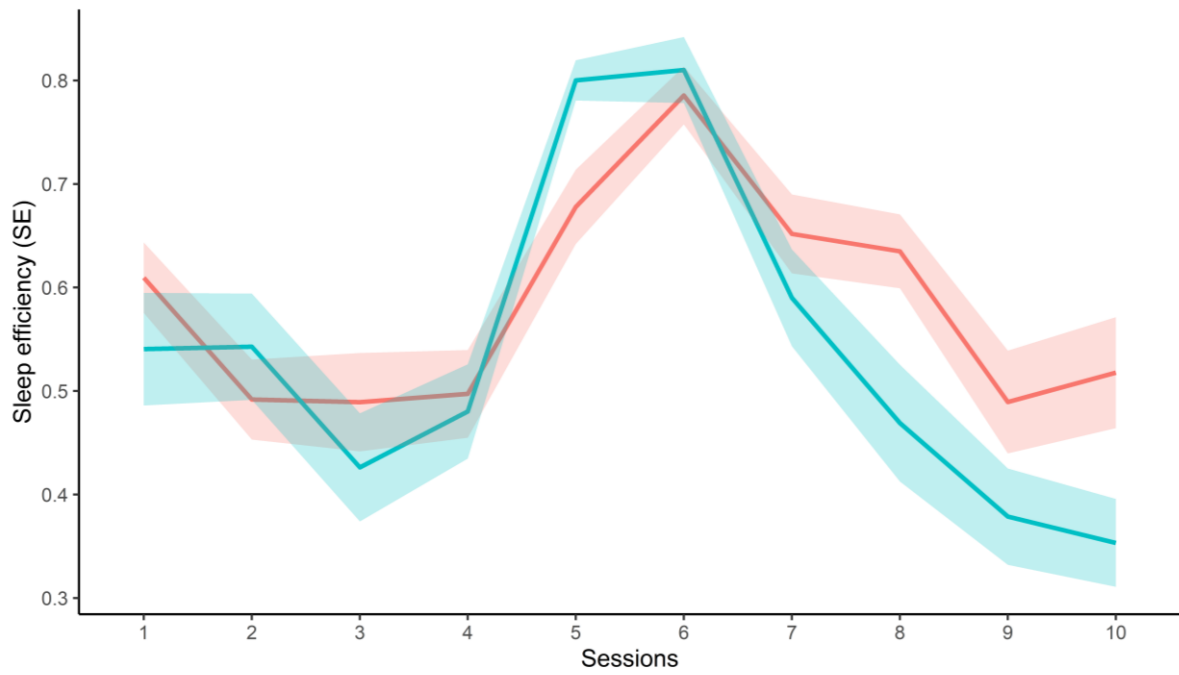


Figure S2. Averaged time course of sleep efficiency (SE) according to sessions and group (blue=non-nappers, red=nappers).

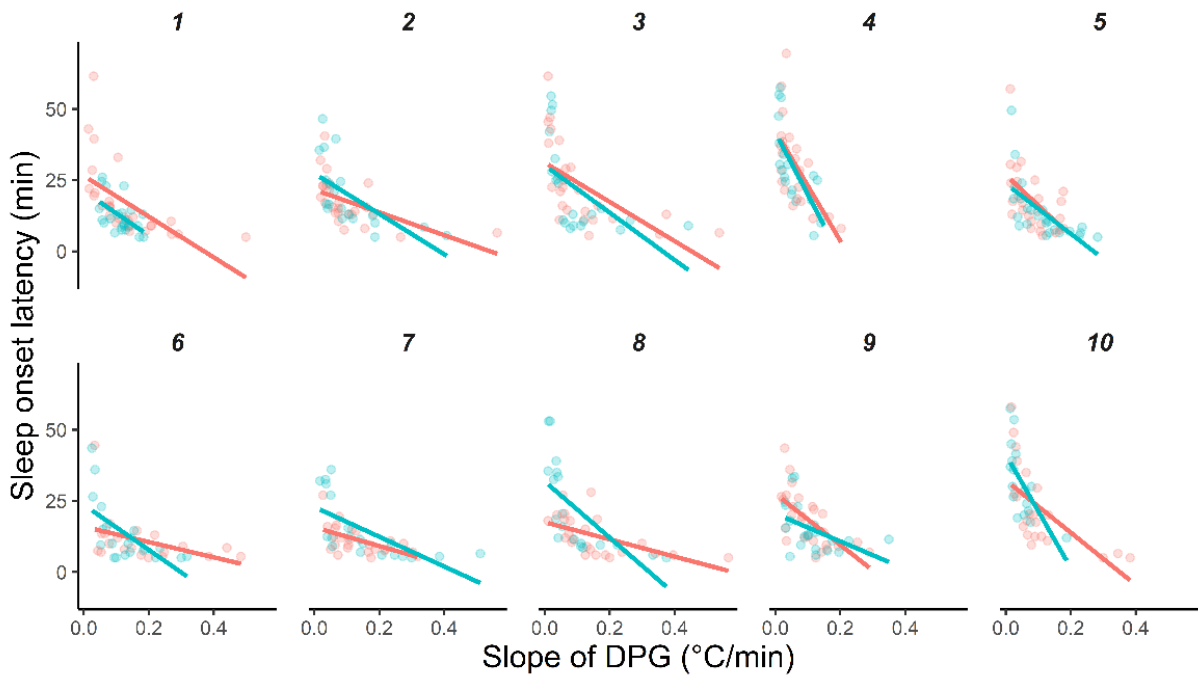


Figure S3. Sleep onset latency according to the DPG slope, by session in both nappers (red) and non-nappers (blue).

Study 3. Breaking the Nap Habit: impact of a one-year nap suppression intervention on cognition in the elderly

Marine Dourte^{1,2,3}, Gregory Hammad¹, Stella de Haan¹, Mathilde Reyt⁴, Michele Deantoni¹, Marion Baillet⁵, Alexia Lesoinne¹, Gilles Vandewalle¹, Fabienne Colette¹, Vincenzo Muto¹, Philippe Peigneux^{1,3}, Christina Schmidt^{1,2}

¹ GIGA-CRC Human Imaging Unit, Sleep and Chronobiology Laboratory , University of Liège, Liège, Belgium.

² Psychology and Neuroscience of Cognition Research Unit (PsyNCog), Faculty of Psychology and Educational Sciences, University of Liège, Liège, Belgium.

³ UR2NF, Neuropsychology and Functional Neuroimaging Research Unit, Center for Research in Cognition and Neurosciences, ULB Neurosciences Institute, Université Libre de Bruxelles (ULB), Brussels, Belgium.

⁴ Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal (CRIUGM) & Concordia University

⁵ Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA

In preparation

Abstract: Napping in later life is a common behaviour shaped by cultural, environmental and biological factors. Although brief naps can enhance alertness and memory, epidemiological evidence linked frequent or prolonged daytime sleep in older adults to poorer physical health and accelerated cognitive decline, including episodic memory, possibly reflecting underlying circadian disruption. In the present study, we tested whether modifying nap habits could preserve age-related cognitive fitness in healthy retirees (59–82 years). Fifty-eight habitual nappers were randomised either to a nap-control condition ($n = 28$), where they continued their usual nap routines, or to a nap-intervention condition ($n = 30$), which consisted of receiving behavioural coaching to reduce the frequency and duration of daytime napping over 12 months. A non-nappers group ($n = 29$) served as a reference. Cognitive performance, with a focus on episodic memory, was assessed at baseline and after a one-year intervention under continuous actimetry monitoring. The nap-intervention group significantly decreased their nap frequency and duration throughout the study. Although cognitive performance tended to decrease after a year in all participants, the nap-control group exhibited a significantly greater impairment in episodic memory as compared to both the non-nappers and the nap-intervention group. These results demonstrate that sleep-wake behaviour in older adults can be modified and suggest that targeted nap reduction may offer an accessible strategy to mitigate age-related decline in specific cognitive domains.

1. Introduction

Ageing is accompanied by functional deterioration across multiple brain systems, including the circadian clock that regulates the 24-hour rhythms in sleep-wake cycles and many other physiological processes (Hastings et al., 2018; Kondratova & Kondratov, 2012). By interacting with the sleep-dependent homeostatic process, this clock provides a temporal organisation to the sleep-wake-cycle (Borbély, 1982; Daan et al., 1984), mainly by facilitating sleep consolidation during the night and sustained alertness and cognitive performance during the day (Cajochen & Schmidt, 2025; D. Dijk & von Schantz, 2005; Muto et al., 2016). With advancing age, the circadian timing system undergoes a functional weakening (Kondratova & Kondratov, 2012), contributing to an increased sleep-wake cycle fragmentation, characterized by frequent nocturnal awakenings and increased daytime sleep propensity (Foley et al., 2004; J. E. Park et al., 2021; Taillard et al., 2021). In older adults, the growing practice of daytime napping emerges as one of the most visible manifestations of this fragmentation (Goldman et al., 2008; Souabni et al., 2022).

Napping is a multifaceted and frequent behaviour among older adults, shaped by cultural, environmental, and developmental influences (Mander et al., 2017; Z. Zhang et al., 2020). Afternoon napping is generally accepted as a good means to reduce subjective sleepiness and improve vigilance and cognitive performance (e.g. Cai et al., 2021; Cross et al., 2015; Mednick et al., 2003; Milner & Cote, 2009). This evidence mostly derives, however, from young healthy cohorts with a focus on immediate, short-term benefits. In older adults, by contrast, large-scale epidemiological studies have linked frequent and long-duration napping to multimorbidity, poorer physical health, elevated mortality risk (Ancoli-Israel & Martin, 2006; Dhand & Sohal, 2007; Zhong et al., 2015), accelerated cognitive decline (Leng et al., 2019; Li et al., 2023; Overton et al., 2024) notably in the episodic memory domain (Álvarez-Bueno et al., 2022; Kitamura et al., 2021; Leong et al., 2022; Li et al., 2022; Owusu et al., 2019; Rey et al., 2022), and an increased incidence of Alzheimer's disease (Li et al., 2023). One possible explanation is that, humans being a diurnal species, chronic napping reflects or exacerbates circadian

disruption, as it intrudes sleep into the active wake period, with potential long-term deleterious effects on brain function. Supporting this view, we recently showed that regular healthy older nappers present altered circadian dynamics, including a reduced amplitude of melatonin secretion and heightened daytime sleep propensity, compared to non-nappers (Deantoni et al., 2024). Noticeably, it has been suggested that nap frequency, duration and intentionality modulate the cognitive outcomes (Li et al., 2022; Mednick et al., 2003; Mednick, 2024; Owusu et al., 2019) across diverse cultural contexts (Cross et al., 2015; Merlino et al., 2010; Owusu et al., 2019; Z. Zhang et al., 2020), although other studies reported neutral or even beneficial effects of napping under specific conditions (Alqurashi et al., 2022; Cai et al., 2021; Keage et al., 2012; Li et al., 2018; Souabni et al., 2022).

Because sleep is a modifiable behaviour, napping may constitute a promising intervention target for supporting cognitive fitness and brain health in ageing populations, particularly as this habit is highly prevalent in older adults. Indeed, if circadian rhythm disruption contributes to cognitive decline in ageing and napping reflects a functional weakening of the circadian clock, then restricting nap habits could help restore the sleep-wake cycle temporal organisation, and favour better cognitive performance. To address this hypothesis, we conducted a 12-month randomized, placebo-controlled intervention study in older retired adults stratified according to their habitual napping status. We hypothesized that a behavioural intervention aimed at reducing nap frequency and duration in regular older nappers would attenuate cognitive decline, with a particular focus on episodic memory, as this domain is especially vulnerable to age-related decline or complains, and, in our cohort, nap frequency was negatively correlated with episodic memory performance (Reyt et al., 2022).

2. Methods

2.1. Participants

The study was approved by the local Ethics Committee of the University Hospital and of the Faculty of Psychology, Speech Therapy and Educational Sciences at the

University of Liège. Recruitment was conducted across a wide range of socio-economic classes via advertisement in newspapers, radio and university, and an already existing GDPR-compliant database at the research unit (see also (Deantoni et al., 2024; Reyt et al., 2022) for publications of cross-sectional data of this study). Seven hundred and seventy-three individuals aged > 60 were initially contacted. Out of this pool, 166 agreed to pass a screening visit. To be included in the final sample, participants should not exhibit moderate or severe depression (Beck Depression Inventory [BDI] < 19, Beck & Beamesderfer, 1974) or severe anxiety (Beck Anxiety Inventory [BAI] < 30, Beck et al., 1988). Additional exclusion criteria included clinical symptoms of possible cognitive impairment evidenced by sub cut-off scores at the Mini Mental State Examination [MMSE score < 26] (Folstein et al., 1975) and the Mattis Dementia Rating scale [score < 130] (Mattis, 1976), out of range Body Mass Index (≤ 18 and ≥ 30 kg/m²), as well as self-reports of a history of diagnosed psychiatric conditions or severe brain trauma, chronic medication affecting the central nervous system, diabetes, smoking, caffeine (> 4 cups/day), excessive alcohol (> 14 units/week) or other drug consumption, and travelling more than one time zone in the 3 months prior to the study begin. Participants with stable treatment (> 6 months) for hypertension and/or hypothyroidism were included in the study. The presence of major sleep disorders was investigated during a polysomnography night in the laboratory (apnea/hypopnea index and period limb movement index > 15/h), leading to exclusion if scores were above the cut-off values. All participants were retired and lived independently at home.

Based on these criteria, eighty-seven retired older participants (mean age = 69.0 years, SD = 5.3) were prospectively recruited with respect to their napping habits. Fifty-eight participants self-reported regularly napping at least 3 times a week for more than 30 minutes and for more than a year. An additional group of non-nappers (n=29) was included as an observational reference group. Participants were matched between groups with respect to age, sex, BMI, habitual sleep quality over the past month (Pittsburgh Sleep Quality Index (PSQI), Buysse et al., 1989) and chronotype (Morningness-Eveningness Questionnaire (MEQ), Horne &

Ostberg, 1976). Demographic characteristics are summarized Table 1 (Results Section).

2.2. Study procedure

After the screening visit, all participants were administered a baseline assessment (T0) including a comprehensive neuropsychological battery evaluating executive functions, episodic memory and attention (see Table S1 in Supplementals for list of tests, mean scores and group comparison). Additionally, anatomical MRI scans were obtained to estimate hippocampal volume. A graphical representation of the study procedure is depicted in Figure 1.

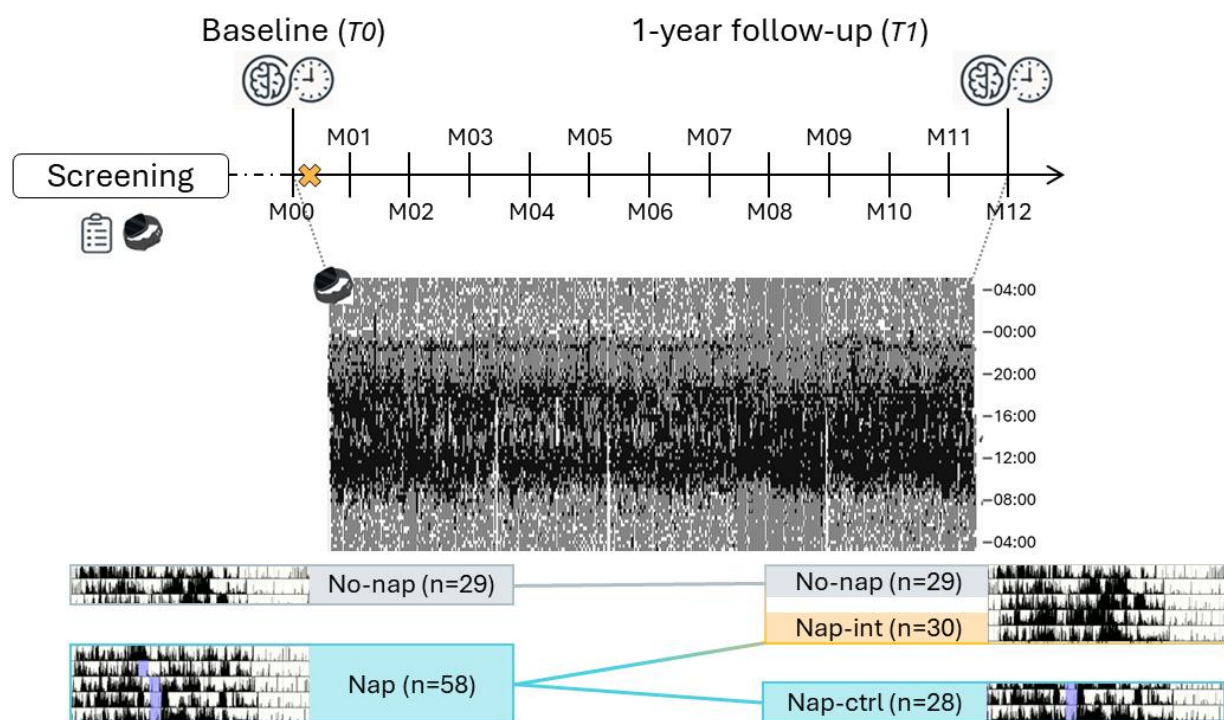


Figure 1: Graphical representation of the study procedure. After eligibility verification during the screening visits, a complete neuropsychological test battery, including episodic memory tests (Free and Cued Selective Reminding Test, Mnemonic Similarity Task, Logical Memory), as well as structural MRI for hippocampal volume computation were acquired at Baseline (T0/M00) and at one-year follow-up (T1/M12). The yellow cross represents the general sleep hygiene somno-education which took place for all groups, as well as the randomised nap-group assignment during which participants were assigned to the nap-control group (could continue to nap) and the nap-intervention group (received specific indication and advice to actively reduce their nap habit over the course of the intervention). The 12-month intervention period (M01 to M12), during which continuous actimetry recording and monthly questionnaires were acquired, is represented in the middle with a one-year long actogram.

After baseline testing at T0, regular nappers were randomly divided into the two subgroups: half were randomly assigned to a nap-intervention group (n = 30, see

below for details on intervention), and the other half to a nap-control group (n = 28). All participants, including non-nappers, underwent a structured somno-education session modelled on cognitive-behavioural therapy principles (Heyde et al., 2018). While all groups received general sleep hygiene advice, participants from the nap-intervention group specifically received additional instructions and support to significantly reduce daytime napping (see details hereunder). Wrist-based motor activity was continuously recorded in all group conditions during the entire one-year intervention period. This allowed to assess the stability or evolution of participants' sleep-wake cycles, daytime rest patterns, and adherence to sleep recommendations. Monthly follow-up sessions were conducted by the experimenters either in-person or via phone calls (mainly during the COVID19-based lock-down) for all participants, to assess daily life changes, sleep quality, activity levels, anxiety, and depression. During these follow-ups, actigraphs' batteries were replaced, and particular attention was paid to participant satisfaction and adherence to the study protocol, to ensure the integrity of the longitudinal data collection.

At the end of the one-year intervention period (T1), participants returned to the laboratory and were administered the same neuropsychological test battery probing episodic memory, attention, and executive function, as well as an anatomical MRI scan. Moreover, to evaluate temporal changes and the potential effect of the nap intervention, all participants repeated the baseline questionnaires (PSQI, MEQ, ESS, BDI, BAI).

2.3. Nap intervention

The aim of the intervention was to suppress or significantly reduce napping habits over one year with the aim of stabilizing circadian regulation of sleep-wake states. The intervention was embedded in general guidelines for cognitive-behavioural therapy (CBT) for insomnia (Heyde et al., 2018). Routines for CBT of insomnia classically include nap suppression as behavioural intervention. A first session provided sleep education (general education on sleep regulation, circadian

rhythms and sleep hygiene), followed by the presentation of the intervention (1-year nap removal) for the nap-intervention group. Sleep education has as primary function to enable participants to better understand the rationale for the behavioural regimen used, which in turn, increases the likelihood that participants will comply with treatment recommendations. Behavioural treatment regimen was then applied, with the instruction to significantly reduce napping habits (frequency/duration) over the course of the one-year study, encompassing a progressive reduction over the first 4 weeks. Adherence was tracked with actimetry over the entire intervention period. Participants were contacted weekly during the first month and monthly thereafter to extract actimetric data, assist them in making needed adjustments in their sleep-wake behaviour and reinforce adherence to nap manipulation. Changes in lifestyle habits (timing and amount of physical activity, alcohol and caffeine consumption) were also assessed during the monthly meetings to track concomitant changes. Participants in the no-intervention conditions (nap-control and no-nap) were also continuously monitored by actimetry and contacted monthly to get information about changes in lifestyle habits and to fill in questionnaires, but without any interventional intent.

2.4. Actigraphy

Participants wore an actigraphic device (Motionwatch 8; CamN-tech) at the nondominant wrist and completed a sleep diary for at least 8 consecutive days, while maintaining their normal routines at home, with a maximum duration of 15 days (13.58 ± 1.81 days) to derive daytime rest (DTR) features prior to group assignment at screening and before baseline assessment (T0). They were then again monitored by actigraphy and sleep diaries for a whole year with monthly check-ups and battery replacements until T1 assessment. Tri-axial activity and light levels aggregated into 30-s epochs were extracted with the MotionWare software (v.1.2.28) and processed using the open-source software pyActigraphy (v1.2, Hammad et al., 2021). Segments in which the actigraphy device was removed

(e.g., shower time or swimming, omissions ...) were identified based on sleep diaries and visual inspections, and then excluded from the analyses. Consolidated rest periods were automatically identified using the Munich Actimetry Sleep Detection Algorithm (MASDA, Roenneberg et al., 2015), with a threshold on activity counts at 15% of the 24-hour centred moving average, as validated in Loock et al. (2021). In order to increase the algorithm sensitivity to detect short daytime rest (DTR) periods, the minimal rest bout duration was however set to 15 minutes, instead of 30 (see Reyt et al., 2022 for the validation of this setting against visual scoring and sleep agenda-derived indices).

To estimate the evolution of daytime napping activity, we selected DTR periods during the day (i.e., between 10h00 and 19h30 as in Reyt et al., 2022), with a duration comprised between 15 minutes and 4 hours. Early morning and late evening transition times were left out of the target time frame to reduce the possibility of confounding late or early night sleep effects. DTR frequency (mean number of DTR bouts per day) and DTR duration (overall mean duration of DTR bouts) were computed at baseline before inclusion and per intervention month resulting in 13 averaged points per participants (M00:M12). Cumulative sums of difference from baseline were computed per participant for DTR-frequency and DTR-duration over the 12-months intervention period. Finally, all detected rest periods were used to compute profiles of rest probability over the 24-hours cycle, before (T0) and after (T1) the intervention period. In order to highlight temporal differences in sleep probability, these profiles were normalised for inter-individual differences in overall sleep propensity, and aligned to the individual sleep midpoint (Lunsford-Avery et al., 2018).

2.5. Neuropsychological assessment

Supplementary Table S1 provides the complete list of the administered neuropsychological tests. Given the previously reported association between DTR frequency and episodic memory in the same cohort (Reyt et al., 2022), we analysed separately the three episodic memory tests. The *Free and Cued Selective Reminding*

Test (FCRST; Grober & Buschke, 1987) was administered in either version A or B at baseline T0, with the alternate version used at T1. Total number of correctly retrieved words at immediate free recall and at cued recall were the variables of interest. The *Mnemonic Similarity Task* (MST; Stark et al., 2013) was used its visual form, and we used the variables Lure Discrimination Index (LDI; accounting for potential bias to use the « similar » response overall) and corrected recognition memory score (REC; i.e., hits minus false alarms). Finally, delayed total recall was the variable of interest for the second story of the *Logical Memory Test* (LM; Wechsler, 2009). Same version of MST and LM were used at T0 and T1.

2.6. Structural MRI: Hippocampal volume

Structural T2-weighted and T1-weighted images were acquired on a whole-body 3T scanner (Magnetom Prisma, Siemens Medical Solutions, Erlangen, Germany) operated with a 64-channel receiver head coil. High-resolution T2-weighted (T2w) images were obtained using a multi-band gradient-echo sequence (TR = 9240 ms; TE = 80 ms; flip angle = 180°; FOV = 180×180 mm (matrix = 448×448); voxel = 0.4 × 0.4 × 1.2 mm; 60 sagittal slices; scan time = 490 s). Hippocampal subfields were automatically segmented with the ASHS toolbox (Yushkevich et al., 2015), using both the T1w and the high-resolution T2w focal scans. We employed the atlas from Iglesias et al. (2015), choosing the ‘usegray’ masks for optimal grey–white differentiation; all outputs remain in native space. The pipeline comprised rigid registration to the ASHS template, multi-atlas label fusion, and manual quality control with corrections of any mis-labels. Subfield volumes and summed total hippocampal volume were extracted for each participant, and corrected for inter-individual differences in total intracranial volume using a power-proportion method (Liu et al., 2014; Sanchis-Segura et al., 2020).

2.7. Statistical analysis

Statistics were computed by using the 4.2.2 version of the R-Studio software (R Core Team, 2020), with data organisation and visualisation packages including

dplyr (Wickham et al., 2023), tidyr (Wickham et al., 2024) and ggplot2 (Wickham, 2016).

2.7.1. Demographics characteristics and Hippocampal volume

Demographical data were explored to confirm group pairing using Kruskal-Wallis tests (Age, Education), Chi-square test (Sex), and Rayleigh's test (Season of Assessment). Furthermore, linear regression models were applied to assess the effect of Group (3-level), Time (2-level) and Group*Time interaction on dependant variables such as BMI, Questionnaires scores (PSQI, MEQ, ESS, BDI, BAI, MMSE), actigraphy-derived average intervention duration, as well as normalised total hippocampal volume.

2.7.2. Actimetry

In a first step, a generalised linear mixed-model (GLMM, glmmTMB package, Brooks et al., 2017) was used to assess the participants' compliance to their group nap-related behaviour over the course of the one-year actimetry follow-up. To do so, the cumulative sum of difference from baseline were compared for DTR-frequency and DTR-duration between groups (3 levels) over time (13 levels). A gamma family with a log link function, as well as a random intercept per subject were applied. Time elapsed between T0 and T1 (see demographics Table 1) was added as a covariate.

Finally, group differences in the temporal organisation of the 24-hour rest probability profiles between T0 and T1 was explored. For 24-h rest probability profiles, linear regressions were first ran via one-dimensional statistical nonparametric mapping (S(n)PM)(Pataky et al., 2015) using the SPM1D Python toolbox (Pataky, 2012). This method employs random-field theory to test for localized effects in continuous signals, such as the rest probability over a 24-h profile. For each group, we built a statistical map, $SPM\{t\}$, by calculating a t-statistic at every 10-minute bin of the 24-h profile. A comparison was marked significant when the $SPM\{t\}$ waveform exceeded its critical threshold t^* , which we established

through 10 000 permutation iterations: t^* equals the 95th percentile of the maximal t-values from all permuted maps. Those same permutations also provided cluster-level p-values (p_{cluster}) for any suprathreshold clusters. We judged findings significant at $p < .05$. Given the limited sample size ($n \approx 30$ per group across three groups) which may reduce the statistical power to detect subtle effects, particularly given the temporal smoothness of the data and the conservative nature of cluster-based inference, pairwise t-tests (2,500 permutations, $\alpha = 0.05$) were conducted within each time condition separately to examine potential localized differences between groups. The statistic z associated with the model was evaluated against a critical threshold (z^*) derived from the permutation distribution, correcting for multiple comparisons across the time series.

2.7.3. Cognition

Separate analyses were conducted for FCRST, MST and LM scores using linear mixed models (lmerT package, Kuznetsova et al., 2017) to assess the effect of categorical factors Group (3-level) and Time (2-level). Model comparison using the Akaike Criterion (AIC) revealed that Age and Sex needed to be added for the FCRST model, while only Sex needed to be part of the LM model. MST did not need any added covariates. In all models, a random intercept by subject was added. Moreover, we tested whether adding a regressor to control for season of assessment would improve the model's fit or warrant any effect changes. As it was not the case (model comparison: $F=1.4829$, $p=0.185$), the simpler model was kept. For each final model, we obtained Type III Wald χ^2 tests of the main effects of Group, Time and their interaction using the *car* package (Weisberg & Fox, 2011). Lastly, we computed standardised β -coefficients with 95 % confidence intervals using the *parameters* package (Lüdtke et al., 2025). Standardised β -coefficients were interpreted on the familiar Cohen's d scale ($|\beta| \approx 0.10$ = small, ≈ 0.30 = medium, ≈ 0.50 = large effect), as this was our primary variable of interest.

3. Results

3.1. Demographics characteristics and Hippocampal volume

All statistical results are depicted in Table 1. We confirmed that groups did not differ in respect to pairing variables, such as age, education level and sex ($p_s > 0.63$). BMI was overall lower in the non-nap group ($p = 0.01$) during the study. For questionnaire scores, participants did not differ in regards to mood ($p_s > 0.07$) nor perceived sleep quality and chronotype ($p_s > 0.84$), but the nap-intervention group reported higher perceived sleepiness scores than the two other groups ($p = 0.04$). MEQ ratings were lower at T1 than at T0 in all groups ($p < 0.001$). When looking at study design parameters, we found that cognitive assessments were uniformly distributed across seasons for all groups ($p_s > 0.07$), and that the average study duration was a lower in the non-nap group as compared to the other groups ($p = 0.049$). Finally, no group, time or interactions effects were observed on hippocampal volume in our study ($p_s > 0.06$).

		T0 Mean (SD)	T1 Mean (SD)	Group p	Time p	Group x Time p
Age (years)	No-Nap	69.2 (5.69)	—	$p=0.63^a$	—	
	Nap-ctrl	69.6 (5.10)				
	Nap-int	68.3 (5.06)				
Education (years)	No-Nap	14.1 (3.51)	—	$p=0.63^a$	—	
	Nap-ctrl	14.6 (3.97)				
	Nap-int	14.7 (3.25)				
Sex	No-Nap	18 men, 11 women	—	$p=0.76^b$	—	
	Nap-ctrl	20 men, 8 women				
	Nap-int	20 men, 10 women				
BMI	No-Nap	<u>24.7 (2.38)</u>	<u>24.4 (2.41)</u>	$p=0.01^d$	$p=0.99^d$	$p=0.99^d$
	Nap-ctrl	25.0 (2.90)	25.6 (3.33)			
	Nap-int	25.8 (3.01)	26.0 (2.90)			
PSQI	No-Nap	5.1 (3.13)	4.46 (2.18)	$p=0.84^a$	$p=0.99^a$	$p=0.99^d$
	Nap-ctrl	4.86 (2.17)	4.77 (2.50)			
	Nap-int	5.37 (2.76)	5.33 (3.25)			
MEQ	No-Nap	64.2 (6.58)	57.3 (7.03)	$p=0.96^d$	$p<0.001^d$	$p=0.31^d$
	Nap-ctrl	64.7 (7.96)	55.4 (8.77)			
	Nap-int	63.7 (7.79)	55.5 (7.38)			
ESS	No-Nap	6.93 (3.27)	5.69 (4.09)	$p=0.04^d$	$p=0.06^d$	$p=0.24^d$
	Nap-ctrl	8.57 (3.73)	8.54 (4.54)			
	Nap-int	<u>9.13 (3.78)</u>	<u>9.47 (2.86)</u>			
BDI	No-Nap	3.38 (3.48)	2.4 (3.16)	$p=0.07^d$	$p=0.99^d$	$p=0.98^d$
	Nap-ctrl	4.5 (3.71)	3.5 (3.89)			
	Nap-int	4.43 (3.12)	4.00 (4.05)			
BAI	No-Nap	3.10 (4.41)	2.88 (3.96)	$p=0.29^d$	$p=0.99^d$	$p=0.26^d$
	Nap-ctrl	3.96 (3.89)	3.27 (3.81)			
	Nap-int	2.70 (4.28)	3.47 (3.59)			
MMSE	No-Nap	29.6 (0.63)	29.5 (1.09)	$p=0.45^d$	$p=0.69^d$	$p=0.33^d$
	Nap-ctrl	29.3 (0.94)	29.5 (0.81)			
	Nap-int	29.5 (0.82)	29.7 (0.55)			
Season of Assessment	No-Nap	8 Sp, 6 Su, 7A, 8 W ($p=0.80^c$)	9 Sp, 5 Su, 7A, 8W ($p=0.34^c$)		—	
	Nap-ctrl	6 Sp, 7 Su, 8A, 7 W ($p=0.64^c$)	5Sp, 7Su, 11A, 5W ($p=0.08^c$)			
	Nap-int	3 Sp, 6 Su, 7A, 14W ($p=0.09^c$)	3Sp, 6Su, 12A, 9W ($p=0.07^c$)			
Average intervention duration (days)	No-Nap		391 (48.8)	$p=0.049^a$	—	
	Nap-ctrl	—	426 (42.2)			
	Nap-int		410 (48.5)			
Normalised hippocampal volume (a.u.)	No-Nap	0.747 (0.10)	0.734 (0.09)	$p=0.82^d$	$p=0.06^d$	$p=0.75^d$
	Nap-ctrl	0.755 (0.09)	0.746 (0.09)			
	Nap-int	0.739 (0.07)	0.721 (0.06)			

Table 1. Demographical, actigraphy-derived and questionnaires data by Group (mean and standard deviation) and Time (Baseline, T0, vs. 1-year follow-up, T1). For statistical analyses, ^a refers to kruskal-wallis test, ^b to Chi-square test, ^c to Rayleigh test, ^d to linear model with factor Group, Time and Group*Time interactions. In case of statistically significant group difference, the score that differed is in bold font. Abbreviations are as follows: No-Nap = No-nap group (n=29), Nap-ctrl = Nap-control group (n=28), Nap-int = Nap-intervention group (n=30), BMI= Body Mass Index, PSQI= Pittsburgh Sleep Quality Index (Buysse et al., 1989), MEQ = Morningness-Eveningness Questionnaire (Horne & Ostberg, 1976), ESS = Epworth Sleepiness Scale (Johns, 1991), BDI = Beck Depression Inventory (Beck & Steer, 1984), BAI = Beck Anxiety Inventory (Beck et al., 1988), MMSE = Mini-Mental State Examination (Folstein et al., 1975), Seasons (Sp= Spring, Su = Summer, A=Autumn, W=Winter).

3.2. Nap intervention reduces daytime rest duration and frequency

We first tested whether the nap restriction intervention significantly modified DTR characteristics in the nap-intervention group, accounting for individual differences at baseline (Figure 2; Raw DTR-duration and DTR-Frequency time courses are provided in Supplementary Figure S1). For cumulative DTR-duration, main Group ($\chi^2(2)=0$, $p=0.999$) and Time ($\chi^2(12)=1.736$, $p=0.997$) effects were non-significant, but there was a Group*Time interaction effect ($\chi^2(24)=71.726$, $p<0.001$). Post-hoc tests disclosed a DTR-duration reduction from baseline from Month 07 in the nap-intervention group ($p_s<0.032$) but not in the other groups (all $p_s > 0.083$; Figure 2 middle panel). Similarly for cumulative DTR-frequency, main Group ($\chi^2(2)=0$, $p=0.999$) and Time ($\chi^2(12)=19.564$, $df=12$, $p=0.076$) effects were non-significant, but there was a Group*Time interaction ($\chi^2(24)=58.261$, $p<0.001$). Post-hoc analyses showed significantly reduced values over the intervention from Month 05 onward in the nap-intervention group (all $p_s < 0.035$) but not in the other conditions (all $p_s > 0.097$; Figure 2 middle panel).

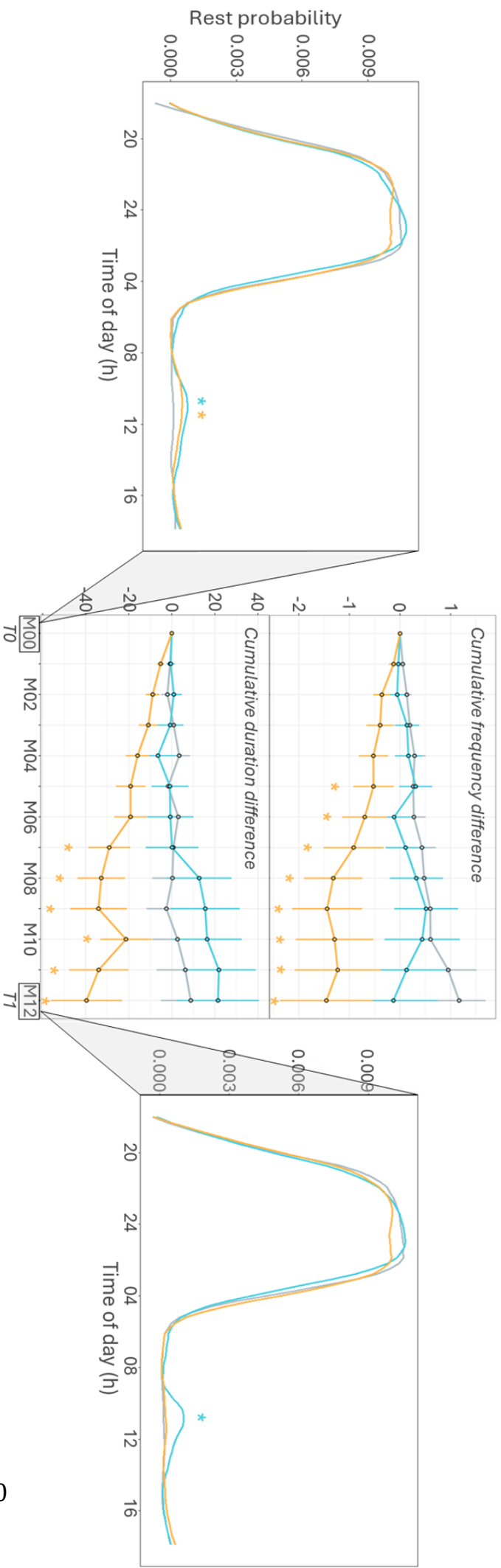


Figure 2. 24-hours rest probability profile plots at baseline (T0, left panel) and post-one year intervention (T1, right panel). Asterisks highlight time points with statistically significant differences between-group differences. At T0, participants in the nap-control and nap-intervention conditions had a higher rest probability during daytime than non-nappers. At T1, only participants in the nap-control condition had a higher daytime rest probability than the two other groups, showing that the nap-reduction intervention was successful. Middle panel: mean and SEM cumulative monthly differences from T0 baseline (M00) to T1 (M12) for DTR frequency (top panel) and duration (bottom panel). Asterisks highlight time points at which DTR parameters significantly differ from baseline in the nap-intervention group (post-hoc tests). Non-nappers: grey; nap-intervention: yellow; nap-control: blue.

In a second step, we analysed potential between-group differences in the rest probability profile at T0 and at T1 (Figure 3, left and right panels respectively). At T0, significant differences were observed between non-nappers and nappers-controls around 14:45 ($p=0.002$, $z > z^* = 3.02$), and between non-nappers and nappers-intervention around 13:30 ($p=0.013$, $z > z^* = 3.04$) and 14:45 ($p=0.006$, $z > z^* = 3.04$). Importantly, no statistically significant difference between nappers-control and nappers-intervention at baseline was found ($p>0.05$, $z < z^* = 3.11$). At T1, a higher rest probability was observed in the nap-control group around 13:45 as compared to both the non-nappers ($p=0.005$, $z > z^* = 3.04$) and the nap-intervention ($p=0.006$, $z > z^* = 3.03$) groups. No group differences were observed when comparing rest probability profiles between the no-nap and the nap-intervention group at T1 ($p>0.05$, $z < z^* = 3.11$). Despite the changes observed at the group level, rest-activity profiles within the nap-intervention group did not significantly differ between baseline and month 12 ($p > 0.05$, $z < z^* = 3.01$). In line with the significant reduction in DTR frequency and duration over the intervention period in the nap-intervention group, rest-activity profiles confirm that the intervention successfully reduced DTR in the active group, while rather stable profiles were kept in both control groups.

3.3. Cognition

We test the hypothesis that episodic memory performance would decline more over the one-year intervention time in the nap-control than in the two other groups. In regards for total number of words freely recalled during the FCRST, no significant Group ($\chi^2(2) = 1.104$, $p=0.576$) and Time ($\chi^2(1) = 1.924$, $p=0.165$) effects were found. There was however a Group*Time interaction effect ($\chi^2(2) = 8.335$, $p=0.015$), with a medium-to-large effect ($\beta=-0.43$, 95% CI [-0.82, -0.05]). Participants from the nap-control group exhibited a decline in performance between T0 and T1 compared to the non-nappers ($\beta=-2.321$, $t=-2.237$, $p=0.028$; Figure 3) and nap-intervention group ($\beta=-2.821$, $t=-2.719$, $p=0.008$). The performance from T0 to T1 did not statistically differ between nappers-

intervention and non-nappers ($\beta=0.500, t=0.490, p=0.625$). The analysis computed on the number of words recalled using given cues disclosed no Group effect ($\chi^2(2)=1.651, p=0.438$). The main Time ($\chi^2(1)=4.030, p=0.045$; post-hoc : $\beta=-1.433, t=-2.007, p=0.048$; medium effect: standardised $\beta=-0.31, [-0.61, -0.01]$) and the Group*Time ($\chi^2(2)=7.061, p=0.029$) effects were significant. Post-hoc tests showed that the nap-control group relied more on cues at T1 than at T0 ($\beta=-2.291, t=-2.229, p=0.029$; medium-to-large effect: standardised $\beta=0.49, [0.06, 0.92]$), as compared to non-nappers. Across both free and cued recall models, age had a small-to-medium effect: older participants freely recalled fewer words ($\beta=-0.226, t=-2.305, p=0.024$; small effect: standardised $\beta=-0.22 [-0.41, -0.03]$) and relied more on cues ($\beta=0.212, t=2.561, p=0.012$; small effect: standardised $\beta=0.24 [0.05, 0.42]$).

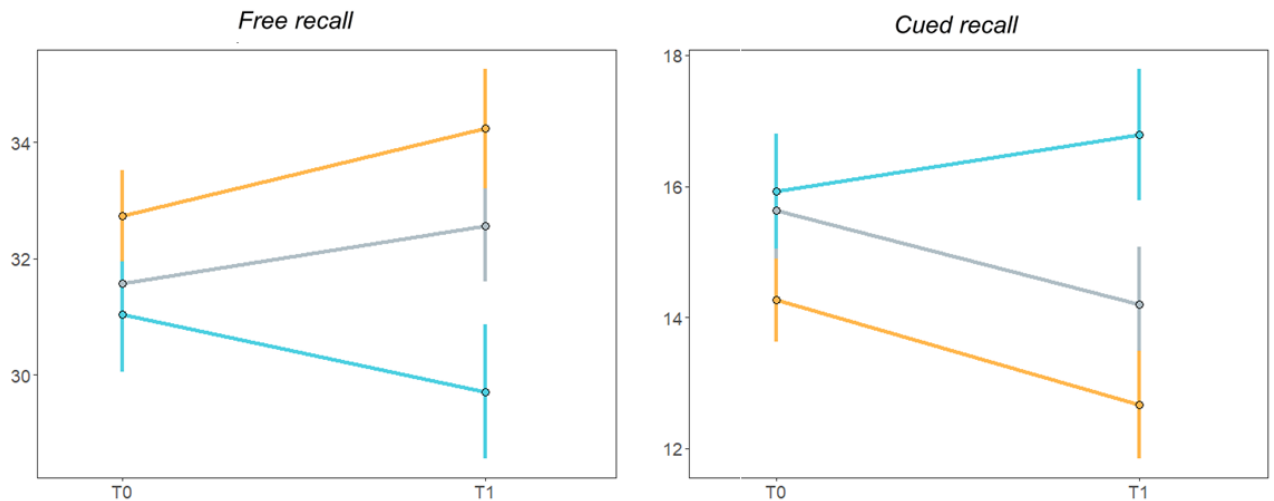


Figure 3. Episodic memory FCRST: changes in the mean total number of words recalled between baseline (T0) and follow-up (T1) for free (left panel) and cued (right panel) recalls. SEM are error bars. Non-nap group : gray, nap-intervention group : yellow, nap-control group : blue.

For MST performance (see Figure S2 panel A in Supplementals), Group ($\chi^2(2)=1.638, p=0.441$), Time ($\chi^2(1)=0.847, p=0.357$) and Group*Time interactions ($\chi^2(2)=1.379, p=0.502$) were non-significant in regards to LDI. Likewise, with REC, no statistically significant effect of Time ($\chi^2(2)=2.990, p=0.084$), Group ($\chi^2(2)=2.567, p=0.277$) nor Group*Time interactions ($\chi^2(2)=0.336, p=0.845$) were found.

Finally, for LM performance (Figure S2 panel B in Supplementals), we did not evidence Group ($\chi^2(2)=2.389$, $p=0.303$) nor Group*Time interaction ($\chi^2(2)=0.200$, $p=0.905$) effects. There was a statistical trend for a main Time effect ($\chi^2(1)=3.782$, $p=0.052$), with participants in all groups tending to perform better at T1 than at T0 ($\beta=1.517$, $t=1.945$, $p=0.055$; medium effect: standardised $\beta=0.35$, $[-0.01, 0.71]$). Furthermore, we found a statistically significant sex effect ($\chi^2(1)=4.448$, $p=0.035$), with women performing better than men in general ($\beta=1.754$, $t=2.109$, $p=0.038$; medium-to-large effect: standardised $\beta=0.41$, $[0.03, 0.79]$).

4. Discussion

This study tests whether modifying a common yet often overlooked behaviour, napping, could be part of a viable strategy to protect cognitive health in ageing. We found compelling evidence first that one can sustainably change napping habit and that such a simple change leads to preserved episodic memory over twelve months.

Daytime napping is a frequent, often well anchored, behaviour in older adults and its prevalence increases with age (Ficca et al., 2010). While often viewed as benign or even restorative, habitual napping has been associated with altered rest-activity rhythms (Leng et al., 2019; J. C. Lo, Ong, et al., 2016) and accelerated cognitive decline (Leng et al., 2019; Li et al., 2023; Overton et al., 2024). We provide longitudinal evidence that one can act on such a strong habit through a nap-suppression intervention using objective data derived from wrist actigraphy over a 12-month period, showing a prolonged reduction of both the frequency and duration of daytime rest episodes. DTR reduction at the group-level became statistically significant from month five onward and persisted until the end of the one-year follow-up.

From a cognitive perspective, our results suggest that reducing habitual daytime rest in cognitively healthy older adults may help preserve episodic memory over time, being a function commonly associated with both subjective and objective decline in ageing (Jessen et al., 2014; Koen & Yonelinas, 2014; Nyberg et al., 2012).

Only the nap-control group, who continued its napping habits, exhibited a significant increase in cue dependency and a sharper reduction in free recall at the FCRST. Age was also associated with a reduction in free-recall and enhanced cue-dependency. These findings suggest that the maintenance of napping behaviour over a one-year period may contribute to subtle but measurable cognitive vulnerabilities, in this case reflected by a reduced capacity in deliberate retrieval strategies. In other words, healthy older adults who napped regularly exhibit a more 'aged-like' profile than people of the same age-group who did not habitually nap, or stopped doing so. The observed decline in episodic memory after the 12-month period in the nap-control group may reflect the cognitive consequences of repeated daytime napping, which is increasingly associated with adverse neurocognitive outcomes in older adults (Álvarez-Bueno et al., 2022; Li et al., 2022). Specifically, frequent naps may induce a form of cognitive fragmentation, characterised by unstable transitions between wakefulness and drowsiness, disrupting the continuity of sustained cognitive engagement (Mander et al., 2016; Vyazovskiy et al., 2011). This pattern may mirror the effects of rest-activity cycle fragmentation, which was robustly linked to poorer memory and general cognitive performance (Kaneshwaran et al., 2019; Lim et al., 2012; Okuda et al., 2021; Oosterman et al., 2009). It is important to emphasize that, despite these shifts in retrieval strategy in the nap-control group, their overall recall remained high. Indeed, we did not see a drop in the total number of remembered words (free and cued together), but rather a greater reliance on cues to achieve the same global performance. By contrast, the nap-intervention group exhibited neither increased cue dependency nor any change in free-recall strategy, suggesting that suppressing daytime naps may help stabilizing how older adults retrieve episodic memories. Taken together, our findings offer valuable insights into potential avenues for clinical and translational application. Specifically, they underscore the relevance of targeting daytime napping as a modifiable behavioural factor to promote cognitive resilience in ageing. In addition, daytime napping could serve as a simple and accessible marker of individuals at increased risk of cognitive decline, which may

carry even greater implications by allowing early identification and timely intervention. Beyond a general stabilization of rest-activity rhythms, the maintenance of performance may also reflect the outcome of the reduced intrusions of sleep into the wake period, leading to more stable cognitive engagement and fewer fluctuations between alertness and drowsiness (Mander et al., 2016; Vyazovskiy et al., 2011). Such wakefulness continuity may support episodic retrieval processes, which are particularly vulnerable to fragmentation. While reduced habitual napping may have stabilised circadian rhythms, further investigation of the physiology of the circadian system associated with a one year napping suppression intervention would be needed to better understand its mediating role in cognitive trajectory. Moreover, repeated long or frequent naps could cause, or reflect the outcome of, impaired nocturnal sleep quality, interfering with memory consolidation and attentional regulation. Although our study did not include additional circadian or sleep markers, future work should incorporate actigraphic-derived rest-activity metrics and polysomnographic measures of nocturnal sleep to determine whether changes in sleep continuity or microarchitecture mediate the cognitive benefits of nap suppression. This nevertheless opens the door to incorporating nap suppression strategies into behavioural sleep interventions aimed at mitigating cognitive decline.

While the present study demonstrates behavioural and cognitive benefits of nap suppression over one year, some limitations chart directions for future work. First, the nap-intervention and nap-control groups unexpectedly differed in episodic memory performance at baseline, with the intervention group already outperforming controls despite similar napping and demographic profiles. This discrepancy could not be explained by differences in napping characteristics (duration, frequency, ...) or by season of assessment. To strengthen causal inferences, future trials could employ pre-trial matching on cognitive reserve or finer-grained cognitive performance (as compared to general mental state examinations), ensuring groups are equivalent before intervention, though it may turn out to be difficult in practice. Second, our sample consisted of a modest cohort

size of highly motivated and very compliant, independently living retirees, which may underpower subtle effects in follow-up measures and limit generalizability to frailer or less compliant older adults. Nevertheless, this study represents a substantial methodological and logistic effort, involving close to 100 cumulative years of continuous actigraphy collected across participants, alongside several hundred hours of cognitive testing. This underscores the robustness and value of the dataset despite its modest sample size. It is noteworthy that the observed effects were specific to episodic memory as assessed by the FCRST, while no significant group differences emerged for either MST or LM measures. This discrepancy may reflect differences in task sensitivity, with FCRST being more vulnerable to subtle changes in retrieval processes induced by daytime napping habits due to the strategic aspect involved. Alternatively, performance on MST and LM may be less influenced by daytime napping and more tightly related to age- or pathology-driven processes. For instance, MST performance has been consistently associated with hippocampal subfields particularly vulnerable to ageing and Alzheimer's disease pathology (Leal & Yassa, 2015; Reagh et al., 2018; Stark et al., 2019), and LM recall has been shown to decline in relation to AD pathology and hippocampal atrophy (Ezzati et al., 2016; Kramer et al., 2004; Wong et al., 2022). A further explanation could be ceiling effects, as overall performance in these follow-up measures remained high across groups. Subsequent studies would benefit from larger, more heterogeneous samples (including cognitively *at-risk* individuals) to test the preventive potential of napping interventions in a broader population, most probably only achievable through a multicentric clinical trial. As regular napping has previously been associated with a decreased brain activity asymmetry in working memory in the same cohort (Reyt et al., 2025), future functional neuroimaging studies could help characterise the impact of nap suppression on brain functioning. Finally, the continued longitudinal monitoring of participants beyond the initial 12-month period would allow the assessment of the durability of the intervention's effects and further clarify the long-term cognitive trajectories associated with changes in daytime napping behaviour.

4.1. Conclusion

Altogether, our findings support the hypothesis that regular daytime napping, while widespread, seems to not be neutral in ageing, and that targeted behavioural interventions may lead to durable changes in both rest-activity rhythms and cognitive trajectories. Nap-suppression intervention could be a promising avenue to prevent age-related functional cognitive decline in healthy old populations, and provides a solid foundation for initiating research on nap suppression and its potential impact on cognitive impairment associated with the onset of neurodegenerative diseases such as Alzheimer's disease.

Supplementals:

		Non-nap		Nap-control		Nap-intervention		Statistical effects		
		T0	T1	T0	T1	T0	T1	Group	Time	Group*Time
Attention	DSST	65.9 ± 12.7	64.8 ± 12.1	63.9 ± 11.5	62.4 ± 12.1	70.5 ± 10.4	69.6 ± 11.8	p=0.06	p=0.46	p=0.98
	TMT (v.A)	35.3 ± 9.69	33.8 ± 8.59	37.0 ± 7.24	37.5 ± 9.98	30.5 ± 9.36	31.3 ± 8.4	p=0.01	p=0.26	p=0.35
	PVT	3.25 ± 2.70	2.82 ± 2.66	3.12 ± 2.59	4.48 ± 3.82	3.52 ± 2.84	2.86 ± 2.42	p=0.93	p=0.57	p=0.04
	D2	399 ± 71.2	378 ± 73.7	383 ± 531	369 ± 84.6	394 ± 61.8	417 ± 66.8	p=0.65	p=0.03	p=0.002
	Visual Attention	843 ± 82	878 ± 86	851 ± 83	827 ± 105	857 ± 94	865 ± 84	p=0.37	p=0.19	p=0.73
	PS	700 ± 102	682 ± 97.8	693 ± 93.3	703 ± 90.9	662 ± 73.3	672 ± 71.1	p=0.29	p=0.91	p=0.94
	1-BACK	642 ± 101	618 ± 62	660 ± 113	635 ± 87.7	622 ± 69	638 ± 78.1	p=0.22	p=0.30	p=0.26
Executive functions	2-BACK	2.35 ± 0.98	2.88 ± 0.76	2.04 ± 0.84	2.46 ± 0.83	2.19 ± 0.82	3.02 ± 0.93	p=0.43	p=0.004	p=0.18
	3-BACK	1.07 ± 0.59	1.63 ± 0.59	0.96 ± 0.51	1.30 ± 0.66	1.12 ± 0.34	1.38 ± 0.29	p=0.53	p<0.001	p=0.11
	Verbal fluency	58.4 ± 15.9	43.7 ± 10.2	54.0 ± 13.3	42.2 ± 10.4	58.3 ± 12.7	45.5 ± 14.3	p=0.38	p<0.001	p=0.55
	TMT (v.B)	81.9 ± 21.9	80.3 ± 22.3	89.5 ± 25.6	84.7 ± 25.3	70 ± 20.4	70.5 ± 21.0	p=0.004	p=0.67	p=0.68
	Digit span	6.5 ± 1.92	6.17 ± 1.60	5.43 ± 1.26	5.54 ± 1.99	6.57 ± 2.01	6.57 ± 1.83	p=0.03	p=0.30	p=0.61
	Stroop	46.9 ± 20.2	49.8 ± 17.0	50.7 ± 14.3	50.0 ± 15.2	52.4 ± 19.2	50.6 ± 17.4	p=0.46	p=0.54	p=0.73
Memory	FCRST	31.6 ± 4.86	32.6 ± 5.25	31.0 ± 5.21	29.7 ± 6.07	32.7 ± 4.28	34.2 ± 5.61	p=0.58	p=0.17	p=0.015
	MST	0.827 ± 0.073	0.804 ± 0.078	0.788 ± 0.095	0.776 ± 0.108	0.812 ± 0.1	0.796 ± 0.083	p=0.28	p=0.08	p=0.85
	Logical Memory	11 ± 4.62	12.5 ± 4.08	9.14 ± 4.10	10.5 ± 3.94	10.4 ± 4.06	11.4 ± 4.53	p=0.30	p=0.052	p=0.91

Table S1. Mean and standard deviations of cognitive scores comprising the cognitive battery, at baseline (T0) and 1-year follow-up (T1), for all groups. Group, Time and Group*Time interaction p-values from a linear regression analyses realized separately on all scores, according to these 2 factors are reported. **Attention tests** are composed of the Digit Symbol Substitution Test (DSST, number of substitution correctly done, Wechsler, 1940), version A of the Trail Making Test (TMT, total time in s, Partington & Leiter, 1949), Psychomotor Vigilance Test (PVT, number of lapses, Dinges & Powell, 1985), D2 (number of targets correctly identified; Brickenkamp & Zilmer, 2011), Visual Attention (Reaction time in ms; Zimmermann & Fimm, 2002), Processing Speed (Reaction time in ms; Zimmermann & Fimm, 2002), 1-back (Reaction times in ms; Kirchner, 1958). **Executive functions** were tested by 2- and 3-Backs (d-prime; Kirchner, 1958), Verbal Fluency (number of words given, both phonological and semantical,), version B of the TMT (in s; Partington & Leiter, 1949), Digit span (number of items correctly recalled; Blackburn & Benton, 1957), and Stroop (timing difference between the interference and denomination trials; (Albaret & Migliore, 1999). **Memory** were represented by the Free and Cued Recall Semantic Test (FCRST, total number of words freely recalled; Grober & Buschke, 1987), Mnemonic Similarity Test (MST, REC; Stark et al., 2013), and story B of the Logical Memory task (total number of details recalled; Wechsler, 2009).

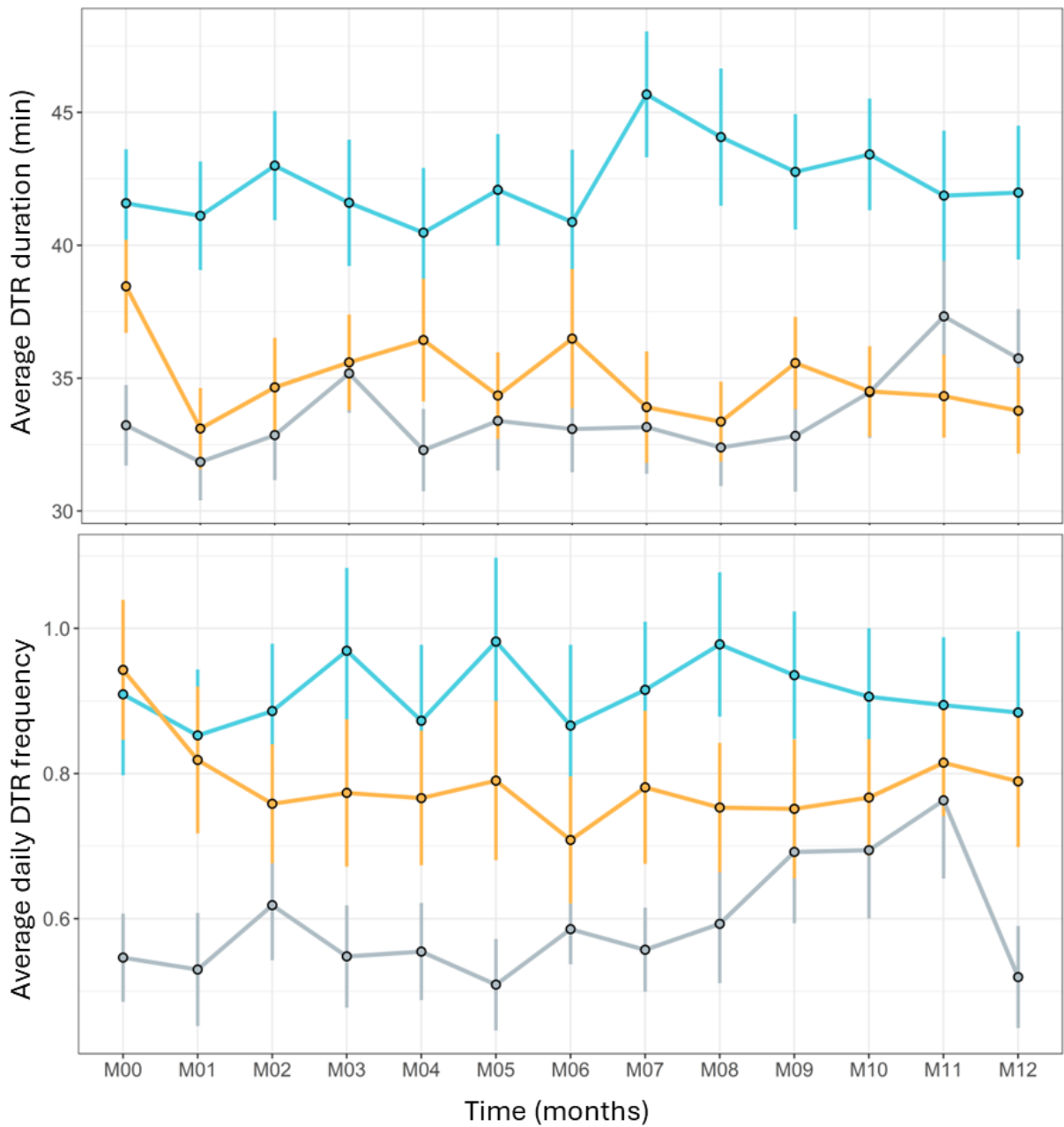


Figure S1. Average time-course of the raw daily daytime rest (DTR) frequency (bottom panel) and duration in minutes (upper panel) according to Groups across the 12-month period, with M00 being the baseline actimetry assessment. SEM are depicted in lines. Non-nap group is in grey, Nap-control group is in blue, and Nap-intervention group is in yellow.

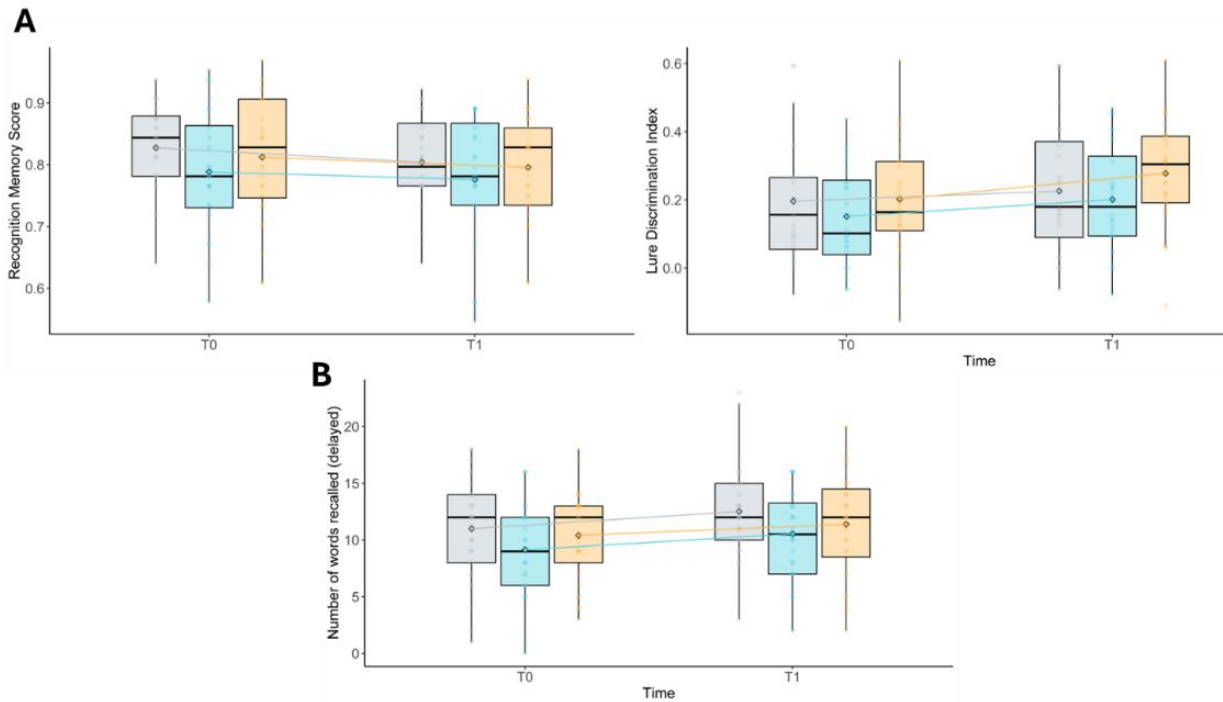


Figure S2. Boxplots represent the distribution of scores at baseline (T0) and follow-up (T1) across groups (median, interquartile range, whiskers). Individual data points are shown as jittered dots (semi-transparent) color-coded by group. Diamonds indicate group means, which are connected by lines to illustrate changes over time. (A) MST performance for Recognition Memory Score (REC) on the left, and Lure Discrimination Index on the right. (B) Logical Memory task performance, as the number of words remembered during the delayed recall. Non-nap group is depicted in grey, Nap-control group is depicted in blue, and Nap-intervention group is depicted in yellow.

Study 4. Acting on napping habits modulates the cerebral correlates underlying working memory in healthy ageing

Marine Dourte^{1,2,3}, Mathilde Reyt⁴, Gregory Hammad¹, Stella de Haan¹, Michele Deantoni¹, Marion Baillet⁵, Alexia Lesoinne¹, Vincenzo Muto¹, Marine le Petit¹, Fabienne Colette¹, Gilles Vandewalle¹, Christophe Philipps¹, Nikita Beliy¹, Philippe Peigneux^{1,3,*},
Christina Schmidt^{1,2,*}

¹ GIGA-CRC Human Imaging Unit, Sleep and Chronobiology Laboratory , University of Liège, Liège, Belgium.

² Psychology and Neuroscience of Cognition Research Unit (PsyNCog), Faculty of Psychology and Educational Sciences, University of Liège, Liège, Belgium.

³ UR2NF, Neuropsychology and Functional Neuroimaging Research Unit, Center for Research in Cognition and Neurosciences, ULB Neurosciences Institute, Université Libre de Bruxelles (ULB), Brussels, Belgium.

⁴ Centre de Recherche de l'Institut Universitaire de Gériatrie de Montréal (CRIUGM) & Concordia University

⁵ Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA

In preparation

Abstract: Ageing is linked to working memory (WM) decline and altered brain activation, often marked by compensatory overactivation and reduced hemispheric asymmetry. Sleep-wake fragmentation, such as habitual napping, further predicts poorer WM and dorsolateral prefrontal cortex (DLPFC) recruitment, in older adults. We tested whether reducing napping mitigates WM decline and neural alterations. Eighty-two older adults were prospectively recruited regarding their non-napping (n=26) or habitual napping (n=56) habits. Twenty-eight nappers completed a 12-month intervention reducing nap frequency/duration, while 28 nap-controls and 26 non-nappers were followed without intervention. WM and brain activity were assessed with fMRI during a Sternberg task, before and after follow-up. Continuous actigraphy confirmed a progressively reduced nap frequency/duration in the nap-intervention group only. WM performance was preserved in intervention and non-nap groups but declined under high WM load in nap-controls. Left-lateralized DLPFC recruitment supported performance in non-nappers but predicted poorer performance in both nap groups. Nap-intervention participants exhibited increased bilateral recruitment in WM-related regions, especially occipital areas, positively linked to performance. Thalamic activation declined across groups, steepest in nap-controls. Sleep-wake behaviour thus appears modifiable to support WM and brain function in ageing, with reduced napping fostering compensation-like activation and continued napping favouring dedifferentiation.

Keywords (5): Working memory; Brain ageing ; Daytime napping ; functional compensation ; Functional MRI

1. Introduction

Successful cognitive ageing is thought to emerge from a dynamic interplay between adverse and compensatory brain mechanisms (Cabeza et al., 2018; Reuter-Lorenz & Park, 2014; Stern et al., 2020), a process that likely contributes to the marked inter-individual variability observed in older adults' cognitive trajectories. Differences range from individuals showing early signs of pathological decline to so-called "successful agers" who maintain performance levels comparable to younger adults (Lupien & Wan, 2004; Nyberg et al., 2012). Especially vulnerable to ageing, working memory (WM) capabilities are supported by structural and functional neural adaptations that change across the lifespan (Kaup et al., 2014; Macpherson et al., 2014; Suzuki & Meehan, 2018).

The dorsolateral prefrontal cortex (DLPFC) plays a pivotal role in WM functioning (Barbey et al., 2013; Haque et al., 2021; Mirino et al., 2024). In WM fMRI studies, young adults show a mostly left-lateralized increase in DLPFC activation with growing task difficulty, with the BOLD signal linearly rising up with difficulty levels (Cappell et al., 2010). In contrast, older adults tend to over-activate the DLPFC and task-related networks even at lower task difficulty levels (Cabeza et al., 2018; Grady, 2012). Moreover, they tend to recruit additional neural networks that are not typically engaged by younger individuals (Cabeza et al., 2018). This could reflect a loss of specificity in neural responses (a phenomenon known as dedifferentiation; Knights et al., 2021; Morcom & Henson, 2018) and/or reduced brain asymmetry (Cabeza et al., 2002; Dolcos et al., 2002). While the recruitment of supplementary neural resources is often associated with successful task performance (Saliasi et al., 2014), the fact that older adults tend to recruit the DLPFC bilaterally in WM tasks at lower difficulty levels entails fewer supplemental or compensatory resources available to behaviourally adapt to increasing task demands (Cappell et al., 2010; Mattay et al., 2006; Nyberg et al., 2009; Reuter-Lorenz et al., 2000; Schneider-Garces et al., 2010). Indeed, as cognitive load increases, older adults approach faster their functional resource limits. It results in a ceiling effect at higher task difficulty levels, first marked by a plateau in DLPFC

activation then a reduced BOLD response and a concomitant decline in task performance (Cappell et al., 2010; Mattay et al., 2006; Reuter-Lorenz & Cappell, 2008; Schneider-Garces et al., 2010). Independently of task demands, it was also reported that increased activation in posterior as compared to prefrontal areas enables older individuals to maintain, or even enhance, their cognitive performance by compensating for age-related sensory deficits in occipito-temporal areas (Davis et al., 2008; Festini et al., 2018).

Importantly, lifestyle factors play an important role in compensatory capacities and brain's cognitive reserve (Cabeza et al., 2018; Stern et al., 2020). This reserve represents the brain's capacity to maintain cognitive function despite age-related changes or pathology (Soldan et al., 2017) by adapting its functioning, flexibility, as well as accumulating resources that will attenuate age-related decline (Stern, 2002; Stern et al., 2020). It is built throughout the lifespan, and the cognitive efficiency as well as its structural and functional brain correlates are modulated by variables including amongst others physical activity, education level, stress or cognitive activity (Cabeza et al., 2018; D'Aurizio et al., 2023; Reuter-Lorenz & Park, 2014; Stern et al., 2023). Sleep-wake cycle characteristics have also been proposed as a main contributing factor in the age-related evolution of both cognition (Heyde et al., 2018; Kokošová et al., 2021; Mander et al., 2013; Scullin et al., 2017) and brain functional compensation (Almklov et al., 2015; Gaggioni et al., 2014; Moon et al., 2020). In this framework, daytime napping can be conceptualised as an intrusion of sleep into the active wake period that reflects a fragmentation of the sleep-wake cycle. It was shown that an increased sleep-wake cycle fragmentation in older participants (Lim et al., 2011; Luik et al., 2013; Zuurbier et al., 2015) is linked to lower cognitive performance (Benkirane et al., 2022; Luik et al., 2015; Oosterman et al., 2009), including in the WM domain (Lim et al., 2012; Okuda et al., 2021). Moreover, the incidence of daytime napping that tend to increase with advanced age (Foley et al., 2007; Leng et al., 2018; Li et al., 2018) was linked with observations that daytime rest is associated with overall inferior cognitive (Blackwell et al., 2006; Cross et al., 2015; Leng et al., 2019; Owusu et al., 2019) and

reduced episodic memory (Reyt et al., 2022) performance, depending on characteristics such as frequency, duration, and intentionality (Li et al., 2022; Mednick et al., 2003; Mednick, 2024; Owusu et al., 2019). Our group found an association between habitual napping in older adults and altered WM-related brain responses, particularly a reduction in hemispheric DLPFC asymmetry (Reyt et al., 2025). While this reduction could theoretically reflect compensatory mechanisms at lower cognitive loads to maintain good performance levels, this additional recruitment is not linked to improved WM performance at higher load in habitual nappers, who furthermore exhibited a performance decline when compared to non-nappers. This may hint towards a compensational limit being reached, and the bilateral and increased activation falling in the domain of dedifferentiation, i.e., not serving any cognitive purpose. From another perspective, we found increased thalamic recruitment in habitual older nappers, which may suggest a heightened wake state instability, possibly reflecting difficulties in sustaining alertness over prolonged cognitive effort in a task setting (Reyt et al., 2025).

In the present study, we tested the hypothesis that reducing nap habits over one year in habitual older nappers would counteract the age-related decline in WM performance and the associated alteration in functional brain correlates. The rationale behind a nap suppression relied on the fact that it would contribute to enhance circadian sleep-wake regulation by re-attributing sleep to the night and wakefulness to the day. According to this hypothesis, as compared to habitual non-nappers, habitual nappers who continue napping over a one-year period would display a more pronounced decline in WM performance, especially at higher WM load. At variance, habitual nappers who significantly reduce napping over the one-year intervention period would exhibit a better outcome at follow-up, more similar to the usual non-nappers' trajectory. We further expected that, while all participants would show an age-related change in brain activation, habitual nappers who continued napping would exhibit at follow-up after one year (a) a non-compensatory overactivation and a further reduced asymmetry in the DLPFC, exacerbated at lower WM load; (b) an increased and bilateral recruitment in a more

extended set of WM-related regions (including frontal, temporal, parietal and occipital regions), reflecting a more aged-like profile of spread activation in the brain; and (c) an increased thalamic recruitment especially in the right hemisphere accounting for a higher wake state instability during task effort, as compared to usual non-nappers and nap-intervention participants. We expected a positive correlation between left-DLPFC BOLD activation and WM performance at both evaluation times for the non-nap group, and only at the one-year follow-up for the nap-intervention group. This would evidence efficient compensatory mechanisms against the age-related decline in these individuals linked to their non-nap habits, or to the nap-reduction in the intervention group. Moreover, we did not expect overactivation in the DLPFC to be linked to WM performance in continued nappers, indicating a dedifferentiation-like over-recruitment.

2. Methods

2.1. Participants

Eighty-two retired participants (mean age = 69.0 years, SD = 5.3) were prospectively recruited with respect to their napping habits (see Supplementals for detailed exclusion criteria). Fifty-six participants self-reported napping at least 3 times a week for more than 30 minutes and for more than a year. Half of these individuals were randomly assigned to either a nap-intervention group (n=28), who received instructions and support to significantly reduce daytime napping, or to a nap-control group (n=28), without any intention to act on the nap behaviour. An additional group of non-nappers (n=26) were included as an observational reference group. Actimetry-derived daytime rest characteristics recorded before inclusion were used to confirm group classification, and a polysomnography night was used to screen for sleep apnoea and periodic limb movements. Groups were matched with respect to age, sex, body mass index (BMI), self-reported sleep quality over the past month (Buysse et al., 1989) and chronotype (Horne & Ostberg, 1976). Demographic characteristics are summarized in Table 1.

		T0 Mean (SD)	T1 Mean (SD)	Group p	Time p	Group x Time p
Age (years)	No-Nap	69.1 (5.61)	—	$p=0.60^a$	—	
	Nap-ctrl	69.6 (5.10)				
	Nap-int	68.6 (5.33)				
Education (years)	No-Nap	14.1 (3.65)	—	$p=0.64^a$	—	
	Nap-ctrl	14.6 (3.97)				
	Nap-int	14.7 (3.36)				
Sex	No-Nap	17 men, 9 women	—	$p=0.83^b$	—	
	Nap-ctrl	20 men, 8 women				
	Nap-int	18 men, 10 women				
BMI	No-Nap	24.8 (2.47)	24.4 (2.41)	$p=0.27^d$	$p=0.51^d$	$p=0.15^d$
	Nap-ctrl	25.0 (2.90)	25.6 (3.33)			
	Nap-int	25.8 (2.91)	26.0 (2.90)			
PSQI	No-Nap	4.77 (2.78)	4.46 (2.18)	$p=0.50^a$	$p=0.69^a$	$p=0.97^d$
	Nap-ctrl	4.86 (2.17)	4.77 (2.50)			
	Nap-int	5.46 (2.84)	5.33 (3.25)			
MEQ	No-Nap	64.1 (6.39)	57.3 (7.03)	$p=0.99^d$	$p<0.001^d$	$p=0.16^d$
	Nap-ctrl	64.7 (7.96)	55.4 (8.77)			
	Nap-int	64.1 (7.69)	55.5 (7.38)			
ESS	No-Nap	6.92 (3.38)	5.69 (4.09)	$p=0.03^d$	$p=0.08^d$	$p=0.41^d$
	Nap-ctrl	8.57 (3.73)	8.54 (4.54)			
	Nap-int	<u>9.36 (3.78)</u>	<u>9.47 (2.86)</u>			
BDI	No-Nap	3.38 (3.48)	2.4 (3.16)	$p=0.07^d$	$p=0.99^d$	$p=0.98^d$
	Nap-ctrl	4.5 (3.71)	3.5 (3.89)			
	Nap-int	4.43 (3.12)	4.00 (4.05)			
BAI	No-Nap	3.10 (4.41)	2.88 (3.96)	$p=0.29^d$	$p=0.99^d$	$p=0.26^d$
	Nap-ctrl	3.96 (3.89)	3.27 (3.81)			
	Nap-int	2.70 (4.28)	3.47 (3.59)			
Season of Assessment	No-Nap	8 Sp, 5 Su, 7A, 6 W ($p=0.96^c$)	9 Sp, 5 Su, 4A, 9W ($p=0.37^c$)	—	—	
	Nap-ctrl	6 Sp, 7 Su, 10A, 5 W ($p=0.50^c$)	2Sp, 7Su, 8A, 7W ($p=0.10^c$)			
	Nap-int	4 Sp, 2 Su, 13A, 9W ($p=0.02^c$)	5Sp, 4Su, 7A, 10W ($p=0.06^c$)			

Table 1. Demographical and questionnaires data by Group (mean and standard deviation) and Time (Baseline, T0, vs. 1-year follow-up, T1). For statistical analyses, ^a refers to kruskal-wallis test, ^b to Chi-square test, ^c to Rayleigh test, ^d to linear model with factor Group, Time and Group*Time interactions. In case of statistically significant group differences, the group that differed from the non-nap reference group is underlined. Abbreviations are as follows: No-Nap = No-nap group (n=26), Nap-ctrl = Nap-control group (n=28), Nap-int = Nap-intervention group (n=28), BMI= Body Mass Index, PSQI= Pittsburgh Sleep Quality Index (Buysse et al., 1989), MEQ = Morningness-Eveningness Questionnaire (Horne & Ostberg, 1976), ESS = Epworth Sleepiness Scale (Johns, 1991), BDI = Beck Depression Inventory (Beck & Steer, 1984), BAI = Beck Anxiety Inventory (Beck et al., 1988), Seasons (Sp= Spring, Su = Summer, A=Autumn, W=Winter).

2.2. Study procedure and napping intervention

The study was approved by the local Ethics Committee of the University Hospital and of the Faculty of Psychology, Speech Therapy and Educational Sciences at the University of Liège (Belgium; n° 30258856) and performed in accordance with the Declaration of Helsinki. Participants gave written informed consent and received a financial compensation.

As stated above, actigraphy was recorded at study enrolment for a minimum duration of eight days while participants maintained their normal sleep-wake routines at home to derive daytime rest (DTR) features (see below). All participants also filled in questionnaires about demographical information, perceived sleep quality (Pittsburgh Sleep Quality Index (PSQI), Buysse et al., 1989) and chronotype (Morningness-Eveningness Questionnaire (MEQ), Horne & Ostberg, 1976), daytime sleepiness (Epworth Sleepiness Scale (ESS), Johns, 1991), Mood (BDI, Beck & Steer, 1984; BAI, Beck et al., 1988), and napping habits. Following this initial phase, participants were administered a baseline assessment (T0) including a working memory task during a functional MRI scan. The latter was generally collected in the afternoon (between 13:30 and 16:00).

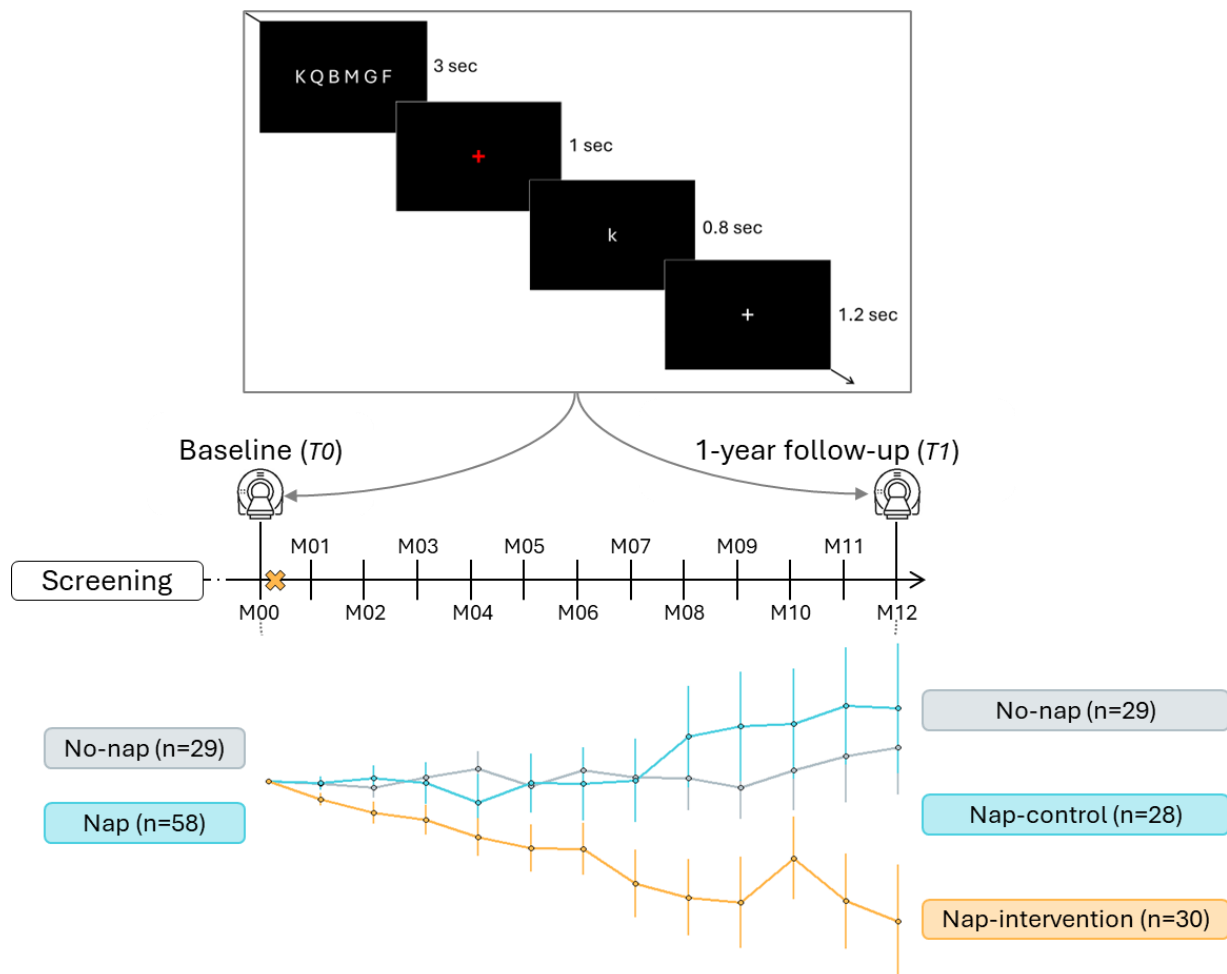


Figure 1. Graphical representation of the study procedure. After eligibility verification during the screening visits, Baseline (T0) and one-year follow-up (T1) are depicted. At both times, the Sternberg paradigm WM task was administered in functional MRI session. The yellow cross represents the general sleep hygiene somno-education delivered to all groups, as well as the randomised new nap-group assignment to either the nap-control group (could continue napping) and the nap-intervention group (received specific indication and advice to actively reduce their nap habit over the course of the intervention).

A graphical representation of a trial of the Sternberg paradigm task is depicted above the study protocol timeline. A 3 second presentation period shows, in this example, a set of 6 upper case consonant letters (MSS 6), followed by a maintenance period of 1 second represented by a red cross. The 2 second retrieval period is comprised of the presentation of the target of one lower case vowel during 0.8 second, in this case a "hit" response, followed by a white centred cross for 1.2 second.

Bottom graph: The 12-month intervention period, during which continuous actimetry recording and monthly questionnaires were acquired, is represented by M01 to M12. The bottom figure timeline depicts the evolution of nap-habit characteristics (average DTR-duration in minutes) by month and group, normalized to M00 (cumulative sums of difference from baseline), illustrating the significant reduction in napping behaviour in the nap-intervention condition.

After baseline testing at T0, regular nappers were randomly attributed to either the "nap-control" (N = 28) or "nap-intervention" (N = 28) condition. All participants, including regular non-nappers, underwent a structured somno-education session modelled on cognitive-behavioural therapy principles (Heyde et al., 2018). All groups received general sleep hygiene coaching, but specific requirements for the

nap-intervention group were given regarding napping habits. A behavioural treatment regimen was applied, with instructions to gradually and significantly reduce napping habits, both in terms of frequency and duration over the course of the one-year study. Wrist-based actimetric activity was continuously recorded in all participants during the one-year intervention period and further used to track participants' adherence to the instructions provided during the intervention and the evolution of daytime rest characteristics for all groups over the follow-up period. Participants were contacted weekly during the first month, and monthly thereafter to extract actimetry data, change batteries, assist participants in making needed adjustments in their sleep-wake behaviour and reinforce adherence to the nap manipulation protocol.

At the end of the one-year intervention period (T1), participants returned to the laboratory and were administered the same Sternberg WM task during a functional MRI scan. To evaluate temporal changes and the potential effect of the nap intervention, all participants repeated the baseline questionnaires (PSQI, MEQ, ESS, nap habit).

2.3. Actigraphy: daytime rest characteristics

Participants wore an actigraphy device (Motionwatch 8; CamN-tech) at the nondominant wrist and completed a sleep diary for at least eight consecutive days during the screening period, with a maximum duration of 15 days (13.58 ± 1.81 days), and then for a whole year with monthly check-ups between T0 and T1. Tri-axial activity data and light levels, aggregated into 30-s epochs, were extracted with the MotionWare software (v1.2.28) and processed by the open-source software pyActigraphy (v1.2, Hammad et al., 2021). Segments in which the actigraphy device was removed (e.g., shower time or swimming, omissions ...) were identified based on sleep diaries and visual inspections and excluded from the analyses. Consolidated rest periods were automatically identified using the Munich Actimetry Sleep Detection Algorithm (MASDA; Roenneberg et al., 2015), with a threshold on activity counts at 15% of the 24-hour centred moving average, as

validated in Loock et al. (2021). In order to increase the algorithm sensitivity to detect short daytime rest periods, the minimal rest bout duration was set to 15 minutes instead of 30 (see also Reyt et al. (2022) for the performance assessment of this setting against visual scoring and sleep agenda-derived indices). For the extraction of daytime rest (DTR) frequency and duration, we identified rest periods during the biological day (between 10h00 and 19h30 as in Reyt et al. (2022)), with a duration comprised between 15 minutes and 4 hours. Early morning and late evening transition times were left out of the target time frame to reduce the possibility of confounding late or early night sleep effects. DTR frequency (mean number of DTR bouts per day) and DTR duration (overall mean duration of DTR bouts) were computed at baseline before inclusion and per intervention month resulting in 13 averaged points per participants (M00:M12). To assess treatment adherence (intervention vs nap- and no-nap-control) over the intervention period, cumulative sums of difference from baseline were computed per participant for DTR-frequency and DTR-duration over the 12-months intervention period. A generalised linear mixed-model (GLMM, glmmTMB package, Brooks et al., 2017) was used to assess the participants' compliance to their group nap-related behaviour over the course of the one-year actimetry follow-up. To do so, the cumulative sum of difference from baseline for DTR-frequency and DTR-duration were compared between groups (3 levels) and over time (13 levels). A gamma family with a log link function, as well as a random intercept per subject was applied.

2.4. Working memory paradigm and analysis

During functional MRI acquisition, participants completed a Sternberg task with six memory set sizes (MSS), ranging from 2 to 7 consonants (except letters P, W, X and Z) to memorize. Letters were presented at the centre of the screen in Arial font with a 120-pixel font size. The Sternberg task was presented using Psychophysics Toolbox Version 3.0.15 (Brainard, 1997; Kleiner et al., 2007) running on Matlab R2017a (The MathWorks, Inc., Natick, MA).

During encoding, a set of 2 to 7 white consonant letters were simultaneously displayed on a black screen, in uppercase letters (Figure 1). Each trial started by the presentation of a memory set during 3-s, followed by a 1-s maintenance interval (red fixation cross). Then, the probe letter was presented during 0.8-s, followed by a white fixation cross during 1.2-s. During this retrieval period (2-s), participants had to indicate as quickly and accurately as possible, by pressing one of the two responses keys, whether the probe was part of the memory set or not. Each block was composed of 4 trials of the same set size and participants completed 48 blocks (8 blocks by 6 MSS). A grey fixation cross was displayed during 15-s between each block, allowing for a short break. The order of block presentation was pseudo-randomized to avoid presentation of consecutive blocks of the same MSS. For each MSS, the probe was part of the memory set on half of the trials. Two lists of different 48 blocks were used, allowing to switch lists between baseline and follow-up, to ensure no test-retest effect.

Before being installed in the MRI scanner, participants underwent a training session, composed of 10 trials using the six MSS. The training was performed as many times as necessary to ensure that participants understood the task and reached at least 70% accuracy. Five trials were also performed just after participants' installation in the MRI scanner to verify response keys functionality and screen visibility.

To assess the effect of Group (3-levels factor: non-nap, nap-control and nap-intervention), WM load (6 level factor: 2-7 letters), Time (2-level factor: T0 vs. T1) and their interaction on WM accuracy, generalised linear mixed models (GLMM) were conducted to account for the non-normality of the data (Shapiro-Wilk, $W=0.90$, $p<0.001$). Non-parametric model comparison using the Akaike information criterion was used to estimate the best model and inclusion of covariates to increase the model's fit. Helmert contrasts were used to compare the performance of a WM load to the averaged performance of all previous memory loads. In a second step, a linear mixed model (lmerTest package; Kuznetsova et al., 2017) was used to assess the effect of same factors and interactions on reaction

times, also using Helmert contrasts coding for the WM load factor. Similarly to WM accuracy, covariates were added after comparing models and keeping the model with the lower Akaike information criterion. All statistical analyses were conducted using R version 4.2.1 (R Core Team, 2020).

2.5. Functional magnetic resonance imaging protocol & analysis

Functional MRI data were collected using a 3 Tesla whole-body scanner (Magnetom Prisma, Siemens Medical Solutions, Erlangen, Germany) equipped with a 64-channel head coil. Functional images were acquired using a T2*-weighted multiband gradient-echo echo-planar imaging (EPI) sequence (CMRR, University of Minnesota), oriented axially to cover the entire brain (36 slices, multiband acceleration factor = 2, field of view = $216 \times 216 \text{ mm}^2$, voxel dimensions = $3 \times 3 \times 3 \text{ mm}^3$, 25% inter-slice gap, matrix size = $72 \times 72 \times 36$, TR = 1170 ms, TE = 30 ms, flip angle = 90°). To mitigate T1 saturation effects, the initial four volumes of each run were excluded from analysis. Physiological signals (cardiac pulse and respiration), were continuously monitored throughout scanning using a pulse oximeter and a respiratory belt, respectively.

To enable distortion correction of the EPI images, field maps were generated using a gradient-recalled sequence that acquired two complex images at echo times of 10.00 ms and 12.46 ms (TR = 761 ms, field of view = $192 \times 192 \text{ mm}^2$, matrix = 64×64 , 48 transverse slices with 3 mm thick-ness and 50% inter-slice gap, flip angle = 90° , bandwidth = 260 Hz/pixel). For anatomical reference, each participant underwent a high-resolution T1-weighted scan using a 3D magnetization-prepared rapid gradient echo (MPRAGE) sequence (TR = 1900 ms, TE = 2.19 ms, inversion time = 900 ms, field of view = $256 \times 240 \text{ mm}^2$, matrix size = $256 \times 240 \times 224$, voxel size = $1 \times 1 \times 1 \text{ mm}^3$, acceleration factor R = 2 along the phase-encoding direction).

2.6. Image preprocessing

Data preprocessing and analyses were carried out using the SPM12 software package (Wellcome Centre for Human Neuroimaging, www.fil.ion.ucl.ac.uk/spm) running on Matlab R2020b.

For each session, participants' T1-weighted anatomical scans were reoriented to match the Montreal Neurological Institute (MNI) template. Functional runs from both sessions were initially corrected for head motion using the "Realign: Estimate & Reslice" procedure, which generated a mean realigned image. This mean image was subsequently segmented into grey and white matter using the unified segmentation framework (Ashburner & Friston, 2005) as implemented in SPM12. Concurrently, echo-planar imaging (EPI) time series and field maps from each session were used to compute voxel displacement maps and underwent motion and distortion correction via the "Realign & Unwarp" module. The anatomical mean image was then co-registered to the resulting mean functional image. All images were normalized to MNI space and spatially smoothed using a Gaussian kernel of 8 mm full width at half maximum (FWHM).

Physiological noise correction was performed by extracting 14 regressors derived from a model accounting for variations linked to both cardiac and respiratory cycles, following the approach described by Hutton et al. (2011). This model incorporates sine and cosine Fourier expansions, extending to the 5th harmonic for cardiac and 3rd harmonic for respiratory components, to capture high-order physiological fluctuations.

For each participant, blood-oxygen-level-dependent (BOLD) signal changes were modelled using the general linear model (GLM). Experimental blocks corresponding to each MSS were represented as boxcar functions convolved with the canonical hemodynamic response function. Regressors for motion and physiological signals were included as nuisance covariates. Within each MSS, separate regressors were defined for all responses (correct and incorrect), incorrect responses only, and omitted responses; however, only the "all responses"

condition was retained for statistical analysis. Reaction time was added as a parametric modulator. A high-pass filter with a cutoff of 250 seconds was applied to remove low-frequency signal drifts. Serial correlations in the fast acquisition data were modelled using the FAST autoregressive model (Corbin et al., 2018).

2.7. Region of interest (ROI) definition and analysis

Regions of interest were defined according to the approach detailed in Reyt et al. (2025), and analyses were conducted using R version 4.2.1 (R Core Team, 2020). The primary ROI was the dorsolateral prefrontal cortex (DLPFC), specifically Brodmann areas 9 and 46, given their known involvement in working memory and age-related cognitive compensation (Altamura et al., 2007; Cappell et al., 2010; Haque et al., 2021; Höller-Wallscheid et al., 2017; Reuter-Lorenz et al., 2000). In addition, a broader WM network was delineated by incorporating regions previously implicated in compensatory processes during the Sternberg task (Cappell et al., 2010; Schneider-Garces et al., 2010). This extended network included multiple frontal lobe areas (BA 6, 9, 12/47, 44, 45, 46, 24, and 32), the medial temporal lobe (specifically the hippocampus and parahippocampal gyrus), the parietal lobe (BA 5, 7, 39, and 40), as well as occipital regions. In addition, the thalamus was also included as a ROI due to its sensitivity to changes in vigilance and wake-state stability. For all ROIs, left and right hemispheres were differentiated, considering the theories proposing reduced hemispheric asymmetry in task-related recruitment as a compensatory or dedifferentiation mechanism in aging (Cabeza, 2002; Festini et al., 2018; Höller-Wallscheid et al., 2017; Knights et al., 2021).

To investigate longitudinal patterns of task-related brain activation, individual parameter estimates were extracted from the BOLD signal for each memory load (2 to 7 letters), across regions of interest (DLPFC, extended set of working memory regions, and thalamus), and hemispheres, both at baseline and at one-year follow-up. ROI coordinates were defined based on peak activation within each region identified using F-tests corrected for multiple comparisons ($p_{FWE} < 0.05$),

constrained by an inclusive grey matter mask (voxel probability > 0.20). Spherical masks of 30 mm radius were centred on these peak coordinates to identify the individual's global maximum per ROI and hemisphere. From these individualized peaks, an 8 mm-radius sphere was constructed to extract the mean beta values of significantly activated voxels ($p < 0.001$) for each memory load and each time point.

In a first step, generalized linear mixed models were computed separately for each ROI (DLPFC, thalamus, and a more extended set of WM-related regions) using the *lme4* function (Bates et al., 2015). Fixed effects included Group (3-level factor: non-nap, nap-control, nap-intervention), MSS (6-level factor: 2–7 letters), Hemisphere (2-level factor: left vs. right), and Time (2-level factor: T0 vs. T1), as well as all interaction terms. A random intercept was modelled per participant. Given the skewed distribution of beta values, a Gamma distribution with a log link function was employed. For the extended analysis, the model additionally included Region (4-level factor: frontal, parietal, temporal, occipital) as a categorical fixed factor. Helmert contrasts were applied to compare each MSS with the mean of previous loads, and treatment contrasts were defined using non-nappers, the left hemisphere, and the frontal region as reference levels. Model comparisons based on Akaike's Information Criterion confirmed that age, sex, education, BMI or daytime sleepiness needed not be included as covariates. For all models, the Wald Chi-Square test was used as an omnibus test to report main effects.

Finally, we aimed to assess how WM accuracy changed over time across groups, and whether this evolution was modulated by MSS and brain activation. Separate models were run for each hemisphere (left and right), with Group, WM load, Time, and BOLD signal as fixed effects, and subjects as random intercepts. Performance at each MSS was compared to the mean performance of all previous MSS using Helmert coding. Treatment contrasts were defined using the non-nap group and T0 as the reference. Age, sex, and education were included based on model comparisons using Akaike Information Criterion.

3. Results

3.1. Daytime rest characteristics: actigraphy

Separate GLMM on the cumulative DTR-duration and DTR-frequency sums of difference were used to assess the effectiveness of the nap-reduction intervention. With regard to DTR-duration, the model disclosed a statistically significant Group*Time interaction effect ($\chi^2(24)=71.726$, $p < 0.001$), such that nap-intervention participants significantly reduced their DTR-duration from Month 07 on ($p_s < 0.032$, see Figure SX in Supplementals), which was not the case in the two other groups (all $p_s > 0.083$). Similarly for cumulative DTR-frequency, there was a Group*Time interaction ($\chi^2(24)=58.261$, $p < 0.001$), showing significantly reduced values over the intervention from Month 05 onward in the nap-intervention group (all $p_s < 0.035$; see Figure SX in Supplementals) but not in the other groups (all $p_s > 0.097$). No main effect of Time (DTR-duration: $\chi^2(12)=1.736$, $p=0.997$; DTR-frequency: $\chi^2(12)=19.564$, $p=0.076$) was evidenced. These results confirm the efficiency of the nap-reduction protocol, with the targeted nap-intervention group significantly reducing both frequency and duration of their DTR habit from baseline.

3.2. Working memory performance

We first tested, using a GLMM, the effects on accuracy performance of the factors WM load (as computed by the MSS: 2-7 letters), Group and Time, as well as their interaction. Helmert contrasts were applied by sequentially comparing each MSS to the average of all preceding, smaller MSS, thereby capturing stepwise changes in performance across load levels. We confirmed that performance accuracy significantly decreased with increasing WM load (main MSS effect: $\chi^2(5)=80.789$, $p < 0.001$, see Table S1 for detailed results per MSS). There was a significant main Group effect ($\chi^2(2)=8.849$, $p=0.012$) driven by the nap-control group generally performing worse than non-nappers ($\beta=-0.221$, $z=-1.995$, $p=0.046$), and a Group*Time interaction ($\chi^2(2)=6.871$, $p=0.032$) with the nap-control group

exhibiting a statistical trend toward a higher decline in accuracy from T0 to T1, as compared to non-nappers ($\beta=-0.139$, $z=-1.846$, $p=0.065$). The interactions Group*MSS ($\chi^2(10)=10.760$, $p=0.377$) and Group*MSS*Time ($\chi^2(10)=9.095$, $p=0.523$) were non-significant. There was a significant main effect ($\chi^2(1)=6.473$, $p=0.011$) of Age (added as covariate in the analysis after model comparisons) with lower performance associated with older age.

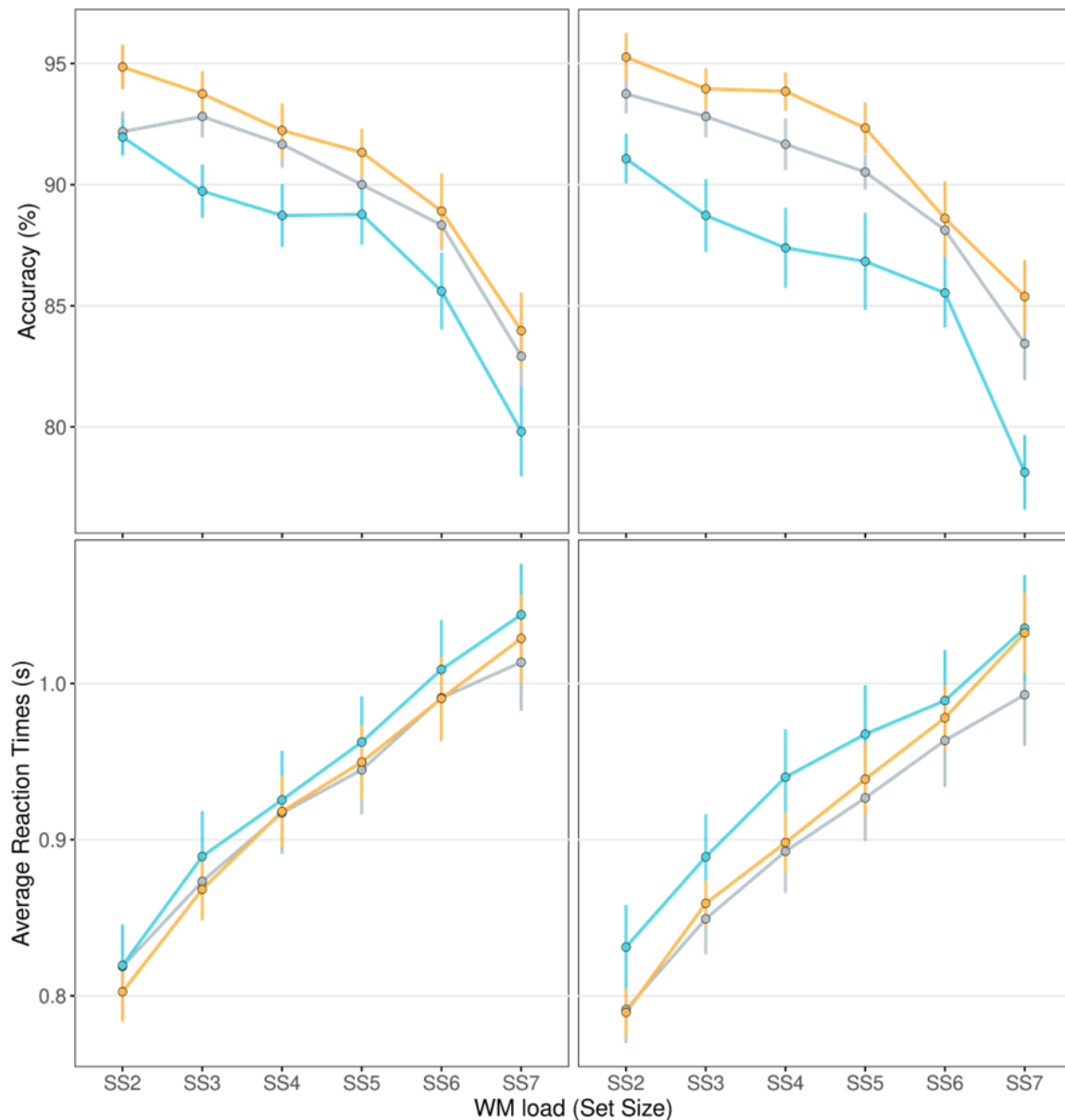


Figure 3. Average (SEM as errorbars) accuracy performance (top panel) and reaction times in seconds (bottom panel) per Group, Memory Set Size (x-axis), and Time (left: T0, right: T1). Non-nappers: grey; nap-intervention: yellow; nap-control: blue

Regarding reaction times, the linear model highlighted that all MSS were associated with significantly higher reaction times than the average of previous MSS ($\chi^2(5)=144.709$, $p<0.001$, see Table S1 for detailed results per MSS). Moreover, there was a significant main Time effect ($\chi^2(1)=5.573$, $p=0.018$) with slower reaction times at T1 than T0. There was no main Group ($\chi^2(2)=0.117$, $p=0.943$), or Time by Group ($\chi^2(2)=3.472$, $p=0.176$) effects. Sex (added as a covariate in the analysis) was not significantly associated with reaction times ($\beta=-0.021$, $t=-0.659$, $p=0.512$).

3.3. ROI analyses

3.3.1. DLPFC

We analysed the beta estimates of the DLPFC BOLD responses using a Gamma-log GLMM. There was a main WM load effect ($\chi^2(5)=38.349$, $p<0.001$) with concomitantly increasing BOLD activation and MSS (Figure 4; see Table S1 for detailed statistical results per MSS), and a main laterality effect ($\chi^2(1)=15.851$, $p<0.001$), with overall higher activation observed in the left as compared to the right hemisphere (see Figure 3 panel A). There was also a statistical trend towards a main Time effect ($\chi^2(1)=3.690$, $p=0.055$) with the DLPFC tending to be more activated at T1 than T0. No main Group ($\chi^2(2)=0.368$, $p=0.544$) nor interactions (all $p_s>0.29$) effects reached statistical significance, indicating that neither Group nor Time modulated the WM load or hemispheric lateralization effects in the current setting.

We further explored whether DLPFC BOLD activation was associated with WM accuracy performance, separately in both hemispheres. To do so, we used a GLMM, specifying a beta-regression with a logit link, including a random intercept for each participant. BOLD was modelled continuously after mean-centring and standardization. As expected, left DLPFC activation was positively associated with performance accuracy ($\chi^2(1)=5.83$, $p=0.016$), indicating that higher activation predicted better accuracy. Furthermore, a significant interaction between Group and left-DLPFC activation ($\chi^2(2)=15.01$, $p<0.001$) indicated that the strength

and/or direction of the activation-accuracy relationship was different between groups. Indeed, whereas higher DLPFC activation was positively associated with performance in non-nappers, the two other groups exhibited an opposite pattern: higher activation was associated with worse accuracy, most markedly in the nap-intervention group (nap-control: $\beta=-0.510$, $z=-2.169$, $p=0.030$; nap-intervention: $\beta=-0.910$, $z=-3.868$, $p<0.001$). The triple interaction Group*Time*BOLD was non-significant ($\chi^2(2)=4.249$, $p=.119$). Regarding the right hemisphere, there was a trend toward a positive association between BOLD and accuracy ($\chi^2(1)=3.14$, $p=0.076$). Other interaction effects were non-significant (all $p_s>0.17$).

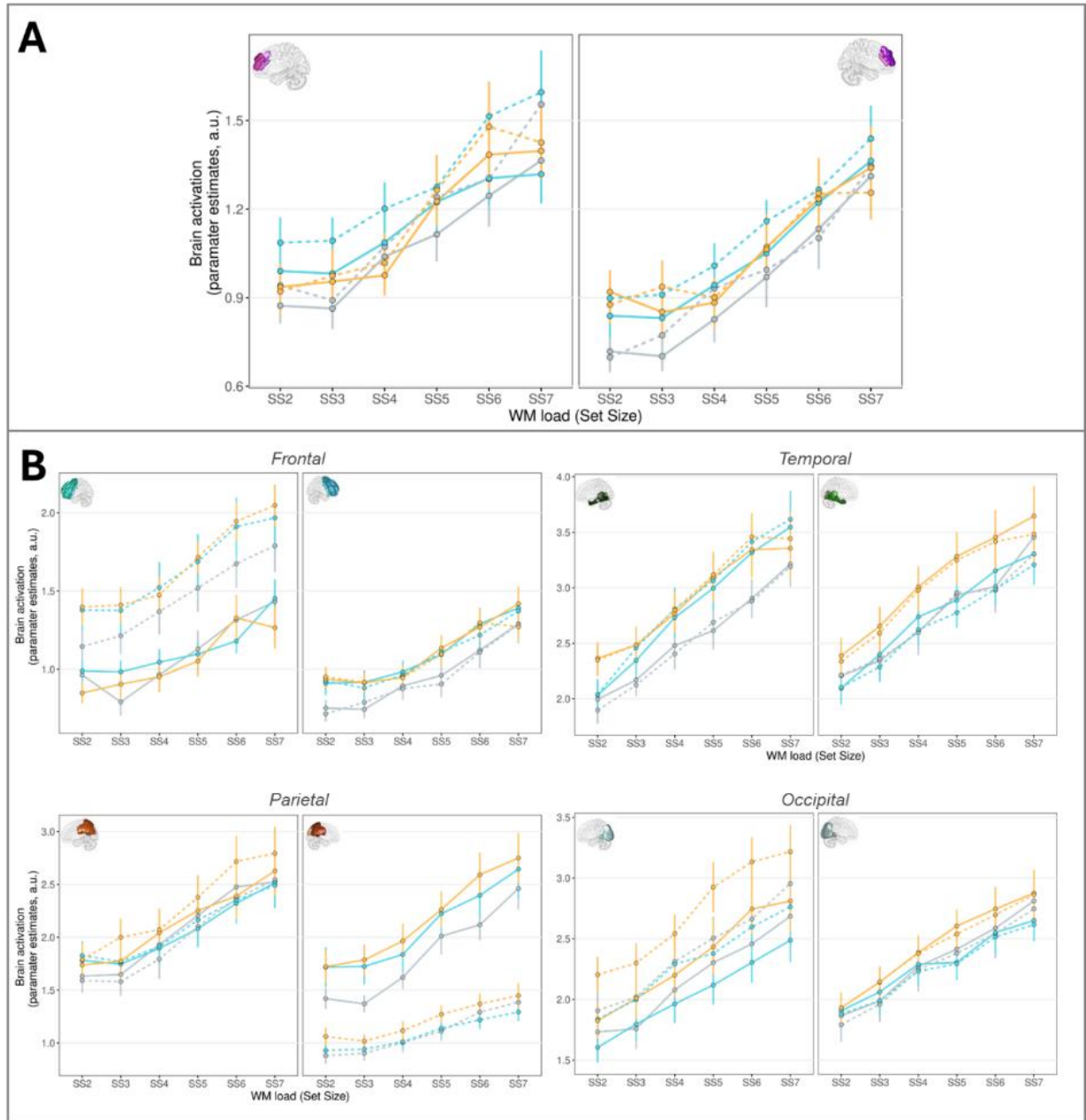


Figure 4. Mean BOLD activation (mean $\pm$ SEM) across memory set sizes for the DLPFC (panel A) and the more extended set of WM-related regions (panel B) including the frontal, parietal, temporal and occipital regions. Continuous lines correspond to T0 and dotted lines represent T1. Left box represents left hemisphere, right box represents right hemisphere. Non-nappers: grey; nap-intervention: yellow; nap-control: blue.

3.3.2. Extended set of WM-related brain regions

To investigate longitudinal patterns of task-related activation within the more extended set of WM-related regions, a GLMM on BOLD responses was used with factors Group, Time, WM load, Hemisphere and ROI (Frontal, Temporal, Parietal and Occipital). The exhaustive set of statistical results is depicted in Table S2, in Supplementals. Again, we found concomitantly increasing BOLD responses and

WM load ($\chi^2(5)=60.43$, $p<0.001$, Figure 3). Besides, overall BOLD activation increased over time (Main effect of Time: $\chi^2(1)=61.10$, $p<0.001$), and there was a Time*ROI interaction effect ($\chi^2(3)=45.66$, $p<0.001$) with the increase driven by frontal ($\beta=0.301$, $z=-5.751$, $p<0.001$) and temporal ($\beta=-0.174$, $z=-3.323$, $p<0.001$) activations, while parietal activation significantly dropped from T0 to T1 ($\beta=-0.309$, $z=-5.900$, $p<0.001$). Finally, there was a Group*Time interaction ($\chi^2(2)=10.615$, $p=0.005$) with the nap-intervention group exhibiting an additional BOLD increase at T1 as compared to T0 and non-nappers ($\beta=0.152$, $z=2.957$, $p=0.003$).

Across all regions, the left hemisphere was overall more recruited than the right hemisphere (Main Hemisphere effect: $\chi^2(1)=12.93$, $p<0.001$). A significant Hemisphere*ROI interaction ($\chi^2(3) =28.54$, $p=0.00028$) suggested regional lateralisation differences with the right occipital more active than the left occipital region ($\beta = 0.207$, $z=3.939$, $p<0.001$). On the contrary, the left hemisphere was more activated in the frontal ($\beta =-0.124$, $z=-3.245$, $p=0.001$) and parietal ($\beta = 0.200$, $z=3.811$, $p<0.001$) ROIs. A statistically significant Group*Hemisphere interaction ($\chi^2(2)=12.378$, $p=0.002$) was driven by the nap-intervention group displaying a stronger right-hemisphere activation ($\beta = 0.178$, $z=3.460$, $p<0.001$). The GLMM also showed group differences across the WM-related regions (Group*ROI: $\chi^2(6)=24.92$, $p<0.001$): participants in the nap-intervention group displayed higher BOLD activity in the occipital ($\beta=0.123$, $z=2.389$, $p=0.017$) than the frontal ROI and non-nappers, suggesting a lower occipital-frontal activation difference in the nap-intervention group. This right occipital activation in the nap-intervention was positively associated with task performance ($\beta = 0.269$, $z=2.343$, $p=0.019$), even more so at higher task levels as evidenced by a statistical trend towards an interaction between MSS7nap-intervention group ($\beta = 0.044$, $z=1.781$, $p=0.074$). WM performance was not associated with BOLD activation in other WM-related areas (all $p_s > 0.37$).

3.3.3. Thalamus

Thalamic activity was analysed by using a GLMM with a Gamma family and a link log function. It confirmed that thalamic activity increased with higher WM load ($\chi^2(5)=68.917, p<0.001$, see Table S1 for detailed results by MSS). A global decrease in thalamic activation was highlighted by a main Time effect ($\chi^2(1)=110.713, p<0.001$). A main Hemisphere effect ($\chi^2(1)=114.761, p<0.001$) showed higher overall activation in the left than the right hemisphere. The main Group effect was non-significant ($\chi^2(2)=2.099, p=0.350$). There was a Group*Hemisphere interaction effect ($\chi^2(2)=6.159, p=0.046$) such that, compared to non-nappers and left hemisphere, nap-controls ($\beta=-0.08, z=-2.167, p=0.030$) and nap-intervention ($\beta=-0.08, z=-2.125, p=0.034$) both exhibited a higher hemispheric asymmetry. Thalamic activity also significantly decreased over Time ($\chi^2(1)=113.540, p<0.001$) and there was a Group*Time interaction ($\chi^2(2)=6.212, p=0.045$) with nap-control participants exhibiting a stronger decrease in thalamic activity from T1 to T0, as compared to non-nappers ($\beta=-0.071, z=-2.003, p=0.050$). A statistically significant Hemisphere*Time interaction ($\chi^2(1)=63.414, p<0.001$) indicated that the left hemisphere was less activated at T1 than T0. Finally, there was a trend towards a triple interaction Group*Hemisphere*Time ($\chi^2(2)=5.466, p=0.065$), with nap-control participants exhibiting a stronger decrease in left hemisphere activation at T1 than T0 and non-nappers ($\beta=0.110, z=2.109, p=0.035$; see Figure 4).

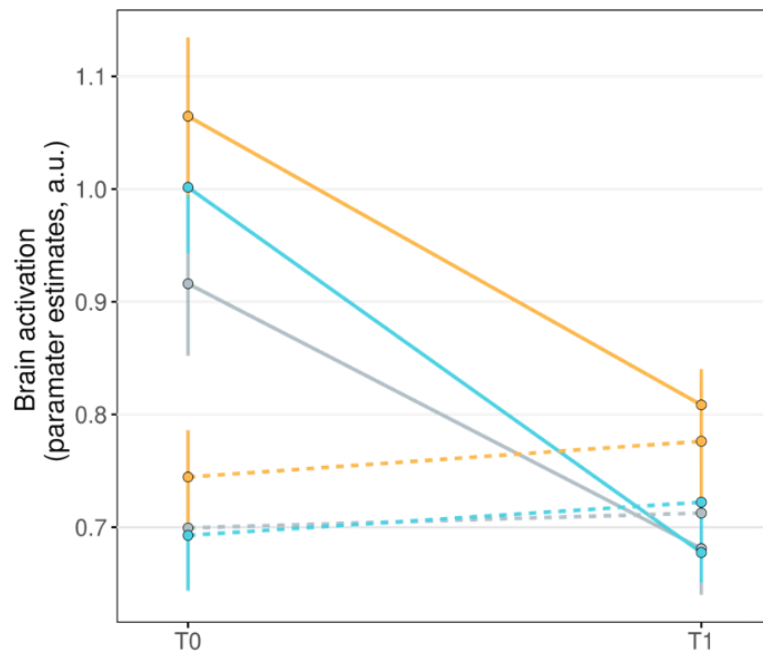


Figure 4. Mean brain activation estimated from BOLD parameters (y-axis) across Time (x-axis; baseline (T0) vs. one-year follow-up (T1)), according to Group and Hemisphere. Solid lines represent the left hemisphere, dashed lines represent the right hemisphere.

4. Discussion

In the present study, we hypothesized that continued regular napping in habitual older nappers over one year would exacerbate the age-related decline in working-memory (WM), particularly at higher load levels, whereas significantly reducing naps frequency a duration would align the WM trajectory with that of non-nappers, reflecting the benefits of extended daytime wake consolidation or restored circadian rhythm. In line with prior studies using similar paradigms (Altamura et al., 2007; Jansma et al., 2006; Wetter et al., 2012), we found increasing WM load associated with a concomitant drop in accuracy. Noticeably, the nap-control group exhibited a significantly greater decline in accuracy from baseline to the one-year follow-up as compared to non-nappers, a decline even more pronounced at the highest WM load. By contrast, the nap-intervention group was not statistically different from non-nappers in either accuracy or reaction-time trajectories, suggesting that restricting daytime naps may help preserve WM performance over a year.

As expected, DLPFC and WM-related ROIs activations correlated with WM load, with higher demands eliciting stronger BOLD responses and a classically observed left-hemisphere bias (Cabeza et al., 2018; Cappell et al., 2010). In line with our predictions, all groups showed increased DLPFC recruitment after one year, confirming global age-related changes (Mattay et al., 2006; Nyberg et al., 2009; Schneider-Garces et al., 2010). However, participants who continued napping did not exhibit any heightened activation compared to other groups, nor a reduced left-dominance. Importantly however, the well-established positive association between left-DLPFC activation and WM performance (Cabeza et al., 2018; Cappell et al., 2010; Grady, 2012) was only observed in non-nappers. In both continued and suppressed-nappers, higher activation correlated with poorer performance. This divergence highlights the limits of the compensatory benefits that can be drawn from overactivation of the DLPFC region in terms of WM performance. This switch suggests a compensatory breakdown (Festini et al., 2018; Reuter-Lorenz & Cappell, 2008; Schneider-Garces et al., 2010) such that over-recruitment no longer benefits performance. In addition, the absence of growing bilateral DLPFC recruitment argues against prefrontal compensation in this healthy sample (Cabeza, 2002; Cabeza et al., 2002; Festini et al., 2018). However, it must be acknowledged that although the negative relationship between overactivation and performance behaviourally manifests as a marked reduction in accuracy in the nap-control group, this correlation does not translate into observable performance deficits in the nap-intervention group.

In a more extended set of WM-related regions, we observed a ROI-specific reconfiguration in activation and lateralisation over the course of the intervention period. Most importantly, we found that nap-intervention individuals displayed higher overall activation after the intervention, especially in the occipital areas. Moreover, they also exhibited increased bilateral recruitment while performing the WM task, most notably in the occipital and temporal regions. This larger increase, as well as a shift toward posterior occipital and bilateral activation, may suggest that the long-term sleep-wake manipulation by restricting naps may have

modulated WM-related activation gains instead of inducing compensation in DLPFC activation patterns. While increased left-DLPFC activation did not correlate to better WM accuracy outcomes in the intervention group, the increased right-hemispheric activation in occipital regions was positively correlated with WM accuracy, even more so in the highest WM load. In the healthy-ageing literature, this pattern cannot be captured by any single model but instead reflects a dynamic interplay of compensatory, dedifferentiation and maintenance processes. The reduction in left-dominance echoes the HAROLD signature of bilateral recruitment in older adults (Cabeza, 2002) and the CRUNCH idea of “overspill” when focal resources are taxed (Reuter-Lorenz & Cappell, 2008). Bilateral engagement is needed as left-hemispheric capacity wanes under ageing effects (Cabeza, 2002; Cabeza et al., 2002; Park & Reuter-Lorenz, 2009). The higher right-hemispheric occipital activation in both nap groups suggests a posterior refocusing once frontal compensation has plateaued (Gutchess et al., 2005), in which older brains, having bilaterally engaged anterior control regions, re-specialize posterior perceptual circuits to sustain performance. This mirrors the negative correlation between DLPFC activation and WM accuracy on one hand, and the positive correlation between posterior right-hemispheric activation and WM accuracy on the other, for the people who followed the intervention. Moreover, the asymmetry in frontal and parietal activation indicates preserved functional specificity in these areas (Nyberg et al., 2009), arguing against a global dedifferentiation (Park et al., 2004). Instead, it supports a process-specific alliance framework (Morcom & Henson, 2018) in which only certain hubs dynamically reconfigure while others maintain their « normal » lateralisation. This suggests that maintained specialization could be in favour of a higher cognitive and brain reserve in our whole sample (Stern, 2009), as evidenced by their high education levels and healthy lifestyle behaviours. High cognitive reserve in this healthy cohort may underlie the preserved general lateralisation, specifically in frontal and temporal regions, and the targeted, adaptive shifts in parietal and occipital nodes.

Thalamic activation decreased over time in all groups, mainly driven by a decreased left-hemispheric recruitment after one year. Meanwhile, the nap-control group showed a higher decrease in overall thalamic activity over time, markedly in the left hemisphere. A plausible interpretation is that the longitudinal drop in thalamic BOLD across all groups, accentuated in the nap-control cohort who also showed less accurate, reflects an insufficient recruitment of thalamic mechanisms that normally stabilise arousal and gate task-relevant information to prefrontal-parietal circuits during working memory (Bolkan et al., 2017; Gomes et al., 2023; Shine et al., 2023). Thalamus is a key partner of prefrontal cortex for WM and cognitive control, and participates in regulating vigilance (Mitchell et al., 2014; Pergola et al., 2013; Rikhye et al., 2018; Schiff & Pfaff, 2009). Improved neural efficiency can yield lower thalamic activation (Neubauer & Fink, 2009), but that account is weakened here by the concomitant behavioural decline in nap-controls. In vigilance-challenged states such as sleep deprivation, thalamic activity can either increase as a compensatory booster or fall alongside performance decrements, underscoring its dual role in sustaining attention (Chee & Choo, 2004; Chen et al., 2022). Reduced but bilateral thalamic recruitment accompanied by poorer performance indicates that the thalamus is no longer sufficiently engaged to boost arousal or gate task-relevant information to cortical networks. The relative right-sided increase alongside the significant left-sided decrease observed in the nap-control group is consistent with a shift toward the right-lateralised attentional/vigilance network (Wen et al., 2021), suggesting a late or partial compensatory attempt rather than efficient specialisation (Corbetta & Shulman, 2002; Langner & Eickhoff, 2013). Conceptually, it mirrors the hemispheric asymmetry reduction highlighted in the “HAROLD” theory, which can index compensation or dedifferentiation when performance deteriorates (Cabeza, 2002).

As stated above, our cohort consisted in healthy, highly educated, and self-selected retirees, which could constrain the external validity of our results. Indeed, a high cognitive reserve may dampen effects that would emerge in more diverse or vulnerable populations (Nyberg et al., 2009). In addition, the true extent of the

intervention is only coarsely indexed, such that we lack the information about what the suppressed naps were replaced with. Moreover, nap-intervention and nap-control already differed in terms of WM performance at baseline. This discrepancy cannot be explained either by season of assessment, objective nap-characteristics differences, different educational levels, nor bias in the group assignment, since baseline evaluations were conducted prior to intervention group attribution. While the impact on time effects and their interaction with the group factor remains limited when baseline differences are properly accounted for in the statistical model (i.e., coding time from baseline and testing the group*time term), such pre-existing disparities still warrant caution in interpretation. Indeed, individuals with lower baseline cognitive performance often exhibit steeper declines, potentially due to more advanced age-related cognitive decline (Morrison & Oliver, 2023; Schaeffer et al., 2021). Future studies should therefore recruit broader samples and explicitly model cognitive reserve, as well as pair groups in terms of finer-grained cognitive performance, to better generalize these findings and understand the nap-related effects.

In conclusion, we provide here evidence for a partially beneficial impact of a longitudinal nap-suppression intervention on functional brain responses underlying WM performance in healthy older adults. Across one year, continuing to nap was associated with a steeper decline in working-memory accuracy, especially at high WM load, and a steeper drop in (left) thalamic engagement. Conversely, suppressing naps aligned behavioural trajectories with those of regular non-nappers. All groups showed load-dependent and left-dominant activation in classic WM regions, yet only non-nappers retained a positive activation-performance coupling in left DLPFC. In both nappers who continued (controls) and who stopped napping (intervention) over the one-year period, greater activation predicted poorer accuracy, signalling reaching or going over the limits of compensatory over-recruitment in prefrontal areas. The WM-related areas of the brain reconfigured in a region- and hemisphere-specific manner over time, leading to a more posterior and bilateral recruitment in participants who stopped napping,

which positively correlated with WM performance. Taken together, our data suggest that acting on the sleep-wake behaviour by consolidating daytime wakefulness may help preserve WM and support more efficient brain recruitment in healthy ageing, hinting towards a scaffold-like compensation. While cognitive and brain reserve might constrain the age-related and nap-induced effects on WM performance and brain correlates, these further confirm that compensatory scaffolds can be modulated by sleep-wake cycle as well as healthy lifestyle.

Supplementals:

Exclusion/Inclusion Criteria: None of the participants indicated moderate or severe depression (Beck Depression Inventory [BDI-II] < 19, Beck et al., 1961) or severe anxiety (Beck Anxiety Inventory [BAI] < 30, Beck et al., 1988). Clinical symptoms of cognitive impairment were assessed by the Mini Mental State Examination [MMSE score > 26] (Folstein et al., 1975) and the Mattis Dementia Rating scale [MDR score > 130] (Mattis, 1976). Screening for major sleep disorders was performed during a night of polysomnography and 72 participants were excluded (apnea/hypopnea index and period limb movement index > 15/h) (for the final sample of 94 participants: mean apnea/hypopnea index: 5.48 ± 4.63 , mean Periodic Limb Movement index: 3.07 ± 5.51). Other exclusion criteria included Body Mass Index (≤ 18 and ≥ 30 kg/m²), participants reporting a history of diagnosed psychiatric conditions or severe brain trauma, chronic medication affecting the central nervous system, diabetes, smoking, caffeine (> 4 cups/day), excessive alcohol (> 14 units/week) or other drug consumption, and travelling more than one time zone in the 3 months prior to the study begin. Participants with stable treatment (> 6 months) for hypertension and/or hypothyroidism were included in the study.

Tables

	Accuracy		Reaction Times		DLPFC		Extended WM		Thalamus	
	T0	T1	T0	T1	T0	T1	T0	T1	T0	T1
MSS3	$t=0.788$ $p=0.433$	$t=-0.629$ $p=0.530$	$t=4.025$ $p<0.001$	$t=4.162$ $p<0.001$	$t=-0.281$ $p=0.779$	$t=-0.850$ $p=0.395$	$t=-1.834$ $p=0.067$	$t=0.633$ $p=0.527$	$t=0.210$ $p=0.833$	$t=-0.526$ $p=0.599$
MSS4	$t=-0.699$ $p=0.485$	$t=-1.400$ $p=0.162$	$t=6.076$ $p<0.001$	$t=5.981$ $p<0.001$	$t=2.068$ $p=0.039$	$t=2.047$ $p=0.041$	$t=1.108$ $p=0.268$	$t=1.812$ $p=0.07$	$t=2.050$ $p=0.040$	$t=0.943$ $p=0.346$
MSS5	$t=-1.976$ $p=0.049$	$t=-1.871$ $p=0.062$	$t=6.797$ $p<0.001$	$t=7.226$ $p<0.001$	$t=2.534$ $p=0.011$	$t=3.774$ $p<0.001$	$t=3.11$ $p=0.002$	$t=3.098$ $p=0.002$	$t=3.952$ $p<0.001$	$t=2.050$ $p=0.040$
MSS6	$t=-3.062$ $p=0.002$	$t=-3.835$ $p<0.001$	$t=9.579$ $p<0.001$	$t=8.935$ $p<0.001$	$t=3.576$ $p<0.001$	$t=3.691$ $p<0.001$	$t=4.532$ $p<0.001$	$t=3.880$ $p<0.001$	$t=5.072$ $p<0.001$	$t=4.418$ $p<0.001$
MSS7	$t=-7.578$ $p<0.001$	$t=-6.147$ $p<0.001$	$t=10.001$ $p<0.001$	$t=10.001$ $p<0.001$	$t=4.009$ $p<0.001$	$t=5.867$ $p<0.001$	$t=4.991$ $p<0.001$	$t=4.068$ $p<0.001$	$t=5.633$ $p<0.001$	$t=4.520$ $p<0.001$

Table S1. Post-hoc results of the main effect of WM load and Time (T0 vs. T1) for Accuracy, Reaction Times, DLPFC activation, Extended set of WM-related regions activation, and thalamus activation. All collapsed within group.

	χ^2	df	p-value
Main effects			
<i>Group</i>	1.4722	2	$p = 0.479$
<i>MSS</i>	60.4263	5	$p < 0.001$
<i>Hemisphere</i>	12.9345	1	$p < 0.001$
<i>Time</i>	61.1049	1	$p < 0.001$
<i>Region</i>	618.4232	3	$p < 0.001$
Two-way interactions			
<i>Group * MSS</i>	12.7265	10	$p = 0.239$
<i>Group * Hemisphere</i>	12.3775	2	$p = 0.002$
<i>Group * Time</i>	10.6147	2	$p = 0.005$
<i>Group * Region</i>	24.9198	6	$p = 0.004$
<i>MSS * Hemisphere</i>	0.9822	5	$p = 0.964$
<i>MSS * Time</i>	3.1488	5	$p = 0.677$
<i>MSS * Region</i>	6.9637	15	$p = 0.959$
<i>Hemisphere * Time</i>	32.8983	1	$p < 0.001$
<i>Hemisphere * Region</i>	28.5390	3	$p < 0.001$
<i>Time * Region</i>	45.6555	3	$p < 0.001$
Three-way interactions			
<i>Group * MSS * Hemisphere</i>	6.2581	10	$p = 0.793$
<i>Group * MSS * Time</i>	6.1208	10	$p = 0.805$
<i>Group * MSS * ROI</i>	14.1159	30	$p = 0.994$
<i>Group * Hemisphere * Time</i>	5.1816	2	$p = 0.075$
<i>Group * Hemisphere * ROI</i>	19.6369	6	$p = 0.003$
<i>Group * Time * ROI</i>	5.0129	6	$p = 0.542$
<i>MSS * Hemisphere * Time</i>	0.8572	5	$p = 0.973$
<i>MSS * Hemisphere * ROI</i>	2.8197	15	$p = 0.999$
<i>MSS * Time * ROI</i>	2.6876	15	$p = 0.999$
<i>Hemisphere * Time * ROI</i>	50.1075	3	$p < 0.001$

Table S3. Main, two- and three-way interactions of the GLMM on BOLD responses with factors Group, Time, WM load (MSS), Hemisphere and ROI (extended WM-related brain regions : Frontal, Temporal, Parietal and Occipital). Wald Chi-Square test was used as an omnibus test to report χ^2 , degrees of freedom (df), and p-value.

Figures

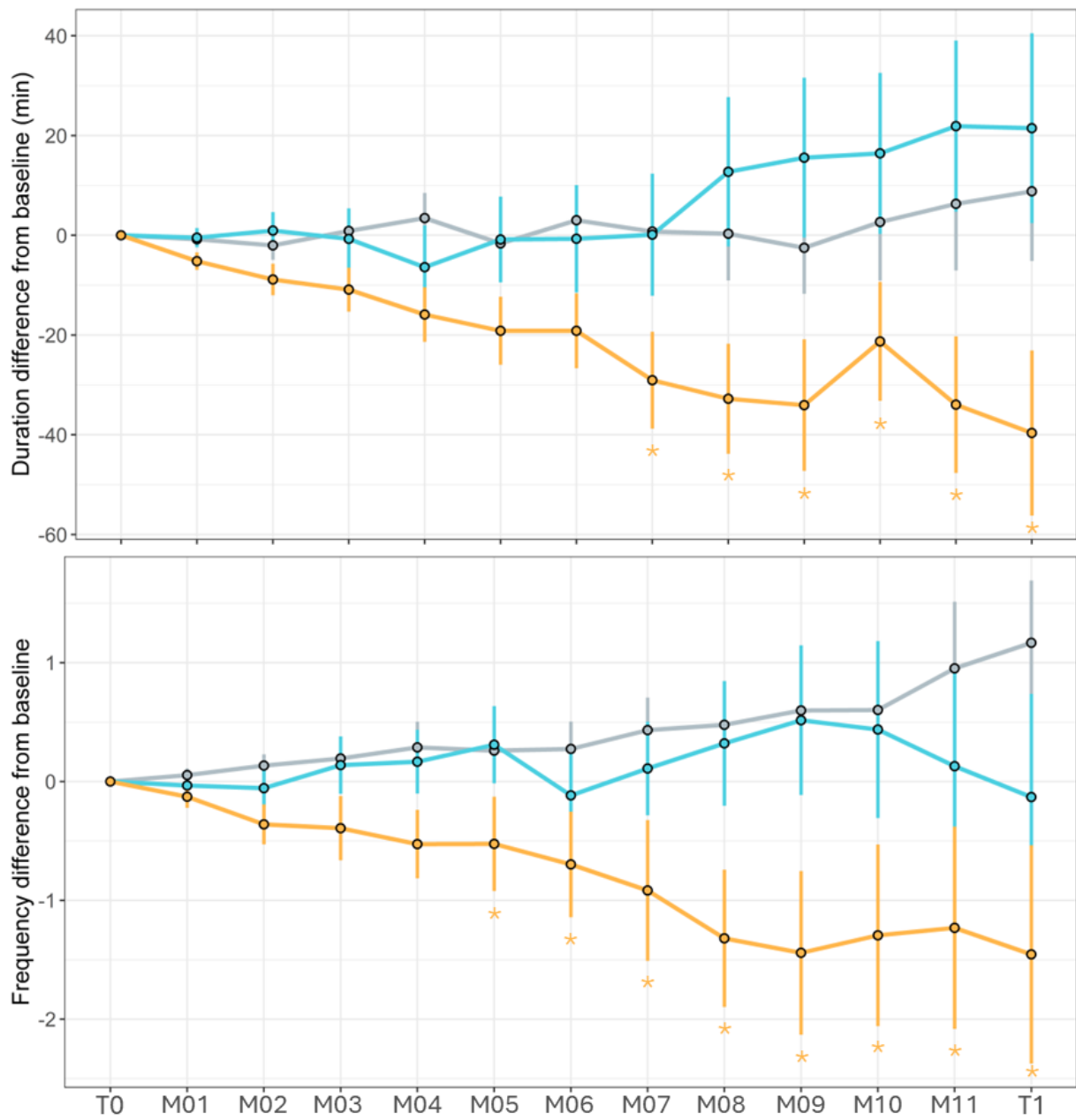


Figure S1. Mean and SEM cumulative monthly differences from T0 baseline to T1 for DTR duration (top panel) and frequency (bottom panel). Asterisks highlight time points at which DTR parameters significantly differ from baseline in the nap-intervention group (post-hoc tests). Non-nappers: grey; nap-intervention: yellow; nap-control: blue.

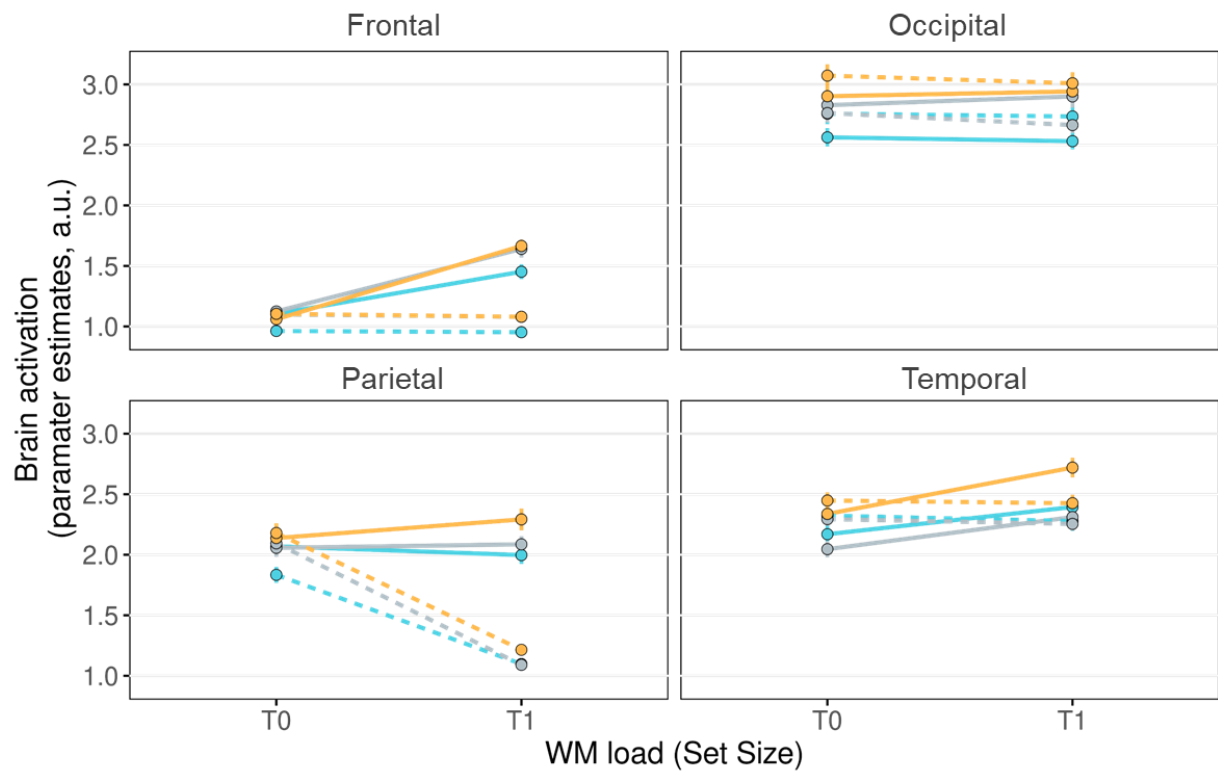


Figure S2. Mean brain activation estimated from BOLD parameters (y-axis) across Time (x-axis; baseline (T0) vs. one-year follow-up (T1)), according to Group and Hemisphere. Solid lines represent the left hemisphere, whilst the dashed lines.

General Discussion

1. Context and hypotheses

Ageing goes along with changes in sleep-wake cycle regulation, cognition, brain structure and function, as well as with a high inter-individual variability and non-linear trajectories. Modern theories regarding cognitive ageing highlight the interplay between structural decline, functional reorganisation, and the modulatory role of biological and lifestyle factors in determining who maintains good cognitive performance, described as successful ageing, and who declines, sometimes up to pathological ageing. In this context, the preservation of a consolidated sleep-wake cycle has been proposed as a protective factor against cognitive decline (Scullin & Bliwise, 2015; Spira et al., 2014). Ageing is typically accompanied by flattened circadian rhythms, less efficient homeostatic sleep buildup, and more fragmented 24-hour patterns of sleep and wakefulness (Cajochen et al., 2006; Taillard et al., 2021). Such dysregulations have been implicated in the everyday functioning of older individuals (Harada et al., 2013). Given the growing proportion of older adults in the population (Lindenberger, 2014), identifying factors that support the maintenance of cognitive performance is of major societal and clinical relevance.

Daytime napping is a particularly common, yet heterogeneous, behaviour in older adults. While it may transiently relieve sleep pressure and support alertness (Li et al., 2022), regular napping can also fragment wake continuity, blunt circadian consolidation, and potentially compromise cognitive stability. Increased napping frequency has been associated with both protective and deleterious effects depending on nap characteristics and population studied: beneficial in young adults (Lovato & Lack, 2010; Milner & Cote, 2009), but increasingly considered as a health risk factor in older populations (Leng et al., 2018, 2019; J. Li et al., 2022; Sun et al., 2022; Xin et al., 2020). Moreover, a fragmented rest-activity rhythm (Cochrane et al., 2012; Luik et al., 2015; Oosterman et al., 2009; Rogers-Soeder et al., 2018; H. W. Roh et al., 2020; Walsh et al., 2014) and habitual, long and frequent naps (Blackwell et al., 2006; Keage et al., 2012; Leng et al., 2019; Leong et al., 2022;

J. Li et al., 2017; Owusu et al., 2019) have both been linked to accelerated cognitive decline.

Circadian and homeostatic regulation of the sleep-wake cycle emerges as an important but underexplored determinant of inter-individual variability in cognitive ageing. This thesis was designed to test a circadian-cognitive approach of ageing in which habitual napping serves as a behavioural marker of temporal dysregulation, and its modulation represents a potential target for cognitive preservation. More specifically, we hypothesised that (1) habitual napping in healthy older adults would be associated with reduced amplitude of the 24-hour circadian temperature rhythm and altered pre-sleep thermoregulatory dynamics, and (2) that acting on the nap habit with a one year-long targeted nap suppression intervention would stabilise circadian rhythms and, in turn, maintain or improve cognitive performance, particularly in episodic and working memory, with measurable effects on functional brain correlates.

In the following discussion, we first review and interpret the main findings from the four studies contained in this thesis, integrating them with our overarching aim: to determine whether daytime napping constitutes a cause and/or a consequence of circadian dysregulation, potentially leading to more pronounced cognitive decline. We then address the main limitations of the present work and outline perspectives for future research. Throughout the discussion, complementary analyses will be proposed to further contextualise the observed results. Finally, we offer a personal reflection, grounded in both the literature and our findings, on the implications of napping for the multifactorial and multisystemic ageing body, the clinical relevance of targeting nap behaviour in the older population and future avenues for nap-related research.

2. Main findings and interpretations

2.1. Napping modulates age-related changes in thermoregulation

In Study 1, we confirmed age-related reductions in DPG amplitude modulation of the 24-hour cycle (Batinga et al., 2015; Czeisler et al., 1992; Harper et al., 2005; Hofman & Swaab, 2006; Martinez-Nicolas et al., 2018; Van Someren et al., 1999) in ecological settings. Clear circadian DPG rhythms were observed in both young and older adults despite uncontrolled home conditions, supporting its validity as a reliable and sensitive marker of circadian phase and amplitude (Hasselberg et al., 2013; Kräuchi, Cajochen, et al., 2006; Kräuchi et al., 1999; Longato et al., 2017; Martinez-Nicolas et al., 2013; van Marken Lichtenbelt et al., 2006).

In Study 2, habitual nappers showed lower DPG during scheduled wakefulness during an in-lab multiple nap protocol, particularly in the afternoon of the second biological day. Both distal and proximal skin temperatures appeared to be lower at that point in time, possibly due to differences in sleep duration in prior nap-opportunities, nap-related thermal changes, or engagement in relaxing behaviours to “warm up”. This lower afternoon DPG contributed to higher apparent amplitude and a stronger 12-hour DPG component. The effect may relate to a more pronounced post-lunch dip, as half of involuntary naps occurred after meals in our sample (see Table S1 of Study 2). An afternoon DPG increase was seen in older adults in Study 1 but not in younger participants, consistent with heightened DPG as a thermophysiological correlate of the post-lunch dip phenomenon, or relaxation-induced sleepiness (Kräuchi, 2007a, 2010).

We also confirmed in Study 2 that sleep onset latency (SOL) was negatively associated with pre-sleep DPG increases (Kräuchi et al., 2005), but the relationship was weaker in habitual nappers. This suggests that, in nappers, sleep initiation is less tightly linked to thermoregulatory dynamics. Given that older adults already showed reduced sensitivity of sleep propensity to distal skin temperature and weaker relationship between pre-sleep heat-loss and sleep latency (Raymann et al.,

2007), habitual nappers may present a more “aged-like” thermoregulation-sleep initiation profile compared to non-nappers.

The reported age-related amplitude reduction in melatonin secretion (Carrier et al., 1996; Dijk & Duffy, 1999) is suspected to lead to attenuated circadian signals during the critical interaction windows of homeostatic and circadian processes, including the wake maintenance zone (WMZ) (Cajochen et al., 2006; Münch et al., 2005). Melatonin is known to play a crucial role in thermoregulation and sleep initiation by promoting increased DPG through distal heat loss mechanisms, which facilitate sleep onset (Kräuchi, 2007a; Kräuchi, Knoblauch, et al., 2006). In our study, habitual nappers were found to exhibit reduced melatonin amplitude (Deantoni et al., 2024) yet displayed distinct thermoregulatory patterns: they showed a greater DPG amplitude, with an earlier evening rise in DPG compared to non-nappers. Despite experiencing smaller post-lights-off DPG increases compared to non-nappers, habitual nappers were nevertheless able to initiate (shorter SOL) and maintain sleep more effectively (higher SE: Deantoni et al., 2024), suggesting potential compensatory or maladaptive mechanisms in thermoregulation. One speculative interpretation is that reduced melatonin amplitude in habitual nappers may alter the typical thermoregulatory signal linked to sleep initiation, potentially leading to reliance on different or less pronounced DPG changes. Given the reduced amplitude of melatonin secretion, the circadian gating of wakefulness may be weakened, potentially exacerbating the influence of homeostatic sleep pressure on subjective sleepiness during the early evening. This coincide with the fact that regular nappers reported a higher subjective sleepiness than non-nappers (ESS score, Table 1 of Study 2). As heightened sleepiness has been linked to higher DPG (Kräuchi, 2007a, 2010), this overall higher perceived sleepiness could coincide with the earlier evening rise in DPG observed in habitual nappers and, in turn, partly account for their ability to initiate sleep more readily during the WMZ. Alternatively, habitual nappers’ lower overall DPG levels during wakefulness, and weakened association between DPG increase and sleep initiation during scheduled nap opportunities, could reflect longer-term behavioural

adaptations to frequent daytime sleep episodes, rather than differences in circadian amplitude *per se*. Changes in skin temperature can affect warm-sensitive neurons in the preoptic area and anterior hypothalamus, which increase their activity at sleep onset and promote sleepiness (Kräuchi, 2010; D. Kumar et al., 2011; Rothhaas & Chung, 2021). It could therefore be hypothesised that thermoregulatory processes associated with napping and daytime sleep opportunities contribute to the modulation of these neuronal activation. This, in turn, would prompt sleepiness or sleep initiation, even with smaller increases in skin temperature.

These skin temperature modulation differences could potentially lead to differences at the cognitive level. Daily modulation of global cognitive performance was found to be negatively associated with DPG daily modulation (Burke et al., 2015; Heyde et al., 2018; M. P. Johnson et al., 1992; Reichert et al., 2017; Santhi et al., 2016), such that performance is highest during the biological day when DPG is at its trough. High-demand tasks appear to be more affected by body temperature changes than easier ones (Wright et al., 2002). However, results from our Study 1 did not highlight any correlation between skin temperature modulation and visuospatial working memory (WM) performance, either in young or older participants. Evidence also suggests that elevating core body temperature (CBT) can lead to decrements in cognitive performance, characterized by faster reaction times but reduced accuracy (Simmons et al., 2008). In line with this, a higher but highly variable amplitude in CBT modulation has also been reported in patients suffering from Alzheimer's disease (AD) (Van Someren, 2002; Van Someren et al., 1999). Moreover, AD patients exhibit higher daytime proximal skin temperature compared with healthy controls, which is associated with increased daytime sleepiness (Most et al., 2012). While our nap-group did not have an elevated proximal skin temperature as compared with non-nappers, they did exhibit a higher amplitude in DPG modulation. This, coupled with their self-reported higher daytime sleepiness, could partially explain the observed negative association

between episodic performance and napping frequency in our cohort (Reyt et al., 2022).

2.2. Nap reduction partly protects episodic memory trajectory

45% of dementia cases may be preventable through risk factor modification such as physical inactivity (Schott, 2025). Therefore, targeting inappropriate napping in ageing could help reduce cognitive and circadian vulnerabilities. In Study 3, the intervention group markedly reduced nap duration and frequency, with afternoon rest-probability disappearing, while (nap and non-nap) control groups remained stable. The nap-suppression intervention was therefore successful and enable a more causal interpretation of follow-up (T1) evaluations.

In Study 3, participants who continued napping showed unchanged total recall of words during the FCRST, but relied more on cues than on free recall, indicating reduced use of automated retrieval strategies and a more ‘aged-like’ profile than non-nappers or intervention nappers in episodic memory recall. This observed shift in episodic memory strategy and retrieval capacity after the 12-month period in the nap-control group may reflect the cognitive consequences of repeated daytime napping (Álvarez-Bueno et al., 2022; Li et al., 2022). Mirroring nocturnal awakenings fragmenting sleep consolidation, long and frequent naps may reflect a form of wakefulness fragmentation, with the same poorer cognitive performance outcomes (Kaneshwaran et al., 2019; Lim et al., 2012; Okuda et al., 2021; Oosterman et al., 2009). Moreover, napping regularly could also fragment cognition, with daily patterns characterised by unstable transitions between wakefulness and drowsiness, disrupting the continuity of sustained cognitive engagement (Mander et al., 2016; Vyazovskiy et al., 2011). This claim is further supported by the finding that the nap-control group also significantly decreased in some attentional performances (PVT number of lapses and D2 accuracy, see Table S1 in Supplementals of Study 3) between T0 and T1, while the non-nappers and nappers-intervention group either remained stable or improved performance across time. As napping is supposedly associated with immediate short-term

enhancement of alertness (for review, see Li et al., 2022) and our participants were mainly tested in the usual afternoon nap window (13h-17h), we could speculate that nap-control individuals have been conditioned to rely on the nap-related alertness boost to maintain overall good cognitive performance throughout the day, and the lack of said nap on testing days was translated into transient vigilance and alertness decrements. In contrast, the nap-intervention group exhibited neither increased cue dependency nor changes in free-recall strategy, suggesting that suppressing daytime naps may help stabilise the retrieval of episodic memories in older adults, through re-stabilisation of rest-activity rhythms. The reduction in sleep intrusions during the wake period, and the resulting decrease in unstable transitions between alertness and sleepiness, could have strengthened the more trait-like cognitive domain that is episodic memory over time.

It should be noted, however, that participants in the nap-intervention group already performed relatively better at baseline than both the nap-control individuals (see Figure 4 of Study 3), and warrants consideration. The presence of baseline differences raises several hypotheses. One possibility is that individuals in the nap-control group were already experiencing a decline in episodic performance due to other, uncontrolled, factors at baseline. Alternatively, it may be inherently easier for lower-performing adults to exhibit further decline compared to higher-performing adults. While differences in educational level do not support this explanation, it remains plausible that the nap-intervention group coincidentally possessed a higher cognitive reserve, enabling them to better sustain episodic performance despite similar wakefulness fragmentation at baseline.

Moreover, our results are based on the FCRST alone, as the Mnemonic Similarity Task (MST) and the Logical Memory test (LM) did not yield any statistically significant effects. Given that the episodic memory changes observed were subtle, and that a one-year interval may not be sufficient to capture clear nap-related decline or post-intervention improvement (e.g., significant reductions emerging from month 5 onward), we conducted an exploratory examination of the two-year

follow-up data for FCRST performance (model definition and statistical results are depicted in Table A1, in Appendix 3).

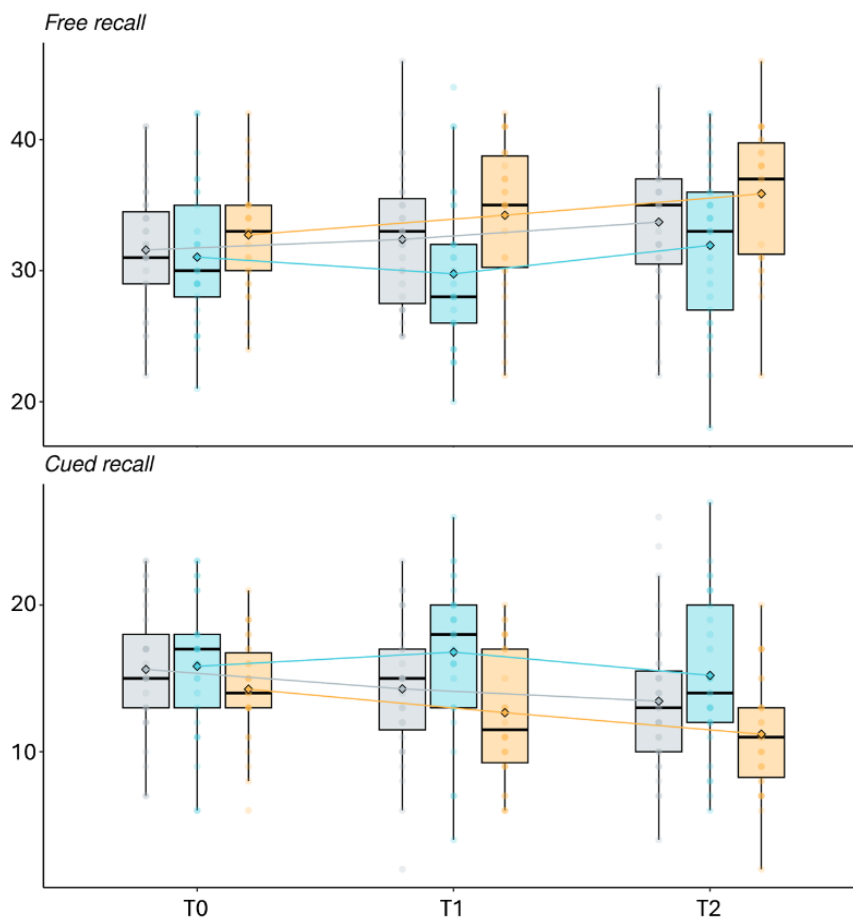


Figure 19. Boxplots represent the distribution of scores at the FCSRT (up: free recall, bottom: cued recall) at baseline (T0), one-year (T1) and two-year (T2) follow-ups across groups (median, interquartile range, whiskers). Individual data points are shown as jittered dots (semi-transparent) color-coded by group. Diamonds indicate group means, which are connected by lines to illustrate changes over time. Non-nap group is depicted in grey, Nap-control group is depicted in blue, and Nap-intervention group is depicted in yellow.

Surprisingly, we found that the nap-related decline in the nap-control group seen at T1 appears to be an isolated event, as they increased their performance at T2 (Figure 19). This finding cannot be explained by outliers skewing data distribution and the mean, either in T1 or in T2. A test-retest effect could be the cause, as individuals with higher cognitive ability tend to benefit more from repeated testing through faster strategy learning or adaptation (Scharfen et al., 2018). Practice effects are also larger with shorter retest intervals, especially under one year, likely due to retention of task-specific strategies or memory traces (Scharfen et al., 2018). Although two equivalent word lists (A and B) were used alternatively for the FCSRT, evidence suggests that their use does not fully eliminate test-retest effects (Stoykova et al., 2013). As our participants were seen with an interval of one year

each time, were highly educated and high-performing, the improved performance at T2 could reflect test-retest effect rather than improved underlying episodic capacity. Anecdotally, some participants spontaneously listed words from the last assessment (one year earlier) without prompting, at follow-up visits, further strengthening the test-retest theory. The lists being the same at T0 and T2, this could partly underlie the overall performance improvement observed here. Within this context, the decline observed in the continued napping group at T1 remains consistent with our main hypothesis, as list versions differed between T0 and T1. The version used at T1 therefore contained new words, was used for the first time, and only one prior exposure to the test architecture existed. If T1 was therefore less influenced by test-retest effects due to the introduction of an alternative list, our findings still support nap suppression as a potential moderator of episodic memory decline over one year. Nonetheless, the two-year follow-up results temper this conclusion, and the overall effects should be interpreted with caution.

2.3. Nap reduction influences working memory trajectory and its underlying cerebral correlates

When it comes to working memory (WM), we confirmed in Study 1 its previously reported age-related vulnerability to task demand (Babcock & Salthouse, 1990; Gazzaley et al., 2005; W. Johnson et al., 2010; Pertzov et al., 2015). Again, building on the success of the nap-suppression intervention in our CogNap study, we aimed to investigate the impact of this intervention on WM performance after one year, as well as its associated functional cerebral correlates.

In Study 4, we further stressed what we already observed in Study 3: after one year, participants in the nap-control group showed a more pronounced decline in WM performance, whereas non-nappers and nap-intervention participants remained stable over time. This decline was most evident at the highest level of task difficulty. At the cerebral level, although all groups exhibited increased DLPFC activation at follow-up, only the non-nappers retained a positive association between greater DLPFC activation and WM accuracy. This finding underscores the limits of the

compensatory benefits that can be derived from DLPFC overactivation for maintaining performance (Cabeza et al., 2018; Cappell et al., 2010; Grady, 2012). In contrast, the nap-intervention group demonstrated a reconfiguration of the extended WM-related brain regions, characterised by increased recruitment of the occipital lobe after the intervention. The increased right-hemispheric activation in occipital regions was positively associated with WM performance in this group, and is thereby consistent with a posterior refocusing pattern (Gutchess et al., 2005), whereby older adults, having bilaterally engaged anterior control regions, re-specialise posterior perceptual circuits to sustain performance. These changes may reflect a compensatory modulation of working memory-related brain regions following long-term sleep-wake reconsolidation (Nyberg et al., 2009), rather than global dedifferentiation (Koen & Rugg, 2019; D. C. Park et al., 2004).

Nap-control participants did not exhibit such a distinctive occipital recruitment or global right-hemispheric shift as observed in the nap-intervention group. Although, like the latter, they showed greater right-hemisphere occipital activation than non-nappers. However, these changes were less marked and not coupled with a performance benefit. Instead, they exhibited a greater decline in WM accuracy over one year. This dissociation between modified activation patterns and declining behavioural performance is more indicative of a dedifferentiation profile (W. Johnson et al., 2010; Koen & Rugg, 2019; D. C. Park et al., 2004), in which neural responses become less specialised and less predictive of successful performance with age, rather than compensatory reorganisation, which by definition should be coupled with performance maintenance or improvement (Cabeza et al., 2018; Reuter-Lorenz & Cappell, 2008). Moreover, they displayed a stronger longitudinal decrease in thalamic activation, particularly in the left hemisphere. Such a pattern could reflect insufficient recruitment of thalamic mechanisms that normally stabilise arousal and gate task-relevant information to prefrontal-parietal circuits during WM tasks (Bolkan et al., 2017; Gomes et al., 2023; Shine et al., 2023).

Overall, nap suppression in older adults may preserve WM by reducing wake-sleep fragmentation and enabling adaptive network reorganisation, whereas continued

napping is linked to neural dedifferentiation, reduced arousal control, and steeper cognitive decline. Taken together with the preserved episodic memory performance in subjects from the nap-intervention group, our findings suggest that the participants having followed the intervention, likely benefiting from both the cessation of habitual napping and from their high cognitive reserve, were able to counteract the more pronounced decline observed in those who continued napping over the year (nap-control group). This combined advantage translated into better behavioural performance and an underlying brain activation profile indicative of efficient functional compensation. In contrast, continued nappers also appeared to possess high cognitive reserve, which allowed them to remain high-performing overall, yet they still exhibited a subtle, non-pathological decline in episodic and working memory, and to some extent, in attentional measures (although not examined in depth in the scope of this thesis). Within the constraints of our study and given the very good health status of our participants, the cognitive impact of continued napping does not appear substantial, although such changes could still carry clinical relevance over longer timescales. Furthermore, baseline differences between groups suggest that the interpretation of the intervention's true impact should be made with caution. Finally, beyond the effects of the intervention on cognition and brain correlates, we also explored, in a set of preliminary analyses, whether nap suppression was associated with measurable changes in circadian markers, in order to determine whether it represents merely a behavioural adjustment in daily life or whether it can also drive a true re-stabilisation of circadian rhythms, as hypothesised in the CogNap study.

2.4. Insight into preliminary data of the nap-suppression intervention effect on skin temperature modulation, melatonin and sleep propensity

The central hypothesis of the CogNap project is that habitual napping is associated, either as a cause, a consequence or both, with circadian dysregulation. This assumption has been reinforced by recent findings from our team, which showed that older habitual nappers exhibited a greater reduction in the amplitude of circadian rhythms such as melatonin secretion and REM sleep propensity than

non-nappers (Deantoni et al., 2024), indicating an exacerbated weakening of their circadian drive and concomitant with reported age-related effects in the literature (Alessi & Martin, 2018; Cajochen et al., 2006; Münch, 2014). Although our thermoregulation results did not go with the usually observed age-related amplitude reduction (Batinga et al., 2015; Czeisler et al., 1992; Harper et al., 2005; Hofman & Swaab, 2006; Martinez-Nicolas et al., 2018; Van Someren et al., 1999), they also came along weakened association with sleep initiation and portrayed a phase advance. As the data from the in-lab multiple protocol of the T1 assessment was available, we wanted to examine the impact of the nap-suppression intervention on melatonin, REM sleep propensity, sleep efficiency and (DPG, distal and proximal) skin temperature, to further explore the link and causality between circadian rhythm organisation and regular napping. We expected that the significant reduction of napping habits in older habitual nappers would re-stabilise the circadian markers and increase the day-night difference, notably in melatonin secretion and REM sleep propensity. Linear mixed models were ran on these 6 markers separately (models specifications and results are depicted in Appendix 3, Tables A2 to A7).

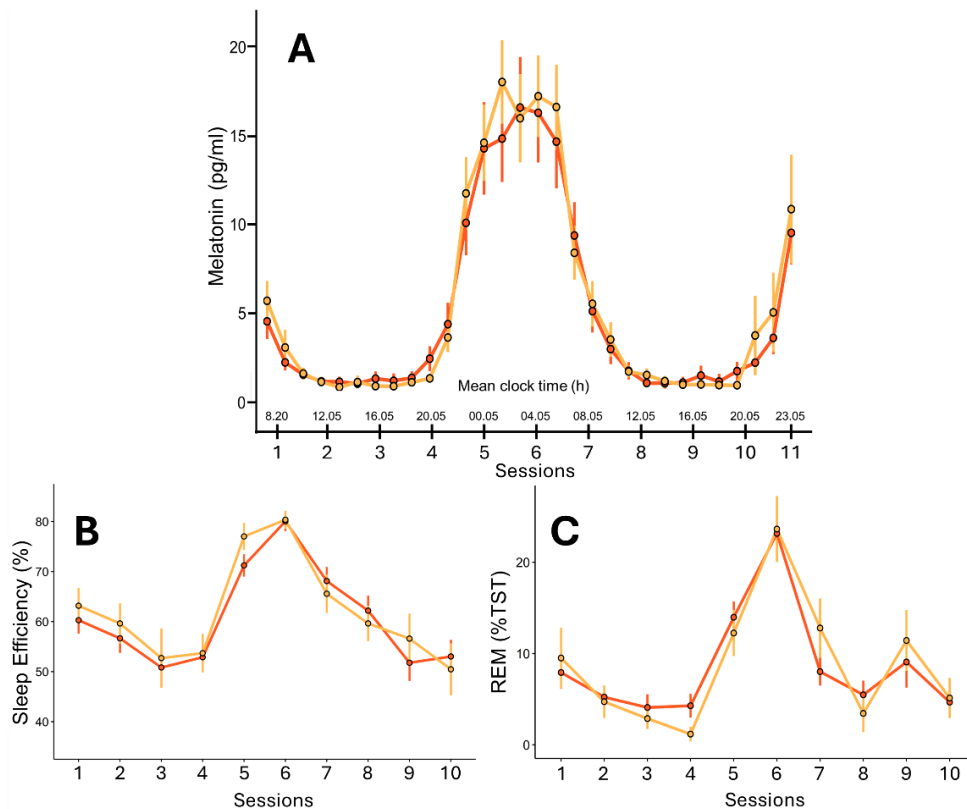


Figure 20. Panel A: Melatonin profile over the 40-hour multiple nap protocol according to time (T0: red, T1: yellow). Panel B & C: Time courses of percentage of sleep efficiency, and of the percentage of REM sleep on total sleep time, respectively, according to nap-opportunities and time (T0: red, T1: yellow). For all panels, SEM are displayed in group-coloured lines.

Although the nap suppression intervention did not yield overall changes over one year in melatonin secretion, REM sleep propensity or sleep efficiency, time-specific effects were observed at the follow-up (Figure 20). Specifically, REM sleep propensity was significantly elevated during the first morning nap opportunity of the second biological day (09:30-10:50), with concomitantly higher melatonin secretion in the subsequent wake period, occurring between 10:50 and 13:30. This pattern is in line with the strong circadian component of REM sleep propensity, which typically peaks in the late night and early morning irrespective of homeostatic sleep pressure (D. Dijk & Czeisler, 1995). An accentuation of REM sleep propensity and melatonin secretion in the morning therefore points to a circadian morning bias rather than a global strengthening of circadian amplitude.

In parallel, we found that DPG was significantly higher during the first two wake bouts of the second morning (06:50-09:30, and 10:50-13:30; Figure 21) at T1 compared to T0, surrounding the sleep opportunity that had an increased REM

sleep propensity. A higher DPG reflects stronger distal vasodilation and heat loss, which facilitates sleep onset and is regarded as one of the best physiological predictors of sleep readiness (Kräuchi et al., 2000). The coincidence of higher DPG, elevated REM sleep propensity and melatonin secretion, coherently reflects a stronger circadian pressure for sleep during this early morning window. The observed melatonin rise during the subsequent wake period is consistent with its known role in promoting distal vasodilation, thereby increasing DPG and facilitating the transition to sleep (Kräuchi, 2007b; Kräuchi, Cajochen, et al., 2006). In addition, harmonic regressions showed a phase delay of approximately 111 minutes between T1 (-45.1° phase angle) and T0 (-72.9° phase angle), such that the acrophase of DPG occurred around 04:49 at T1, and 02:58 at T0. DPG amplitude, after one year, was reduced by approximately 0.3°C. Finally, the 12-hour component of the harmonic regression observed at T0 disappeared after the one-year long intervention, suggesting the disappearance of bi-phasic temperature modulation.

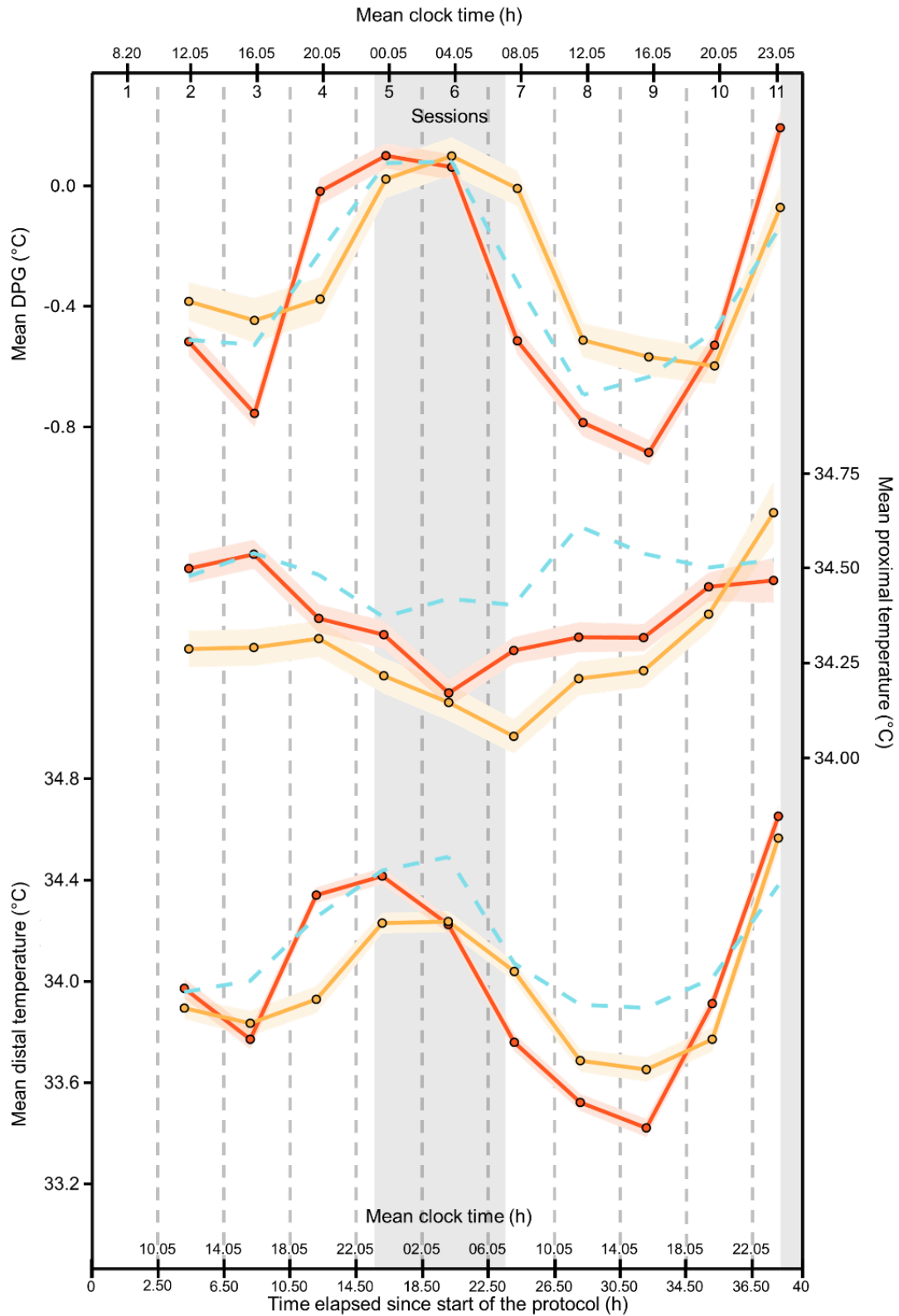


Figure 21. Averaged time course of DPG, proximal skin temperature and distal skin temperature according to session and time. Nappers before the intervention (T0) are depicted in red, nappers after having followed the intervention (T1) are in yellow, with SEM displayed in shaded colour. Dashed semi-transparent blue line represent the non-napper group at baseline, for better comparison. Grey dashed lines indicate the occurrence of nap opportunities between sessions. The top x-axis depicts the midpoint of the mean clock time for each session (averaged across individuals), while the bottom x-axis shows the mean clock time midpoint for nap opportunities (averaged across individuals) and the time elapsed since the start of the protocol. The biological night is shaded in grey.

Taken together, these findings point towards a subtle reorganisation of circadian timing, with a phase delay of thermoregulatory markers and a morning consolidation of circadian outputs, rather than a reinforcement of circadian amplitude. In line with previous reports of age-related phase advances and weakened circadian drive (Duffy et al., 2015; Hood & Amir, 2017; Münch et al., 2005), habitual nappers initially displayed a phase advance in skin temperature alongside reduced amplitudes of salivary melatonin secretion and REM sleep propensity. After one year of nap reduction, the thermoregulatory peak shifted later and more closely resembled the pattern of non-nappers. This phase delay coincided with a morning strengthening of circadian markers and with the disappearance of the 12-hour harmonic component, which aligns with actigraphy data suggesting reduced fragmentation of the rest-activity cycle. Thus, even though changes were modest, the suppression of habitual napping over one year appears to support a partial reconsolidation of circadian rhythmicity. This is consistent with the observation that participants reduced nap duration more strongly than frequency, suggesting that naps may occur under circadian pressure rather than voluntary choice. While they could not prevent their occurrence, they could consciously shorten their naps. These individuals might then counteract this drive behaviourally, thereby helping to stabilise circadian organisation. In this sense, the intervention may act as a means of interrupting or slowing a vicious cycle of circadian weakening. Nevertheless, the subtlety of the effects indicates that one year may be insufficient to induce more robust changes, which also helps to explain why the cognitive outcomes mirrored this pattern and remained moderate. Importantly, however, the disappearance of the 12-hour harmonic component may signal a protective effect of the one-year long nap reduction, as reduced circadian fragmentation is often associated with attenuated cognitive decline. This could account for the stabilisation of episodic and working memory performance observed in the intervention group, as well as with the compensatory brain regions reconfiguration, in contrast to the decline and brain dedifferentiation seen in persistent nappers.

3. Limitations and Future Perspectives

3.1. Sample characteristics

The absence of striking or significant cognitive effects in our studies may, at least in part, be attributed to a ceiling effect resulting from the exceptionally high functioning of our sample. The stringent eligibility criteria likely led to the recruitment of a highly selective subgroup of older adults who can be considered as “super healthy agers” (Depp & Jeste, 2006; Lupien & Wan, 2004; Rowe & Kahn, 1987). These individuals are typically characterised by preserved physical and mental health, high cognitive reserve, and the absence of major modifiable risk factors for cognitive decline (Stern, 2009). Indeed, discrepancies in socio-economic status between the CogNap sample and the general ageing population must be acknowledged. According to 2024 data from Wallonia⁴, the education level of individuals aged 60 to 75 is distributed as follows: 34.3% have a low level of education (lower secondary, <9 years), 36.3% have a medium level (high school, <12 years), and 29.3% have a high level (tertiary education >12 years). In contrast, the participants recruited for our protocol display a markedly higher level of education, with a mean of around 14 years of formal schooling. Specifically, 65% of the sample held a high, or even very high qualification (> 17 years of education), indicating a substantial underrepresentation of individuals from lower and medium educational backgrounds. This can be partly explained by the fact that several exclusion criteria targeted behaviours or health conditions more prevalent among individuals with lower socio-economic status, such as smoking (Marmot, 2005).

An additional feature of our cohort is the exceptionally low drop-out rate observed over the two-year period, which likely reflects both the strong commitment of participants and the high level of intrinsic motivation. Unlike many longitudinal studies involving older adults, where attrition due to health deterioration,

⁴<https://www.iweps.be/indicateur-statistique/niveau-de-diplome-de-population-de-25-ans-plus/>

disinterest, or logistical barriers is common (for review, see Chatfield et al., 2005), the CogNap project benefitted from sustained participant engagement. This is probably due in part to the implementation of high-quality interpersonal interactions between participants and the research team, which fostered a sense of trust, value, and continuity. All these factors are known to positively influence study adherence (Galea & Tracy, 2007). Beyond retention, motivation may also have had a direct impact on cognitive performance. Previous research has shown that motivation and effort can significantly affect outcomes in cognitive tasks (Di Rosa et al., 2015; Hess et al., 2012), particularly in domains such as inhibition or selective attention (Swirsky & Spaniol, 2020), as well as episodic memory (Swirsky et al., 2023). Moreover, motivation, specifically perceived cognitive capacity, has been identified as a mediating factor between cognitive reserve and actual cognitive performance in older adults (Vallet et al., 2018). In a highly motivated sample such as ours, participants may have exerted greater cognitive effort, resulting in uniformly high performance across cognitive tests, thereby contributing to a restricted variability in scores and reinforcing the ceiling effect hypothesis previously discussed.

Finally, the CogNap study exhibited a gender imbalance, with only a third of female participants in the final sample. This disproportion results from the prospective recruitment strategy centred on napping behaviours, which are consistently reported to be more prevalent among older men (Gislason et al., 1993; Jung et al., 2013). This gender imbalance has important implications for the interpretation of cognitive findings, amongst others. Sex differences in cognitive ageing are well documented, with women generally showing greater resilience to age-related cognitive decline compared to men (McCarrey et al., 2016), particularly in verbal learning, memory, and psychomotor speed (Munro et al., 2012).

In the context of CogNap, where participants were selected based on optimal health criteria, it is possible that the interaction between high education, good health, high motivation and male predominance created a particularly homogeneous sample in terms of cognitive outcomes, thus limiting the emergence of detectable group

differences. While the extensive exclusion criteria employed in the CogNap protocol offer the advantage of isolating a clearly defined and relatively homogeneous phenotype, they also constitute a major limitation in terms of generalisability. Consequently, cognitive performance across participants may have approached the upper bounds of standardised neuropsychological tests, resulting in restricted variance and reduced sensitivity to detect subtle interindividual differences, a classic manifestation of the ceiling effect (Salthouse, 2010, 2017). In such high-functioning cohorts, cognitive scores tend to cluster near the maximum values, limiting the ability to observe meaningful associations with behavioural or physiological variables, such as napping habits or changes over one year time. Furthermore, this particularly homogeneous subsequent cognitive profile could have reduced the sensitivity of traditional neuropsychological tools. Although this provides some evidence that our results, even if subtle, are truly linked to napping, it highlights a broader methodological issue in ageing research: standard cognitive assessments may lack the resolution necessary to detect early or nuanced cognitive changes in elite ageing populations (Tucker-Drob, 2011). Future studies should strive for greater demographic diversity, including balanced gender representation and varied educational and health backgrounds, and incorporate more sensitive cognitive measures. Addressing these methodological challenges is essential to capture the nuanced interactions between ageing, behaviour, and brain health, and to move beyond ceiling effects that obscure meaningful individual differences.

3.1.1. Baseline differences between nap-groups

Although all high performing and before group assignment, individuals from the two nap groups (nap-control and nap-intervention) already differed in cognitive performance at baseline, be it in episodic or working memory, as observed in Studies 3 and 4. These differences could not be explained by differences in educational levels, nor by objective nap characteristic differences: they did not differ in regards to DTR-duration ($p=0.424$) nor DTR-frequency ($p=0.964$). However, it should be noted that while the nap-control group displayed higher levels than non-nappers for both metrics at baseline (DTR-duration: $p=0.005$, DTR-

frequency: $p=0.023$), the nap-intervention group statistically differed from the non-nap group only for DTR-frequency ($p=0.009$) and not for DTR-duration ($p=0.101$). This placed the nap-intervention individuals at an “in-between” place in terms of nap duration (Figure 22).

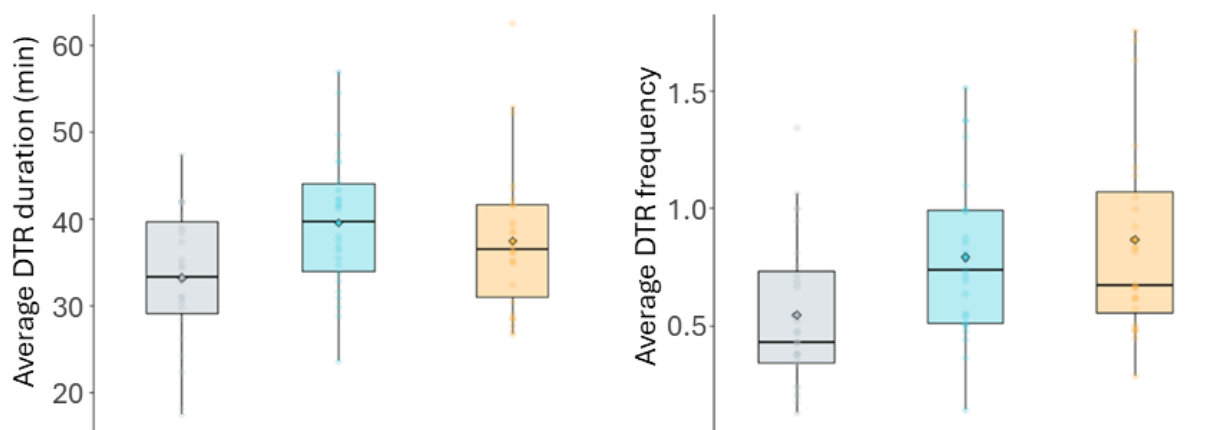


Figure 22. Boxplots represent the distribution of DTR-duration (left) and DTR-frequency (right) at baseline across groups (median, interquartile range, whiskers). Non-nappers = grey; nappers-control = blue, nappers-intervention = yellow.

If we take the stance by which, although not statistically significant, individuals from the nap-control group tended to nap longer than the nap-intervention group, this could partly explain the baseline difference observed at the cognition level. Long-duration and frequent naps are associated with lower cognitive performance, specifically poorer attention, processing speed, and memory performance (J. Li et al., 2022; Overton et al., 2024; Souabni et al., 2022), faster cognitive decline (Álvarez-Bueno et al., 2022; Gao et al., 2025) and higher risk of dementia (Leng et al., 2019; J. C. Lo, Ong, et al., 2016).

Another possibility is that the difference does not emerge from observed nap metrics but rather lie in the reason these people nap. Nap intentionality plays a mediating role in both sleep-wake regulation (Ficca et al., 2010; Monk et al., 2001) and cognitive outcomes (Li et al., 2022; Mednick et al., 2003; Mednick, 2024; Owusu et al., 2019), particularly in older adults. Planned, prophylactic naps, taken intentionally to restore alertness or reduce sleep pressure, have been shown to alleviate homeostatic sleep drive without disrupting nocturnal sleep onset or altering circadian phase, thus supporting stable 24-hour rhythms and optimal

cognitive functioning (Ficca et al., 2010; Scullin et al., 2017). In contrast, recuperative or opportunistic naps, often taken later in the day in response to acute fatigue or excessive sleepiness, are more likely to fragment rest-activity rhythms, blunt evening circadian alerting signals, and correlate with poorer cognitive outcomes (Leng et al., 2019; Monk et al., 2001). A third type, appetitive naps, which are taken for pleasure or boredom, typically occur during periods of low sleep pressure and may reflect lifestyle patterns more than physiological need. While often brief and self-initiated, such naps in older adults have been associated with increased intra-daily activity fragmentation and minimal gains in sleep quality or cognition (Ficca et al., 2010; Milner & Cote, 2009). Importantly, nap frequency, duration, and intentionality interact to modulate these outcomes, with longer and more frequent unintentional naps consistently linked to poorer cognitive performance, whereas short, intentional naps may offer protective or enhancing effects (J. Li et al., 2022; Mednick et al., 2003; Mednick, 2024; Owusu et al., 2019). While some studies report neutral or even beneficial effects of habitual napping under specific conditions (Alqurashi et al., 2022; Cai et al., 2021; Keage et al., 2012; J. Li, Vitiello, et al., 2018; Souabni et al., 2022), the emerging consensus suggests that the why, when, and how of napping are as important as its mere presence. As such, if the nap groups differ in terms of intentionality and phenotype, it could partly explain the baseline discrepancies.

Out of our sample, self-reported nap intentionality could be computed from the LiNap questionnaire (Appendix 4). According to the latter, 47% of the nap-control individuals and 63% of the nap-intervention participants reported sometimes napping involuntarily (*“do you sometimes nap involuntarily -falling asleep without planning to-?”*). The main reason for unintentionally falling asleep in both groups were : watching TV (73%), after eating a meal (21%) or a combination of both (18%). In contrast, only 15% of the nap-control group and 7% of the nap-intervention group reported to usually plan their naps (*“do you plan your naps?”*). Not only did we not reveal a clear difference in planification between groups, but we also note that 11 nap-control as well as 9 nap-intervention individuals do report

napping, but do not state to either plan their naps nor to nap involuntarily. When asked “why” they nap, the reasons appear to be mixed for both groups. However, the nap-control group seems to lean toward a prophylactic and appetitive phenotype (45% because of tiredness, 31% by pleasure, 17% for recuperation after a bad night, 7% other), and the nap-intervention tends to rather present a mix between prophylactic and recuperative phenotype (37% because of tiredness, 27% for recuperation after a bad night, 23% for pleasure, 13% other). Finally, when asked about the perceived need to nap (“*is napping a need for you?*”), the nappers-control usually reported a moderate-to-strong need (20% small, 50% moderate, 20% high, 10% extreme), while nappers-intervention displayed a small-to-moderate perceived need (13% no need, 27% small, 37% moderate, 20% high, 3% extreme).

This suggest that participants in the nap-intervention group reported a lower subjective need to nap than those in the nap-control group, despite showing a slightly higher frequency of unintentional naps and a more restorative-driven reason underlying their nap behaviour. This paradox may reflect a distinct nap phenotype: less driven by intentional rest and more by passive fatigue or inactivity, such as after a poor night’s sleep. Crucially, this lower perceived need could make adherence to a nap-suppression protocol easier for these individuals, potentially biasing intervention outcomes by overestimating its effectiveness. Moreover, while the intervention group reported napping primarily due to tiredness or poor nocturnal sleep, nappers-control more often cited both tiredness and pleasure, suggesting different motivational profiles. However, these differences in nap intention and planning do not fully account for the baseline cognitive discrepancies observed between groups. Indeed, both appetitive and recuperative napping have been associated with poorer cognitive outcomes cognition (Ficca et al., 2010; Monk et al., 2001), and thus are unlikely to explain the divergence.

Importantly, because group assignment occurred after the baseline cognitive assessment, neither recruitment bias nor nap characteristics can explain these initial differences. This points to a critical limitation of randomisation strategies

that rely solely on demographic matching. Future intervention studies should consider including baseline cognitive performance, motivational nap profiles, and cognitive reserve indicators in their group allocation process, to better control for underlying interindividual differences that may influence responsiveness to behavioural interventions.

3.2. Intervention characteristics

3.2.1. Nap detection during the intervention

While actigraphy is widely accepted, validated and reliable for estimating sleep parameters and circadian rhythms in naturalistic settings (Ancoli-Israel et al., 2003; Sadeh, 2011) and for detecting rest periods during the day (Cellini et al., 2013; Kanady et al., 2011), it nevertheless lacks specificity. In particular, actigraphy cannot reliably distinguish between actual naps, quiet wakeful rest, or periods of physical inactivity accompanied by cognitive engagement, such as meditation. Consequently, it remains uncertain whether participants classified as “napping” were genuinely asleep or instead engaged in other restful yet mentally active behaviours. Several studies investigating meditation techniques such as breath awareness, focused attention, or mindfulness, have reported improvements in attention, working memory, and episodic memory in healthy older adults (Dwivedi et al., 2021; Ford et al., 2020; Pandya, 2019; Requier et al., 2023). This possibility could represent one incidental difference between our two nap groups, potentially contributing to the baseline disparities observed.

Beyond the inter-individual variability in nap reduction observed within the nap-intervention group over the one-year period, meaningful variability was also present in the nap-control and non-nap groups. Some participants initially classified as non-nappers began napping regularly during the follow-up, while certain nap-control participants either reduced or increased their napping habit without any prompting. This observation nuances the interpretation of the T1 findings, as behavioural modification was not confined to a single group. In retrospect, a more rigorous control design could have included a specific

intervention phase for the nap-control and non-nap groups, in which nap behaviour was deliberately stabilised from baseline to follow-up, thereby reducing the confounding influence of spontaneous behavioural change. Additionally, baseline classification was not entirely free from misallocation. In some cases, individuals were placed in the non-nap group on the basis of their self-reported behaviour during screening and partial confirmation from a short actigraphy recording but were in fact napping in their daily life. In contrast, some participants were assigned to the nap group despite objectively failing to meet the inclusion threshold of at least three naps per week of 30 minutes or more. While these misclassifications were few, identified and corrected in the studies presented in this thesis, they highlight the complexity and fluidity of napping as a behavioural construct. Importantly, the use of such a threshold means that “non-nappers” are rarely truly nap-free. Instead, they nap too infrequently or too briefly to meet our operational definition of a napper. As such, group allocation is not a black-and-white distinction but a pragmatic categorisation within a behavioural continuum. Self-reports are further susceptible to bias, as some individuals deny napping and describe their behaviour as “resting” or “taking quiet time”, whereas others consider low-activity periods as naps despite not really falling asleep. This discrepancy between objective and subjective detection of naps in everyday life warrants further investigation. It may be linked to the role of nap intentionality, as discussed earlier, whereby an individual’s perception and labelling of rest episodes could contribute to distinct nap phenotypes with potentially different physiological and cognitive implications.

It must be highlighted that, while the cumulative sum of difference from baseline exhibits a clear reduction in both nap duration and frequency during the one-year intervention period, the examination of raw levels of DTR duration and DTR frequency reveals a nuance in the intervention’s efficacy. In that regard, and as already introduced sporadically in this discussion, while DTR duration decreased from the first month of monitoring and remained stable at non-napper levels throughout the intervention, DTR frequency did not show such a pronounced

reduction. Instead, frequency declined gradually over the first three months and subsequently stabilised at a level lower than the group's baseline, yet still higher than that observed in non-nappers (see Figure S1 of Study 3). This pattern suggests that participants in the nap-intervention group were more effective at reducing the duration of their naps than their frequency. The lower reduction in frequency may reflect naps occurring spontaneously, rather than as a deliberate behaviour, and joins in the observation that most of the nap-intervention report napping involuntarily. In this view, participants may have been more aware of their inclination to nap thanks to the intervention and acted consciously to shorten the episodes when they occurred, thereby accounting for the observed reduction in duration. Moreover, we do not have clear data on what replaced the afternoon nap in the daily routines of participants in the intervention group during the follow-up period. The preserved cognitive performance in this group could therefore reflect the substitution of napping with more cognitively stimulating, physically active, or socially engaging activities. These types of activities are well established as protective for cognitive health in older adults (Callow et al., 2024) and promoting cognitive reserve (Stern, 2009; Stern et al., 2019). There is robust evidence that physical activity, particularly of the aerobic type, is associated with benefits for various aspects of cognition in healthy older adults, including motor function, cognitive processing speed, delayed memory functions, and both auditory and visual attention (Angevaren et al., 2008; Lautenschlager et al., 2008; Vaportzis et al., 2019). In fact, the introduction or intensification of physical activity in older adults at 'high-risk' of cognitive decline has been shown to improve cognitive performance over an 18-month period (Lautenschlager et al., 2008). Social engagement is likewise linked to better cognitive outcomes in healthy older populations (Bassuk et al., 1999). Active and frequent social interactions, particularly face-to-face exchanges, are associated with improvements in global cognition, executive functioning and in some cases, memory (Zhu et al., 2023). It is therefore plausible that the initiation of more stimulating and beneficial activities in place of the habitual afternoon nap could account for part of the preserved, and

in some domains even improved, cognitive performance observed in the nap-intervention group rather than nap reduction alone.

Another limitation is that our actigraphy protocol only identified daytime rest episodes lasting at least 15 minutes. Consequently, micro-naps or brief episodes of drowsiness shorter than 15 minutes, sometimes referred to as “power naps” (A. Brooks & Lack, 2006), were not detected. Such brief naps have been reported to enhance alertness and cognitive function (Mednick et al., 2003). Furthermore, the relationship between nap duration and cognitive outcomes in older adults appears to follow an inverted-U pattern (J. Li, Chang, et al., 2018). Short to moderate naps (less than 30 minutes) tend to be associated with cognitive benefits, whereas longer naps (more than 90 minutes) have been linked to poorer cognitive performance (J. Li, Chang, et al., 2018). Since our intervention primarily reduced, rather than eliminated, nap duration, it is possible that participants shifted from a long and potentially detrimental nap profile to a shorter and more advantageous one. As such, the maintenance of cognitive performance in the nap-intervention group may reflect the adoption of an optimal nap pattern rather than the complete cessation of daytime napping.

3.2.2. Length of the intervention

In light of recent evidence from multidomain lifestyle interventions (Schott, 2025), it is plausible that the one-year duration of our nap-reduction intervention may have been insufficient to capture the full extent of potential cognitive benefits. Schott’s work suggests that cognitive gains from behavioural interventions can follow a non-linear S-shaped trajectory, with an initial improvement, a plateau phase, and a subsequent secondary improvement over a two-year period. If this pattern holds true for sleep-wake cycle interventions, our one-year follow-up may coincide with the end of the initial improvement phase or the plateau stage, thereby underestimating the long-term effects. Furthermore, our approach targeted only a single behavioural domain, daytime napping, whereas multidomain interventions incorporating physical activity, diet, cognitive training, and social engagement have

demonstrated additive beneficial effects on cognitive outcomes (Schott, 2025). A more inclusive intervention could, for instance, combine nap reduction with structured replacement activities, such as moderate-intensity exercise, socially engaging tasks, or cognitively demanding leisure hobbies, each of which is independently associated with better cognitive ageing trajectories. The lack of systematic monitoring and control over what participants did instead of napping in our study leaves open the possibility that variability in these replacement behaviours contributed to the observed interindividual differences in cognitive change. Future work should investigate whether embedding nap regulation within a broader, controlled, and multimodal behavioural programme, possibly extending beyond two years, enhances both the durability and magnitude of cognitive benefits, and whether such benefits translate into clinically meaningful reductions in the incidence of mild cognitive impairment and dementia.

While our study included a two-year follow-up for all participants, they were free to modify their nap habits between T1 and T2. Consequently, changes observed at T2 cannot be interpreted as reflecting the sustained effect of the original nap-reduction intervention alone but are more likely to represent a combination of natural age-related changes and self-directed behavioural evolution. This limits our ability to directly attribute T2 outcomes to the controlled intervention phase. Analyses on the T2 follow-up will be useful to contextualise the T1 results found here. From a methodological perspective, future analyses could make more nuanced use of the longitudinal data by moving beyond the baseline-defined groups (non-nap, nap-control, nap-intervention) and instead modelling nap characteristics such as average nap duration or frequency, as continuous predictors. Alternatively, participants could be re-clustered based on how their nap behaviours evolved over the entire follow-up period, thereby enabling the investigation of whether different nap-related trajectories (e.g., sustained reduction, intermittent resumption, stable short napping) are differentially associated with cognitive and brain outcomes. Finally, a longer-term follow-up (more than 5 years) could also be used to assess the cognitive trajectory and

possible emergence of neurodegenerative diseases, such as AD, in our sample. Based on this, cognitive and brain results could be interpreted in light of the known successful or pathological ageing of each participant, or recreate new groups (successful ageing vs. pathological ageing), to investigate how napping mediates this evolution. Such approaches could help disentangle the specific role of nap behaviour from other lifestyle and ageing-related influences and might yield a more precise understanding of the conditions under which nap modification contributes to long-term cognitive resilience.

4. Conclusion : the “chicken or the egg” question

Is it the nap that precedes circadian dysregulation, or circadian dysregulation that precedes the nap? In CogNap, we grounded our hypotheses on a simple yet powerful premise: sleep is good, but it is potentially even better when initiated at the appropriate (circadian) time. Through cross-sectional studies and a nap-reduction intervention, our aim was to move beyond association and provide a more causal interpretation of the link between habitual napping and circadian dysregulation on the one hand, and its impact on cognitive performance and brain function on the other. While much work remains to be done within the constraints of this project to fully uncover the extent of habitual napping’s effects across multiple domains, this thesis contributes to a new understanding of its impact on the ageing brain and body, and how acting upon it may potentially reverse these effects.

Taken together, the findings of this thesis converge on a central proposition: in ageing, the stability of the sleep–wake cycle, and particularly the integrity of circadian and homeostatic regulation, acts as a modulator of cognitive trajectories, with habitual napping emerging as both a marker and a potential modifiable contributor to dysregulation. Across studies, habitual nappers showed altered thermoregulatory dynamics, lower melatonin amplitude, lower capacity to create efficient cognitive strategies in episodic memory, greater vulnerability to task

difficulty in working memory and an underlying brain activation profile indicative of dedifferentiation. All these are consistent with a state of “temporal fragmentation” in which brain and body oscillate more frequently between wake and sleep states, eroding circadian consolidation and sustained cognitive engagement, leading to a more ‘aged-like’ profile both in terms of physiology and cognition. The nap-suppression intervention results indicate that even in late life, behavioural modification of daytime sleep patterns can stabilise cognitive performance and promote compensatory neural reorganisation.

However, the preliminary findings presented in the discussion of this thesis provide important nuances to these conclusions. First, the cessation of napping was neither complete nor multimodal: the reduction in nap frequency was considerably smaller than the reduction in nap duration. Physiologically, no re-emergence of a stronger day–night contrast was observed in melatonin secretion, REM sleep propensity, or sleep efficiency. This pattern suggests that while napping is indeed a modifiable behaviour in older adults, its occurrence may be rooted in an underlying circadian dysregulation. A weakened circadian signal may trigger the need for naps, which could explain the limited reduction in nap frequency. Nonetheless, the intervention appeared to enable participants to both detect episodes of drowsiness and actively restrict them, thereby reducing nap duration. An alternative possibility is that after years of engaging in habitual napping, participants may have only partially “recovered” from this behaviour at both behavioural and physiological levels, insufficiently so to erase the detrimental impact already incurred.

Yet the picture is not entirely negative. Despite the absence of amplitude restoration, the intervention was associated with a phase delay and an maintained cognitive performance, suggesting that participants shifted towards a profile closer to baseline non-nappers. Specifically, they showed signs of morning reconsolidation of sleep-related signals, alongside the disappearance of both the late-afternoon thermoregulatory phase advance and the 12-hour biphasic profile. Therefore, it seems that reducing rest-activity fragmentation helped optimising the temporal alignment of cognitive demands with stable wakefulness. It remains

possible that our intervention was not sufficiently stringent (whether in duration or in the extent of enforced nap suppression) to elicit stronger physiological and cognitive changes. The current findings often resemble subtle shifts, or even the premise of change, that might have become more pronounced had the intervention lasted longer. For this reason, I remain convinced that these results mark the beginning of a potential and important avenue of research, one that CogNap has only started to open.

The growing body of literature points to habitual, frequent, and prolonged napping as detrimental for both physical health and cognition, and, to my knowledge, this project is the first to provide evidence that such effects may be at least partially reversible. Future work should extend the intervention period, test more stringent or multifactorial approaches (light exposure, exercise, meal timing, ...), and examine cognitive outcomes in greater depth, while also addressing sampling biases beyond demographic matching. This would help identify the threshold at which nap characteristics transition from adaptive to maladaptive, opening a pathway for personalised chronotherapy to promote cognitive resilience in ageing. If the methodological limitations highlighted in this thesis can be overcome, subsequent studies may uncover more substantial effects and help answer the fundamental question that has guided this project from the very beginning: is it the nap that precedes circadian dysregulation, or circadian dysregulation that precedes the nap? What remains clear, however, is that while *sleep is good, it is better when initiated at the right time.*

Appendices

Appendix 1 : List of Publications

First author:

Dourte, M., Hammad, G., Schmidt, C., & Peigneux, P. (2025). Uncorrelated Age-Related Changes in Visuo-Spatial Working Memory Binding and Thermoregulation. *Clocks & Sleep*, 7(2), Article 2. <https://doi.org/10.3390/clockssleep7020017>

Reyt, M.*, **Dourte, M.***, DeHaan, S.*, Deantoni, M., Baillet, M., Lesoinne, A., Laloux, S., Hammad, G., Collette, F., Peigneux, P., Muto, V., Vandewalle, G., Bahri, M. A., Phillips, C., & Schmidt, C. (2025). *Napping alters Functional Brain Responses in the Aged* (p. 2025.06.10.657597). bioRxiv. <https://doi.org/10.1101/2025.06.10.657597>

Other:

Lazar, R., Fazlali, F., **Dourte, M.**, Epple, C., Stefani, O., Spitschan, M., & Cajochen, C. (2025). Afternoon to early evening bright light exposure reduces later melatonin production in adolescents. *Npj Biological Timing and Sleep*, 2(1), 25. <https://doi.org/10.1038/s44323-025-00040-6>

de Haan, S., **Dourte, M.**, Deantoni, M., Reyt, M., Baillet, M., Berthomier, C., Muto, V., Hammad, G., Cajochen, C., Reichert, C. F., Maire, M., Schmidt, C., & Postnova, S. (2025). Impact of Varying Sleep Pressure on Daytime Sleep Propensity in Healthy Young and Older Adults. *Clocks & Sleep*, 7(1), Article 1. <https://doi.org/10.3390/clockssleep7010002>

Deantoni, M., Reyt, M., **Dourte, M.**, De Haan, S., Lesoinne, A., Vandewalle, G., Phillips, C., Berthomier, C., Maquet, P., Muto, V., Hammad, G., Schmidt, C., & Baillet, M. (2024). Circadian rapid eye movement sleep expression is associated with brain microstructural integrity in older adults. *Communications Biology*, 7(1), 758. <https://doi.org/10.1038/s42003-024-06415-y>

Deantoni, M.*, Reyt, M.*, Baillet, M., **Dourte, M.**, De Haan, S., Lesoinne, A., Vandewalle, G., Maquet, P., Berthomier, C., Muto, V., Hammad, G., & Schmidt, C. (2024). Napping and circadian sleep-wake regulation during healthy aging. *Sleep*, 47(5), zsad287. <https://doi.org/10.1093/sleep/zsad287>

Deantoni, M., Reyt, M., Berthomier, C., Muto, V., Hammad, G., De Haan, S., **Dourte, M.**, Taillard, J., Lambot, E., Cajochen, C., Reichert, C. F., Maire, M., Baillet, M., & Schmidt, C. (2023). Association between circadian sleep regulation and cortical gyrification in young and older adults. *Sleep*, 46(9), zsad094. <https://doi.org/10.1093/sleep/zsad094>

Appendix 2 : Napping alters Functional Brain Responses in the Aged

Mathilde Reyt^{1,2,*}, Marine Dourte^{1,3,5,*}, Stella DeHaan^{1,*}, Michele Deantoni¹, Marion Baillet⁴, Alexia Lesoinne^{1,3}, Sophie Laloux¹, Gregory Hammad¹, Fabienne Collette^{1,3}, Philippe Peigneux^{1,5}, Vincenzo Muto¹, Gilles Vandewalle¹, Mohamed Ali Bahri¹, Christophe Phillips¹, Christina Schmidt^{1,3}

¹GIGA-Research, CRC-Human Imaging Unit, University of Liège, Liège, Belgium.

²Institut Universitaire de Gériatrie de Montréal, Montréal, Canada

³Psychology and Neuroscience of Cognition Research Unit (PsyNCog), Faculty of Psychology and Educational Sciences, University of Liège, Liège, Belgium

⁴Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA

⁵Center for Research in Cognition and Neurosciences, Université Libre de Bruxelles, Bruxelles, Belgium

*Equal contribution

Submitted and Under Review

Abstract

Background: Circadian rhythms shape the temporal organization of sleep and wakefulness and evolve throughout the adult lifespan, leading to higher sleep-wake cycle fragmentation with ageing. The increasing prevalence of daytime napping represents a visible manifestation of such fragmentation and has been suggested to forecast age-related cognitive decline.

Methods: We assessed the impact of napping on functional brain correlates of working memory performance. To do so, 30 habitual nappers and 30 non-nappers were prospectively recruited and individually matched with respect to age, gender, educational level and season of assessment. Working memory performance was assessed with the Sternberg WM paradigm (that allows for a parametric modulation of working memory load in a functional magnetic resonance imaging (fMRI) environment).

Results: As compared to non-nappers, nappers showed reduced hemispheric asymmetry in the dorsolateral prefrontal cortex (DLPFC, $p < 0.001$) and decreased performance at high WM load levels. Only in non-nappers was increased ipsilateral activation in the DLPFC associated with better performance at high WM load levels ($p < 0.05$), while contralateral activation across all WM load levels was not associated with better performance.

Conclusion: Our results provide first evidence for altered functional brain compensation and dedifferentiation processes according to the napping phenotype in the aged. The latter could serve as a marker of inter-individual differences in cognitive and brain aging, potentially driven by circadian sleep disruption.

Keywords: aging, napping, working memory, functional brain responses, functional compensation, dedifferentiation

1. Introduction

Large-scale population-based studies revealed that inter-individual variability characterizes the aging process as well as its associated cognitive decline (Lindenberger, 2014; Lupien & Wan, 2004; Nyberg et al., 2012). Increased group variance in cognitive processes implies that some individuals show very poor performance (up to pathological aging), whereas others maintain high levels of performance (Lupien & Wan, 2004). Poor performance has attracted much interest as it might be indicative of forthcoming disease, such as Alzheimer's dementia. However, staying cognitively sharp at older age is not an exception. Successful agers are characterized by performance levels comparable to younger adults and keeping superior performance levels over time within their age-group (Lupien & Wan, 2004; Nyberg et al., 2012). Evidence from structural and functional neuroimaging are increasingly integrated to explain how the combined effects of adverse and compensatory neural processes produce both variable levels of cognitive change over the aging trajectory (Cabeza et al., 2018; Stern et al., 2020). Within this context, it has been suggested that high performing older adults recruit extra neural supply to allow maintenance of cognitive performance, despite an apparent age-related reduction in available neural resources, a concept referred to as compensation (Festini et al., 2018). Working memory (WM)-related brain activity has been particularly studied within this context. For instance, it has been observed that young adults show unilateral activation at low WM load but bilateral activation at high WM load in fronto-parietal networks, indicating the recruitment of supplemental brain areas to meet task demands (Bennett et al., 2013; Cappell et al., 2010; Mattay et al., 2006; Nyberg et al., 2009; Reuter-Lorenz et al., 2000; Schneider-Garces et al., 2010). On the other hand, older adults appear to already recruit bilateral neural resources in the dorsolateral prefrontal cortex (DLPFC) already at lower cognitive load levels, and would therefore have fewer supplemental or compensatory resources available at higher WM loads in order to adapt to the increasing task demands (Bennett et al., 2013; Cappell et al., 2010; Mattay et al., 2006; Nyberg et al., 2009; Reuter-Lorenz et al., 2000; Schneider-Garces et al.,

2010). Besides the supplemental recruitment of contralateral frontal areas, a shift between relative activity levels in anterior and posterior brain areas is also observed (Davis et al., 2008), such that older adults show less activation of posterior brain regions and higher activation in anterior brain regions, compared to young adults. Importantly, literature reviews suggest that the manner and success of compensation is modulated by lifestyle variables, referred to as proxies of cognitive reserve (Cabeza et al., 2018; Stern et al., 2020). Life-course factors, such as stress, physical activity or intellectual engagement have been shown to contribute to the developmental progress of brain structure and function, as well as cognition over time (Dixon & Lachman, 2019; Reuter-Lorenz & Park, 2014).

How a fundamental mechanism such as sleep regulation impacts on age-related changes in cognitive processes remains largely underexplored. Aging goes along with changes in sleep timing, duration and structure (Taillard et al., 2021), as well as an overall increased sleep-wake cycle fragmentation (A. S. P. Lim et al., 2011; Luik et al., 2013; Zuurbier et al., 2015). The latter has been associated with worsened cognitive performance (Luik et al., 2015; Oosterman et al., 2009), including WM (A. S. P. Lim et al., 2012). In the same vein, a particular emphasis has been attributed to the impact of habitual napping on cognitive performance in aging. Napping habit, reported in questionnaire or objectively quantified, using actimetry has been linked to decreased cognitive performance (Blackwell et al., 2006; Leng et al., 2019; Owusu et al., 2019) and suggested to constitute a health risk factor for the prognosis and progression of Alzheimer's disease (Leng et al., 2019; J. Li et al., 2022; A. S. P. Lim et al., 2013; Musiek et al., 2018; Weissová et al., 2016). Habitual napping in the aged is far from being uncommon and was reported to increase with advancing age such that more than half of adults aged 70 and above nap at least twice a week (Leng et al., 2018, 2019; J. Li et al., 2017; Milner & Cote, 2009). Here, we argue that the increased incidence of napping in older people is at least in part attributed to altered circadian sleep regulation. The latter is timed to achieve consolidated periods of sleep during night-time and a continuous period of wakefulness during daytime (Dijk & Archer, 2009). Circadian rhythms thereby

shape the temporal organisation of sleep and wakefulness leading to consolidated bout of sleep during night-time and a continuous period of wakefulness during the day. This temporal sleep-wakefulness organization evolves throughout the adult lifespan, leading to higher sleep-wake cycle fragmentation with ageing. The increasing occurrence of daytime napping becomes in turns the most visible manifestation of this fragmentation. Hence, napping may reflect an “index of circadian disruption” (Deantoni et al., 2024) with putative deleterious effects on cognitive and brain function. Accordingly, we reported that frequent daytime rest in people older than 60 years was not only associated with an altered 24-h organization of the rest-activity cycle, but also with reduced episodic memory performance (Reyt et al., 2022).

Based on the fact that the temporal organization of sleep-wake states is fundamental to brain function and prone to disruption during the aging process, we therefore explored whether habitual daytime napping interferes with functional brain compensation, underlying inter-individual variability in cognitive performance. After in-depth cognitive, sleep and circadian phenotyping, 60 healthy and cognitively unimpaired older adults (59 – 82 years old), prospectively recruited with respect to their napping habits (30 self-reported regular nappers vs 30 matched self-reported non-nappers), performed a Sternberg WM task while undergoing functional Magnetic Resonance Imaging (fMRI). We hypothesised that, compared to non-nappers, habitual nappers would be not only characterized by worse WM performance, but also by more “old age-like” functional dynamics in the brain responses corresponding to enhanced recruitment, mainly of the DLPFC, at lower WM loads. Given its potential position at the interface between vigilance and cognition (Portas, 1998), we further explored whether groups differ in task-related thalamic activation.

2. Results

2.1. Participants

After an extensive eligibility check (see methods), 30 habitual nappers and 30 non-nappers were prospectively selected and individually matched with respect to age, gender, educational level and season of assessment. Participants were classified as habitual nappers when subjectively reporting to nap at least three times a week for at least 45 minutes. As a consequence, habitual nappers did report a higher napping frequency ($X^2 = 37.03$, $p < 0.001$) and duration ($X^2 = 28.48$, $p < 0.001$) in their sleep agendas. In addition, actigraphy-derived outcomes (Figure 1) further confirmed a significantly higher daytime rest frequency ($W = 84.5$, $p < 0.001$) and duration ($t = -3.59$, $p < 0.001$) in habitual nappers as compared to non-nappers. Groups did not significantly differ, however, with respect to age, self-reported gender, and many potential confounding factors (education, subjective sleep quality, chronotype, affective state) (Table 1, all $p_s > 0.05$). Importantly, groups also did not significantly differ with respect to their global cognitive status (MMSE and PACC5 score, all $p_s > 0.05$). Despite exclusion of participants with indices ≤ 18 and $\geq 30 \text{ kg/m}^2$ at study entrance, regular nappers presented a higher body mass index (BMI), compared to non-nappers ($t = -2.06$, $p < 0.05$). Also, habitual nappers reported a higher habitual daytime sleepiness than non-nappers (Table 1, Epworth Sleepiness Scale (ESS), (Johns, 1991): $W = 264.5$, $p < 0.01$), while they did not differ in their subjective state of sleepiness ($p > 0.05$, Table 1, Karolinska Sleepiness Scale (KSS); Akerstedt & Gillberg, 1990) assessed before performance on the WM task in the MRI scanner.

2.2. Napping affects WM performance at high load levels

Working memory performance was assessed with the Sternberg WM paradigm (Figure 1; Sternberg, 1966), that allows for a parametric modulation of working memory load and has been extensively studied using fMRI. Participants had to indicate whether a probe letter was part of a series of previously presented letters.

WM load or Memory Set Size (MSS) corresponds to the number of letters presented during the encoding phase (2-7 letters, see methods). We first assessed the impact of WM load, nap group as well as their interaction on task performance using generalised linear mixed models (GLMM), including BMI and daytime sleepiness as covariates. According to the Akaike criterion (see methods for model comparisons), the model assessing performance accuracy also included demographical variables (age, sex and educational level).

As expected, higher WM load was associated with decreasing accuracy from MSS 5 onwards (all $p < 0.01$, Table 2, Figure 2) and increased reaction times from MSS 2 onwards (all $p < 0.001$, Table 2, Figure 2). Significant interactions for both d' and reaction times revealed that, as compared to habitual nappers, non-nappers performed faster ($t = 2.31$, $p < 0.05$, Figure 2) and better ($t = -1.98$, $p = 0.048$, Figure 2) at MSS 7. In addition, accuracy decreased with increasing age ($t = -2.87$, $p < 0.01$) and women showed lower performance compared to men ($p = 0.04$).

2.3. Habitual napping affects the functional brain correlates underlying WM

Brain activation was operationalized using the BOLD signal derived from functional MRI during the performance of the Sternberg paradigm. The involvement of the dorsolateral prefrontal cortex (DLPFC), particularly Brodmann's area (BA) 9/46 in this WM task has been crucially reported (Bennett et al., 2013; Cappell et al., 2010; Haque et al., 2021; Mattay et al., 2006; Reuter-Lorenz et al., 2000; Schneider-Garces et al., 2010) to be dynamically recruited over increasing WM load (Altamura et al., 2007; Bennett et al., 2013; Cappell et al., 2010; Höller-Wallscheid et al., 2017; Schneider-Garces et al., 2010).

Generalised linear mixed models were first computed to assess whether BOLD activation in the DLPFC is modulated by WM load (2-7 letters, Helmert contrasts), group (habitual nappers vs non-nappers, treatment contrast: reference = non-nappers), hemisphere (left vs right, treatment contrast: reference = left), as well as their interactions. Laterality was included as a factor, considering that compared to younger adults, older adults have been reported to show more bilateral activation

(Bennett et al., 2013; Cappell et al., 2010; Mattay et al., 2006; Nyberg et al., 2009; Reuter-Lorenz et al., 2000; Schneider-Garces et al., 2010) and putatively less differentiated hemispheric recruitment (Cabeza, 2002). Finally, BMI, daytime sleepiness and regional volume were included as covariates. Higher WM load was associated with a higher BOLD signal in the DLPFC (BA 9/46) starting at MSS 6 ($p < 0.001$; Table 2, Figure 3). Furthermore, a significant laterality*group interaction revealed that, independently of WM load and as compared to non-nappers, regular nappers presented higher BOLD activation in the right DLPFC ($t = 3.35$, $p < 0.001$, Figure 3), while no significant differences were observed in the left DLPFC.

Some studies highlighted that hemispheric asymmetry reduction observed in older adults could not be explained by compensation-based models (McDonough et al., 2013; Roe et al., 2020) but may rather reflect less specific neural responses, also-called dedifferentiation (Knights et al., 2021; Morcom & Henson, 2018). Age-related bilateral activation during a Sternberg task is indeed consistent with both dedifferentiation and compensation-based models (Carp et al., 2010). One requirement to define compensation is that increased BOLD activation is linked to performance improvement (Cabeza et al., 2018). If hemispheric asymmetry reduction in nappers is compensatory, WM performance should therefore be explained by BOLD signal in the DLPFC. We thus performed GLMM to test whether task performance (d' or reaction time) was associated with WM load (2-7 letters, Helmert contrasts), group (habitual nappers vs non-nappers, treatment contrast: reference = non-nappers), BOLD signal as well as their interactions. Daytime sleepiness and BMI were added as covariates and, according to Akaike criterion (see methods for model comparisons), model assessing accuracy also included age, gender and educational level. An WM load*BOLD signal*group interaction effect revealed that higher BOLD signal in the left DLPFC at MSS 7 was associated with accuracy only in non-nappers ($t = -2.00$, $p = 0.047$). No significant results were observed for the right hemisphere and reaction times (all $p_s > 0.05$).

2.4. Habitual napping & regional specificity in BOLD signal dynamics underlying working memory performance?

Studies investigating age differences in compensation-related processes have reported recruitment of supplemental brain areas in a more widespread WM-related brain network (Cappell et al., 2010; Schneider-Garces et al., 2010). Accordingly, region of interest (ROI) analyses were conducted on task-related BOLD signals in the DLPFC, but also in the frontal, parietal, temporal and occipital regions (extended WM-related brain network ROI, see methods, Figure 1). Besides differences in bilateral recruitment, compensatory-based models also posit a posterior-anterior shift in brain activation during WM performance, such that increased activation in anterior brain regions and reduced activity in posterior brain regions are associated with better performance in older adults (e.g. Davis et al., 2008; Festini et al., 2018). To assess whether napping habits affects brain activity in this framework, we extracted the BOLD signal in the ROIs encompassing the frontal, parietal, temporal and occipital lobes in the WM-network previously reported to be recruited by older adults during the Sternberg task (Cappell et al., 2010; Schneider-Garces et al., 2010). GLMMs were computed to assess whether brain activity is modulated by WM load (2-7 letters, Helmert contrasts), group (nappers vs non-nappers, treatment contrast: reference = non-nappers), regions (frontal, parietal, temporal, occipital, treatment contrast: reference: frontal) and hemisphere (left vs right, treatment contrast: reference = left), with covariates BMI, daytime sleepiness and regional volume. Increasing WM was associated with higher BOLD signal starting at MSS 5 (all $p < 0.001$, Table 2, Figure 4). Overall, the left hemisphere was more activated ($t = -13.79$, $p < 0.001$) than the right hemisphere (Figure 4). Compared to the frontal region, BOLD signal was higher in parietal ($t = 5.79$, $p < 0.001$, Figure 4), temporal ($t = 4.61$, $p < 0.001$, Figure 4) and occipital regions ($t = 11.87$, $p < 0.001$, Figure 4). Hemisphere*regions interaction effects revealed higher activation in the left parietal ($t = 5.27$, $p < 0.001$, Figure 4), left temporal ($t = 6.40$, $p < 0.001$, Figure 4) and left occipital lobe ($t = 7.86$, $p < 0.001$, Figure 4). Furthermore, as compared to non-nappers, BOLD signal was higher in

habitual nappers in parietal than in frontal regions (interaction group*regions: $t = -1.97$, $p = 0.048$, Figure 4).

2.5. Habitual napping & hemispheric asymmetry reduction

Finally, a separate ROI analysis was performed by extracting BOLD signal in the thalamus (Figure 1). Task-evoked thalamic BOLD activation has been shown to play a mediating function in the interaction between attention and arousal (Portas, 1998). Likewise, responses have been suggested to counter arousal-modulating effects in response to sleep loss or circadian misalignment (e.g. Muto et al. 2016), as may be expected in nappers. Building on our previous findings, showing altered circadian sleep regulation and vigilance modulation in habitual nappers (Deantoni et al., 2024), we performed GLMM to assess whether thalamic BOLD activation is modulated by WM load (2-7 letters, Helmert contrasts), group (habitual nappers vs non-nappers, treatment contrast: reference = no-nappers), and hemisphere (left vs right, treatment contrast: reference = left). As expected, a significant effect of WM load was observed in the thalamus with higher BOLD activation starting at MSS 5 (all $p < 0.01$, Table 2, Figure 5). Interestingly, as compared to non-nappers, habitual nappers activated more the thalamus over all WM and both hemispheres ($t = 2.17$, $p = 0.03$, Figure 5). Finally, while the right thalamus was overall more activated, compared to the left thalamus ($t = 14.33$, $p < 0.001$, Figure 5), a significant group*hemisphere interaction revealed that the BOLD signal in the right hemisphere was higher in regular nappers, compared to non-nappers ($t = 3.53$, $p < 0.001$, Figure 5).

3. Discussion

The older proportion of the population is increasing worldwide (Lindenberger, 2014), and cognitive decline represents a prominent factor for determining the health span of an older and aging population. In the absence of a strong genetic program (B. J. Morris et al., 2019), person-specific endowments, environmental

opportunities and constraints act as modulators and modifiers on cognitive and brain aging (Cabeza et al., 2018; Reuter-Lorenz & Park, 2014; Stern et al., 2020). The sleep-wake cycle and its age-related fragmentation reflect potentially malleable life-style components for cognitive aging (A. S. P. Lim et al., 2012; Luik et al., 2015; Oosterman et al., 2009). The increased incidence of napping and/or daytime rest has been recently suggested to be associated with or even forecast cognitive decline in longitudinal settings (Leng et al., 2019; J. Li et al., 2022; Reyt et al., 2022). This aligns with growing epidemiological evidence linking habitual napping to health risk factor in older adults (J. Li et al., 2022; Sun et al., 2022). Additionally, we highlighted altered circadian regulation in regular nappers (Deantoni et al., 2024), suggesting that such disruptions may contribute to these negative cognitive and health-related outcomes. Besides behavioral differences detectable at high working memory load, our results provide first evidence of altered WM-related brain responses in healthy older habitual nappers, most strongly expressed as a specifically reduced hemispheric asymmetry in the DLPFC.

The Compensation-Related Utilization of Neural Circuits Hypothesis (Reuter-Lorenz & Cappell, 2008) has been developed based on age-related changes in behavioural and cerebral responses to increased WM load. This model predicts higher brain activation with increasing WM load to meet task demands. In line with this prediction, we observed increased BOLD activation with increasing WM load in all ROIs and in both groups. Working memory processes critically involve the DLPFC, and more particularly the left DLPFC (Haque et al., 2021). Furthermore, the CRUNCH model posits that age-related brain alterations result in an over-activation that can be expressed as bilateral activation (Cabeza, 2002). During the Sternberg task, at low cognitive loads, young adults showed an asymmetric recruitment in the ipsilateral (left) hemisphere whereas a bilateral activation was observed in older adults (Cappell et al., 2010; Schneider-Garces et al., 2010). Within this context, increased recruitment of the contralateral hemisphere in the DLPFC in habitual nappers suggests that they may be characterized by a more “old age-like” brain function. At the behavioural level, we observed that, as compared to non-nappers,

regular nappers did not significantly differ in their performance (accuracy and reaction times), except for the highest WM load (MSS 7). Worse performance of nappers at the highest WM load indicates that they may have reached earlier their maximal WM capacity limit. This hypothesis is supported by a trend towards higher BOLD activation in the ipsilateral hemisphere in non-nappers at the highest WM load and higher BOLD signal in the contralateral hemisphere in habitual nappers, as compared to non-nappers. Whereas non-nappers might compensate with higher brain activity and thus maintain performance levels, performance decline in habitual nappers could be explained by reaching their maximal brain activity. Recruitment of additional resources associated with maintenance of performance are characteristics of compensatory process described in the context of successful aging. Our data might thus suggest that habitual nappers compensate at the functional level, until maximal WM capacity is reached and/or supplemental recruitment is no more possible, thereby resulting in performance decline (Cabeza & Dennis, 2012).

However, the analysis assessing the association between performance and BOLD signal does not indicate that the contralateral activation observed in regular nappers is linked to WM performance. Besides functional compensation, hemispheric asymmetry reduction in older adults has been assimilated to brain “dedifferentiation” (Knights et al., 2021; Morcom & Henson, 2018). This process refers to a reduced distinctiveness of neural responses, leading to less specific brain activation patterns. Single neuron-recordings in animals (Ding et al., 2017; Hua et al., 2006; Schmolesky et al., 2000) provide strong evidence for an age-dependent reduction in the neural selectivity, also defined as smaller differences between activity for the specific and non-specific stimuli of a brain region (Koen & Rugg, 2019). Notably, the nature of the task, its behavioural responses, as well as the BOLD signal dynamics in task-related brain regions should be considered to determine if hemispheric asymmetry reduction reflects compensation, dedifferentiation, or both. The absence of a significant association between performance and contralateral recruitment may suggest that hemispheric

asymmetry reduction observed in the context of napping habits is not necessarily related to functional compensation. Nonetheless, an association between WM performance and higher BOLD signal at the highest WM load in the ipsilateral hemisphere might indicate functional compensation in non-nappers. Our study was not designed to differentiate between both processes, but compensation and dedifferentiation are not incompatible, and have been suggested to act simultaneously in a study investigating age-related changes in performance during a Sternberg paradigm (Carp et al., 2010). Actually, functional compensation is a process to counteract adverse effects of brain alterations, such as dedifferentiation.

The arousal-promoting thalamus is implicated in the maintenance of stable wake states and plays a key role in mediating the interaction between attention and arousal in humans (Portas, 1998, Sturm, 1999). Increased thalamic activity has also been observed with increasing cognitive demands (Schiff, 2008) and the thalamus is increasingly recognized as a significant contributor to cognitive decline and the development of dementia (Biesbroek et al., 2024), highlighting its crucial role cognitive processes. Besides, thalamic activity has been consistently shown to increase under conditions of sleep deprivation and circadian misalignment (Ma, 2015, Muto et al. 2016). Within this context, Maire et al. (2015) observed for example that individuals more vulnerable to sleep deprivation need to recruit more the thalamus across the duration of the task, compared to behaviorally more resilient individuals (who exhibit less attentional lapses, reduced task disengagement). Here, we did not proceed to such a sleep manipulation, but observed that habitual nappers, characterized by more daytime rest bouts and increased overall sleepiness during daytime, also showed enhanced thalamic recruitment during task engagement. These results potentially point towards an increased wake state instability. In this respect, napping, as an intrusion of sleep into the active wake period, might be used as a strategy to counteract the inability of older adults to maintain wake states over extended periods of time (Carskadon et al., 1982). Additionally, the rising frequency and duration of napping in older adults may be partially attributed to altered circadian sleep regulation, as our

recent findings reveal associations between napping habits and these disruptions. Habitual nappers also exhibited altered modulation in sleepiness and vigilance at specific circadian phases (Deantoni et al., 2024). Considering the thalamus' role in regulating sleep-wake cycles, these circadian disruptions may impair thalamic activity, leading to sleep pattern alterations and potentially affecting cognitive performance. Whether these changes are specifically driven by circadian sleep and/or wake-promoting mechanisms remains to be assessed.

This is to the best of our knowledge the first study to explore the impact of habitual napping on the functional brain responses underlying a WM challenge. Our data indicate hemispheric asymmetry reduction in habitual nappers, compared to non-nappers, that may be underlined by processes of dedifferentiation and functional compensation, depending on behavioral performance. Notably, age-related structural brain changes are now considered in conceptual models of cognitive aging (D. C. Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014), positing that compensatory neural activation is an adaptive mechanism in response to decline, both in brain function and structure. Future studies should investigate the potential consequences of napping habits on brain structure and assess whether brain activity differences could also be underpinned by structural brain modifications, particularly in relation to cortical gyrification. Considering the association between circadian sleep regulation and cortical gyrification, as suggested by previous findings linking distinctive REM sleep allocation to regional brain structure changes in aging (Deantoni et al., 2024), it would be valuable to explore how these modifications may contribute to brain maintenance concepts derived from structural MRI (Cabeza et al., 2018; Stern et al., 2020). Dedifferentiation and functional compensation are dynamic and modifiable by lifestyle factors, suggesting that acting on protective factors, such as a good sleep hygiene, could enhance these mechanisms and thus improve cognitive performance. Our study thereby supports the need of longitudinal designs on napping habits during aging and to determine whether the restoration of a consolidated 24-h rest-activity

pattern could lead to cognitive improvement and the generalization to a less selective and more representative sample of the general population.

4. Methods

This cross-sectional study consisted of three phases: (1) a telephone interview and screening visit, (2) a pre-laboratory field actimetry and sleep diary study, and (3) a cognitive assessment followed by a functional MRI scanning during a WM task, collectively scheduled to the afternoon hours. Further details of the study procedure can be found in Reyt et al. (2022) and Deantoni, et al. (2024).

4.1. Participants

Recruitment aimed at covering a wide range of socio-economic classes and was performed via advertisement in newspapers, radio and university and by taking advantage of already existing GDPR-compliant databases at the research unit. All contacted volunteers were retired and lived independently at home. Seven hundred and seventy-three individuals aged ≥ 60 were initially contacted. Out of the sample, 166 passed the screening visit. None of the participants indicated moderate or severe depression (Beck Depression Inventory [BDI-II] < 19 , Beck et al., 1961) or severe anxiety (Beck Anxiety Inventory [BAI] < 30 , (Beck et al., 1988). Clinical symptoms of cognitive impairment were assessed by the Mini Mental State Examination [MMSE score > 26], Folstein et al., 1975) and the Mattis Dementia Rating scale [score > 130], Mattis, 1976). Screening for major sleep disorders was performed during a night of polysomnography and 72 participants were excluded (apnea/hypopnea index and period limb movement index $> 15/h$) (for the final sample of 94 participants: mean apnea/hypopnea index: 5.48 ± 4.63 , mean Periodic Limb Movement index: 3.07 ± 5.51). Other exclusion criteria included Body Mass Index (≤ 18 and ≥ 30 kg/m²), participants reporting a history of diagnosed psychiatric conditions or severe brain trauma, chronic medication affecting the central nervous system, diabetes, smoking, caffeine (> 4 cups/day),

excessive alcohol (> 14 units/week) or other drug consumption, and travelling more than one time zone in the 3 months prior to the study begin. Participants with stable treatment (> 6 months) for hypertension and/or hypothyroidism were included in the study.

For this cross-sectional assessment, a group of 30 nappers and 30 non-nappers were selected out of the sample and matched at the group level with respect to age, gender, educational level and season of assessment. Demographic characteristics of the two groups are summarized Table 1. Participants reported their napping habits through a questionnaire. Daytime rest duration and frequency were retrospectively assessed through actimetry recordings in both groups (see also below). Habitual nappers were defined as individuals who napped at least three times per week for a minimum of 45 minutes, consistently for at least one year. The non-napping group included individuals who reported either not napping, napping only occasionally, or taking naps lasting for a maximum of 10 minutes.

The study was approved by the local Ethics Committee of the University Hospital and of the Faculty of Psychology, Speech Therapy and Educational Sciences at the University of Liège (Belgium) and performed in accordance with the Declaration of Helsinki. Participants gave written informed consent and received a financial compensation.

4.2. Actigraphy: daytime rest characteristics

As described in Reyt et al. (2022), daytime rest habits were assessed over a period of at least 8 days (13.60 ± 1.90 days, range 8-15) during which participants wore an actigraphic device (Motionwatch 8, CamNtech, UK) at the non-dominant wrist and completed a sleep diary. In this latter, participants were asked to report actigraph removal periods, which were visually identified and excluded from the analysis. Motor activity was aggregated into 30-sec activity counts and the Munich Actimetry Sleep Detection Algorithm (MASDA) (Roenneberg et al., 2015) was used to detect consolidated daytime rest periods. The performance of this algorithm against visual scoring was previously reported (Reyt et al., 2022). Actigraphy data were

processed using the open-source software pyActigraphy (v1.0) (Hammad et al., 2021).

Daytime rest periods were identified during the biological day (see Reyt et al. (2022)) and their duration ranged from 15 minutes to 4 hours. Based on detected daytime rest periods, frequency was calculated as the mean number of these periods per day and duration defined as the overall mean duration.

4.3. Questionnaires

Questionnaires were administered at study entrance and included the Pittsburgh Sleep Quality Index (PSQI, Buysse et al., 1989), the Epworth Sleepiness Scale (ESS, Johns, 1991), the Morningness-Eveningness Questionnaire (MEQ, (Horne & Östberg, 1976), the Beck Depression Inventory (BDI-II, (Beck et al., 1961) and the Beck Anxiety Inventory (BAI, Beck et al., 1988).

4.4. Cognitive assessment

Before the fMRI scan, participants completed a cognitive assessment including the Mini-Mental State Examination (Folstein et al, 1975), the Mattis Dementia Rating scale (Mattis, 1976), as well as the Pre-clinical Alzheimer's Disease Composite Score (PACC, Papp et al., 2017).

4.5. Working memory paradigm

Data were usually acquired during the afternoon (between 13:30 and 16:00) to avoid confounding effects of time of day on cognitive performance and its underlying cerebral correlates. Participants completed a Sternberg task including six memory set sizes (MSS) varying from 2 to 7 during a functional MRI acquisition session (see below). Stimuli were consonants (except letters P, W, X and Z due to their high distinctiveness). Letters were presented at the screen's centre, in "Arial" font and a 120-pixel font size. Uppercase letters were displayed for encoding and lowercase letters were used for probes. During encoding, a set of 2 to 7 white letters were simultaneously displayed on a black screen (Figure 1). Each trial started by

the presentation of a memory set during 3 sec, followed by a 1 sec maintenance interval (red fixation cross). At retrieval, the probe letter was presented during 0.8 sec, followed by a white fixation cross during 1.2 sec. During the retrieval period (2 sec), participants had to indicate as quickly and accurately as possible, using one of the two response keys, whether the probe was part of the memory set or not. Each block was composed of 4 trials of the same MSS and participants completed 48 blocks (8 blocks by 6 MSS). A grey fixation cross was displayed during 15 sec between each block. The order of block presentation was pseudo-randomized to avoid presentation of consecutive blocks of the same MSS. For each MSS, the probe was part of the memory set on half of the trials.

Before being installed in the MRI scanner, participants underwent a training session, composed of 10 trials using the 6 MSS. The training was performed as many times as necessary to ensure that participants understood the task and reached at least 70% accuracy. Five trials were also performed just after participants' installation in the MRI scanner to verify response keys functionality.

The Sternberg task was presented using Psychophysics Toolbox Version 3.0.15 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) running on Matlab R2017a (The MathWorks, Inc., Natick, MA).

4.6. Behavioural data analysis

Generalised linear mixed models (GLMM) were conducted to assess the effect of group (habitual nappers vs non-nappers, reference = non-nappers), memory load (2-7 letters) as well as their interaction on WM accuracy (d' ; (Stanislaw & Todorov, 1999) and reaction times, separately. Group and memory load were defined as categorical fixed effects and subjects as random effect. Performance at each MSS was compared to the mean performance of all previous MSS (Helmert coding). Non-nappers were defined as the reference group for the treatment contrast. In order to determine whether demographical variables, such as age, gender and educational level, should be considered as covariates in GLMM, we compared models with and without these variables. The comparison was performed in R

version 3.6.3 (R Core Team, 2020), requiring the package AICcmodavg (Mazerolle, 2020). The model with the lower Akaike criterion was selected. After model comparisons, age, sex and education had to be included as covariates for WM performance, but not for reaction times. Daytime sleepiness and BMI were also included as covariates since group significantly differ on these variables. Significance was based on a $p\text{-value} < 0.05$. Statistical data analyses for performance measures were conducted on R version 3.6.3 (R Core Team, 2020), using packages stats (R Core Team, 2020), tidyr (Wickham et al., 2019), lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017) and Rmisc (<https://www.rdocumentation.org/packages/Rmisc/versions/1.5.1>).

4.7. Functional magnetic resonance imaging protocol

Functional MRI time series were acquired on a whole-body 3T scanner (Magnetom Prisma, Siemens Medical Solutions, Erlangen, Germany) operated with a 64-channel receiver head coil. Multislice T2*-weighted functional images were acquired with the multi-band gradient-echo echo-planar imaging sequence (CMRR, University of Minnesota) using axial slice orientation and covering the whole brain (36 slices, multiband factor = 2, FoV = $216 \times 216 \text{ mm}^2$, voxel size $3 \times 3 \times 3 \text{ mm}^3$, 25% inter-slice gap, matrix size $72 \times 72 \times 36$, TR = 1170 ms, TE = 30 ms, FA = 90°). The four initial volumes were discarded to avoid T1 saturation effects. During fMRI acquisition, cardiac pulse and respiration were recorded with a pulse oximeter and respiration belt. A gradient-recalled sequence was applied to acquire two complex images with different echo times (TE = 10.00 and 12.46 ms respectively) and generate field maps for distortion correction of the echo-planar images (EPI) (TR = 761 ms, FoV = $192 \times 192 \text{ mm}^2$, 64×64 matrix, 48 transverse slices (3 mm thickness, 50% inter-slice gap), flip angle = 90° , bandwidth = 260 Hz/pixel). For anatomical reference, a high-resolution T1-weighted image was acquired for each subject (T1-weighted 3D magnetization-prepared rapid gradient echo (MPRAGE) sequence, TR = 1900 ms, TE = 2.19 ms, inversion time (TI) = 900 ms, FoV = $256 \times 240 \text{ mm}^2$, matrix

size = 256x240x224, voxel size = 1x1x1 mm³, acceleration factor in phase-encoding direction R=2).

4.8. fMRI data: pre-processing and analysis

Image processing and analysis were performed using the SPM12 software (Centre for Human Neuroimaging, www.fil.ion.ucl.ac.uk/spm) running on Matlab R2017a. EPI time series were reoriented into the MNI space using the SPM template, then corrected for motion and distortion using the “Realign and Unwarp” module (Andersson et al., 2001) together with the FieldMap toolbox (Hutton et al., 2002). A mean realigned functional image was then produced by averaging all the realigned and unwarped functional scans. The structural T1 image was segmented into grey and white matter, using the unified segmentation approach (Ashburner & Friston, 2005) as implemented in SPM12, and then coregistered to the mean functional image. Finally, the warped functional images were spatially smoothed with an isotropic Gaussian kernel of 8 mm of full-width at half maximum (FWHM). Artifact reduction software (ART; http://www.nitrc.org/projects/artifact_detect) was used to account for motion artifact and outliers in the global mean signal intensity.

Based on (Hutton et al., 2011), an in-house developed Matlab toolbox was used to extract 14 physiological regressors, obtained from a physiological noise model constructed to account for signal variability related to cardiac and respiratory phase and changes. Basis sets of sine and cosine Fourier series components extending to the 5th harmonic for the cardiac phase and 3rd harmonic for the respiratory phase were used to model the physiological fluctuations.

For each subject, changes in BOLD responses were estimated using a general linear model in which the blocks for each MSS were modelled using boxcar functions and convolved with the canonical hemodynamic response function. Motion and physiological regressors were added in the model and considered as covariates of no interest. Correct, incorrect and no responses were separately modelled in the design matrix for each MSS and the analysis was performed only on correct

responses. The design matrix also included a parametric modulator to consider reaction time. A cutoff period of 250s was used for the high-pass filter to remove low-frequency drifts from the time series, while preserving signal of interest. Due to the rapidly sampled fMRI series, the “FAST” model implemented in SPM was used to estimate serial autocorrelations (Corbin et al., 2018).

4.9. ROI analysis

ROIs extraction was performed using the MATLAB based toolbox BRANT (BRAInNetome Toolkit) (K. Xu et al., 2018). We defined 3 main ROIs: (1) the dorsolateral prefrontal cortex and more particularly BA 9/46, the main region of interest (Altamura et al., 2007; Cappell et al., 2010; Haque et al., 2021; Höller-Wallscheid et al., 2017; Reuter-Lorenz et al., 2001); (2) a more extended WM network considering regions that have been implicated in age-related compensatory processes during the Sternberg task (Cappell et al., 2010; Schneider-Garces et al., 2010), including regions from the frontal lobe (BA 6, BA 9, BA 12/47, BA 44, BA 45, BA 46, BA 24, BA 32), the medial temporal lobe (the hippocampus and the parahippocampal gyrus), the parietal lobe (BA 5, BA 7, BA 39, BA 40) and the occipital lobe; (3) the thalamus; as we supposed that napping habits affect vigilance state and associated arousal regulation (Deantoni et al., 2024). As compensation models suggest a bilateral recruitment in both hemispheres, we distinguished left and right hemispheres in each ROI. The WM network was first divided into regions (frontal, parietal, temporal, occipital) and we then extracted individual parameter estimates of BOLD signal by memory load (2-7 letters), by ROI (DLPFC, frontal, parietal, temporal and occipital regions of the WM network and thalamus) and by hemisphere. On the whole sample, global maximum coordinates of each hemisphere by ROI were extracted by computing F-tests ($p_{FWE-corr} < 0.05$) after application of an inclusive grey-matter mask derived from tissue probability maps (probability of voxel belonging to grey matter above 0.20) and by using the small volume correction to determine the ROI. These coordinates were then used at the individual level to determine a sphere of 30 mm in which the global

maximum location was determined for each participant. From the individual's global maximum location, a new sphere of 8 mm was created to extract the BOLD signal of significantly activated voxels ($p < 0.001$) by MSS. Generalised linear mixed models were conducted first to assess the effect of group (habitual nappers or non-nappers), memory load (2-7 letters), hemisphere (left or right), as well as their interactions on the extracted BOLD signal in the task-related brain region (DLPFC). The same model was computed on thalamic BOLD signal. To assess region-specificity of BOLD signal, a separate GLMM further included the factor region (frontal, parietal, temporal and occipital) and their interactions. Group, memory load, hemisphere and regions were defined as categorical fixed effects and subjects as random effects. Brain activity at each MSS was compared to the mean activity of all previous MSS (Helmert coding). Treatment contrasts were computed with non-nappers, left hemisphere and frontal lobe as references. As for behavioural data, model comparisons were performed and Akaike criterion determined that age, sex and education had not to be included as covariates. Daytime sleepiness and BMI were included as covariates as group significantly differed in these variables. Statistics were performed using R (version 3.6.3) (R Core Team, 2020).

In the context of functional compensation, hemispheric asymmetry reduction should be associated with performance maintenance (Cabeza, 2002; Reuter-Lorenz & Cappell, 2008). Generalised linear mixed models were thus conducted to assess whether task performance (d' or reaction time) was predicted by WM load (2-7 letters), group (habitual nappers vs non-nappers), BOLD signal as well as their interactions. Separate models were computed for the left and right hemisphere. Group and memory load were defined as categorical fixed effects and subjects as random effects. Performance at each MSS was compared to the mean performance of all previous MSS (Helmert coding). Treatment contrast was computed with non-nappers as reference. Daytime sleepiness and BMI were added as covariates. Model comparisons were also performed and according to Akaike criterion, models assessing accuracy also include age, gender and educational level.

Tables & Figures

	Habitual Nappers	Non-Nappers	Statistics
Demographical variables			
N (f, m)	30 (21, 9)	30 (18, 12)	p = 0.42
Age (y)	69.2 ± 5.25	69.37 ± 5.89	p = 0.86
Education level (y)	14.60 ± 2.91	14.13 ± 3.58	p = 0.49
BMI (kg/m ²)	25.84 ± 2.83	24.41 ± 2.50	p = 0.04
Ethnic status, <i>Caucasian</i> n(%)	30 (100%)	30 (100%)	/
Self-reported napping habits			
Frequency			
<i>Never</i>	0	14	p< 0.001
<i>Less than once a week</i>	1	9	
<i>1-2 times per week</i>	4	2	
<i>3-4 times per week</i>	11	0	
<i>4-5 times per week</i>	5	3	
<i>5-6 times per week</i>	4	1	
<i>Once a day</i>	5	1	
Duration			
<i>0 min</i>	0	14	p< 0.001
<i>1-10 min</i>	0	4	
<i>10-30 min</i>	5	5	
<i>30-60 min</i>	22	6	
<i>1-2 h</i>	2	1	
<i>More than 2 hours</i>	1	0	
Reason			
<i>Appetitive</i>	9	2	p = 0.12
<i>Restorative</i>	20	9	
<i>Others</i>	2	4	
Daytime rest characteristics			
Frequency	0.73 ± 0.32	0.26 ± 0.21	p< 0.001
Duration (min)	49.95 ± 14.22	32.87 ± 21.79	p< 0.001
Questionnaire-derived scores			
ESS score (0 – 24)	9.07 ± 3.18	6.50 ± 3.42	p< 0.01
KSS score (1 – 9)	3.3 ± 2.03	2.48 ± 1.08	p = 0.24
PSQI score (0 – 21)	5.03 ± 2.66	4.93 ± 2.91	p = 0.74
MEQ score (16 – 86)	63.17 ± 8.44	63.13 ± 7.40	p = 0.81
BDI score (0 – 63)	3.93 ± 3.03	3.2 ± 3.19	p = 0.29
BAI score (0 – 63)	3.23 ± 3.72	2.77 ± 3.52	p = 0.51
MMSE (0 – 30)	29.60 ± 0.62	29.52 ± 0.69	p = 0.67

Table 1. Demographical, self-reported napping habits, actigraphy-derived and questionnaire data by group (mean ± standard deviation). Note: f = female; m = male; y = years; BMI = Body Mass Index; ESS = Epworth Sleepiness Scale (Johns, 1991); KSS = Karolinska Sleepiness Scale (Akerstedt & Gillberg, 1990); PSQI = Pittsburgh Sleep Quality Index (Buysse et al., 1989); MEQ = Morningness-Eveningness Questionnaire (Horne and Östberg, 1976); BDI = Beck Depression Inventory (Beck et al., 1961); BAI = Beck Anxiety Inventory (Beck et al., 1988); MMSE = Mini-Mental State Examination (Folstein et al., 1975).

Memory Set Size (MSS)	Accuracy	Reaction times	DLPFC	Extended WM related brain regions	Thalamus
MSS 3	t= 0.36 p= 0.72	t= 3.95 p< 0.001	t= -0.12 p= 0.90	t= 0.72 p= 0.47	t= 0.07 p= 0.95
MSS 4	t= -1.07 p= 0.29	T= 5.50 p< 0.001	t= 1.99 p= 0.05	t= 2.15 p= 0.03	t= 1.76 p= 0.08
MSS 5	t= -2.93 p<0. 01	t= 6.67 p< 0.001	t= 2.39 p= 0.02	t= 3.62 p< 0.001	t= 2.97 p< 0.01
MSS 6	t= -2.65 p< 0.01	t= 8.97 p< 0.001	t= 4.00 p< 0.001	t= 4.40 p< 0.001	t= 3.53 p< 0.001
MSS 7	t= -7.13 p< 0.001	t= 9.78 p< 0.001	t= 4.54 p< 0.001	t= 3.86 p< 0.001	t= 4.12 p< 0.001

Table 2. Effect of working memory load during the Sternberg task on accuracy, reaction times and BOLD signal in the three regions of interest (Helmert coding). Note: WM = working memory

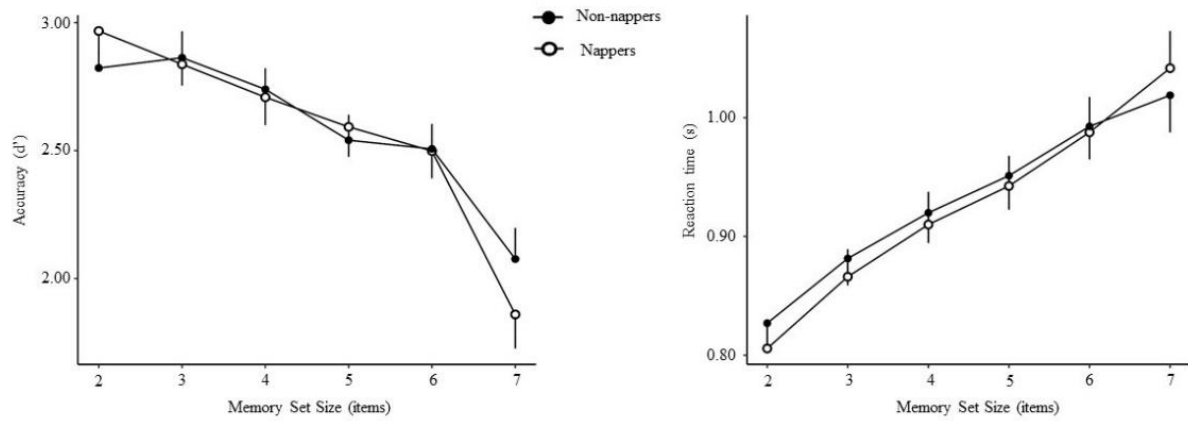


Figure 2. Mean accuracy (d' measure, on the left) and median reaction times (on the right) across memory set sizes for non-nappers (black circles) and habitual nappers (white circles) (mean $\pm$ SEM).

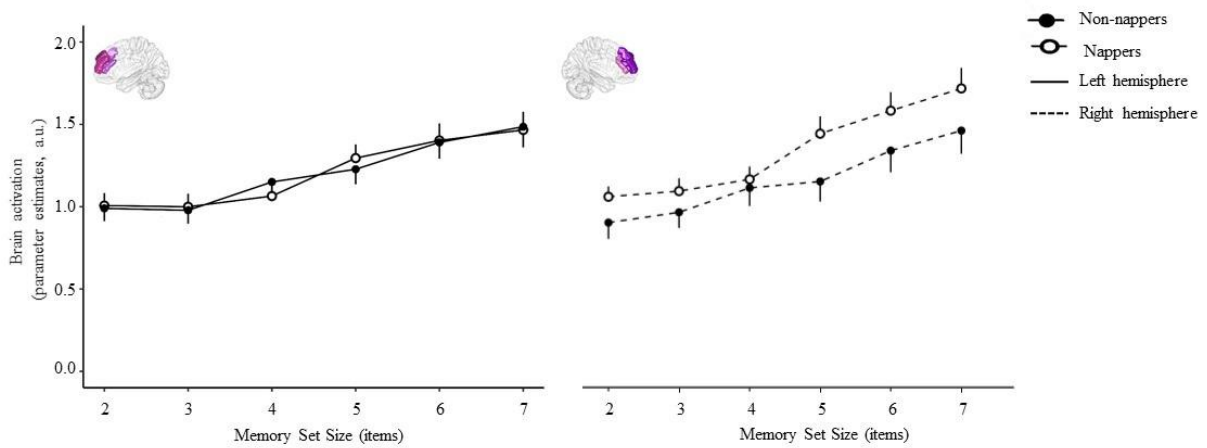
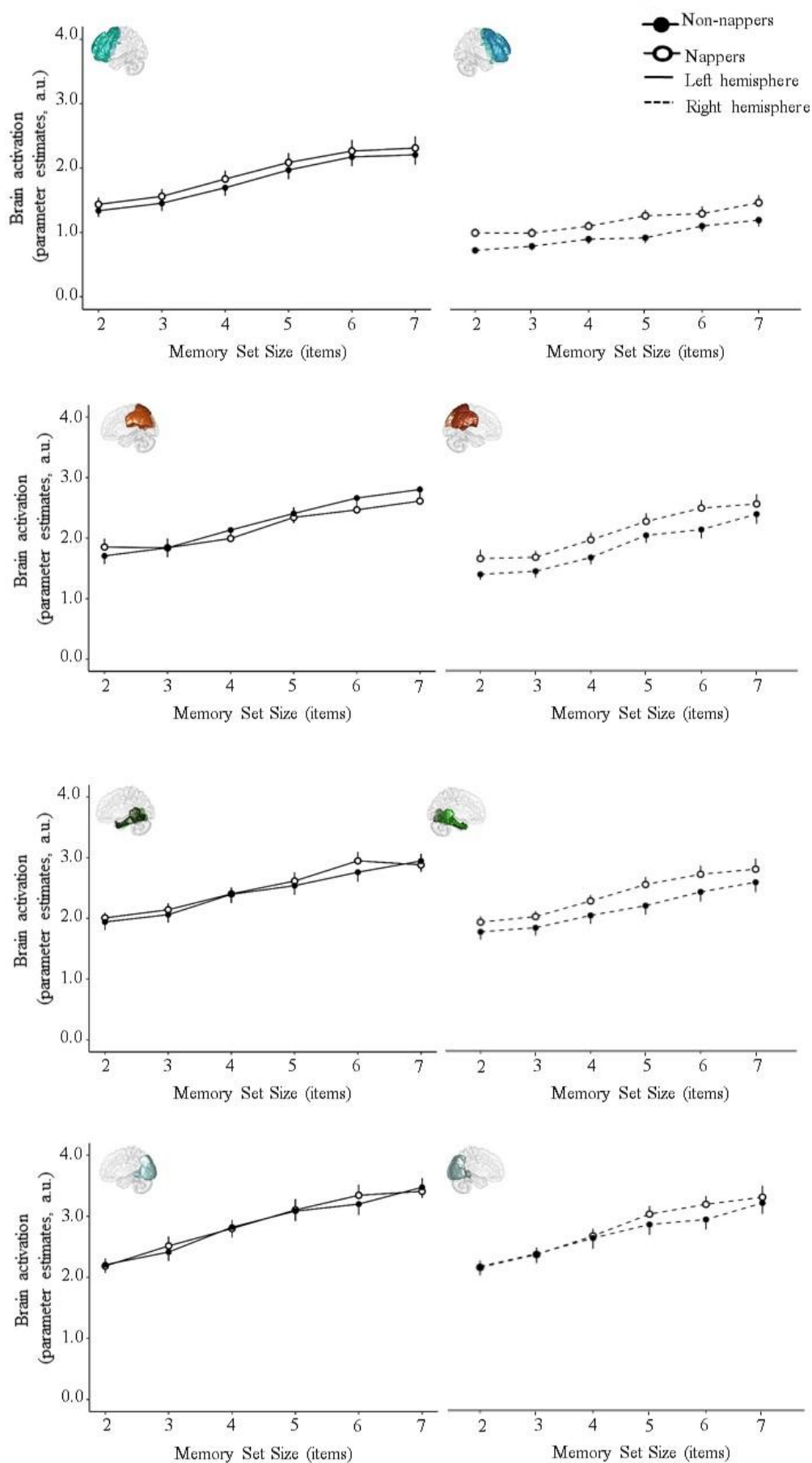


Figure 3. Mean BOLD signal across memory set sizes for the left dorsolateral prefrontal cortex (DLPFC) (on the left) and right DLPFC (on the right, dotted lines) for non-nappers (black circles) and habitual nappers (white circles) (mean $\pm$ SEM).

Figure 4. Mean BOLD signal across memory set sizes for the frontal, parietal, temporal and occipital regions for non-nappers (black circles) and habitual nappers (white circles) (mean $\pm$ SEM). Continuous lines correspond to left hemisphere and dotted lines represent the right hemisphere.



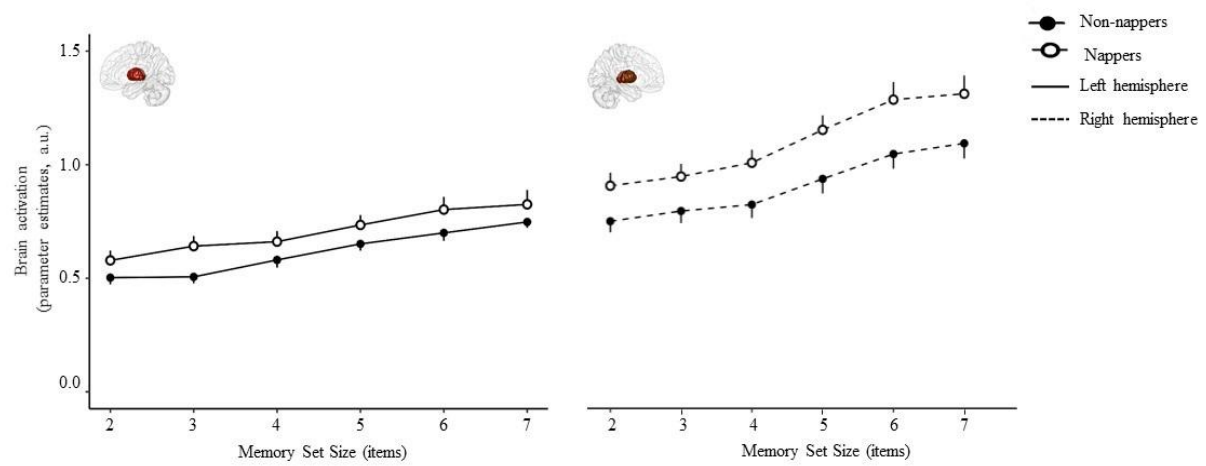


Figure 5. Mean BOLD signal across memory set sizes for the left thalamus (on the left) and right thalamus (on the right, dotted lines) for non-nappers (black circles) and habitual nappers (white circles) (mean $\pm$ SEM).

Appendix 3 : Preliminary results

		Estimate (β)	t value	p-value
Free recall	Group	<i>Nap-control</i>	-0.040	0.978
		<i>Nap-intervention</i>	1.962	0.173
	Time	<i>T1</i>	0.704	0.373
		<i>T2</i>	2.407	0.002
	Group * Time	<i>Nap-control * T1</i>	-2.082	0.050
		<i>Nap-control * T2</i>	-1.511	0.170
		<i>Nap-intervention * T1</i>	0.761	0.492
		<i>Nap-intervention * T2</i>	0.521	0.637
Cued recall	Group	<i>Nap-control</i>	-0.206	0.865
		<i>Nap-intervention</i>	-1.346	0.257
	Time	<i>T1</i>	-1.185	0.121
		<i>T2</i>	-2.482	0.001
	Group * Time	<i>Nap-control * T1</i>	2.151	0.043
		<i>Nap-control * T2</i>	1.861	0.080
		<i>Nap-intervention * T1</i>	-0.351	0.743
		<i>Nap-intervention * T2</i>	-0.376	0.725

Table A1. Statistical results (parameter estimate [β], t-value and p-value) of the free- and cued-recall of the FCRST, from a linear mixed model with Group (3-level factor: non-nap, nap-control, nap-intervention) and Time (3-level factor: T0, T1, T2) as categorical fixed factors. Non-nap and T0 were used as reference, and a random intercept by subject was applied. Separate models were used for free- and cued-recall.

		Estimate (β)	t value	p-value
Time		-0.236	-1.052	0.293
Session	Session 1	-2.196	-4.249	< 0.001
	Session 2	-5.349	-4.273	< 0.001
	Session 3	-5.278	-4.809	< 0.001
	Session 4	-3.245	-4.774	0.002
	Session 5	13.791	4.817	< 0.001
	Session 7	1.548	1.056	0.317
	Session 8	-4.396	-7.842	< 0.001
	Session 9	-4.894	-6.036	< 0.001
	Session 10	-3.655	-4.525	< 0.001
	Session 11	4.561	4.724	< 0.001
Time * Session	T1 * Session 1	1.523	2.638	0.008
	T1 * Session 2	0.386	0.880	0.379
	T1 * Session 3	0.345	0.782	0.435
	T1 * Session 4	0.054	0.111	0.912
	T1 * Session 5	-0.667	-1.218	0.224
	T1 * Session 7	0.718	1.330	0.184
	T1 * Session 8	1.067	2.345	0.020
	T1 * Session 9	0.304	0.698	0.486
	T1 * Session 10	0.3029	0.065	0.949
	T1 * Session 11	-2.459	-3.059	0.002

Table A2. Statistical results (parameter estimate [β], t-value and p-value) of the salivary melatonin concentration (pg/ml), from a generalised linear mixed model (GLMM) with Time (2-level factor: T0 vs. T1) and Session (10-level factor) as categorical fixed factors. T0 and Session 6 (mid-night, around 04:00) were used as references.

		Estimate (β)	t value	p-value
Time		0.222	0.376	0.707
Session	Session 1	-0.193	-0.196	0.845
	Session 2	-1.032	-1.074	0.286
	Session 3	-4.337	-5.057	< 0.001
	Session 4	-2.745	-2.993	0.003
	Session 5	9.647	6.736	< 0.001
	Session 7	-0.287	-0.296	0.768
	Session 8	-1.722	-1.840	0.070
	Session 9	-1.334	-1.095	0.278
	Session 10	-2.447	-2.430	0.017
Time * Session	T1 * Session 1	-0.579	-0.421	0.674
	T1 * Session 2	0.256	0.167	0.867
	T1 * Session 3	1.169	0.771	0.441
	T1 * Session 4	-1.437	-0.913	0.362
	T1 * Session 5	-2.329	-1.114	0.266
	T1 * Session 7	3.5322	2.203	0.028
	T1 * Session 8	-2.514	-1.347	0.179
	T1 * Session 9	1.676	0.977	0.329
	T1 * Session 10	0.189	0.112	0.911

Table A3. Statistical results (parameter estimate [β], t-value and p-value) of proportion of REM sleep over total sleep time (%), from a generalised linear mixed model (GLMM) with Time (2-level factor: T0 vs. T1) and Session (10-level factor) as categorical fixed factors. T0 and Session 6 (mid-night, around 04:00) were used as references.

		Estimate (β)	t value	p-value
Time		1.959	1.542	0.124
Session	<i>Session 1</i>	-0.188	-0.086	0.931
	<i>Session 2</i>	-3.886	-1.611	0.111
	<i>Session 3</i>	-9.895	-3.589	0.001
	<i>Session 4</i>	-8.107	-3.293	0.002
	<i>Session 5</i>	19.661	9.890	< 0.001
	<i>Session 7</i>	7.719	3.415	< 0.001
	<i>Session 8</i>	1.991	0.811	0.420
	<i>Session 9</i>	-10.221	-3.721	< 0.001
	<i>Session 10</i>	-7.726	-2.519	0.014
Time * Session	<i>T1 * Session 1</i>	1.959	0.574	0.567
	<i>T1 * Session 2</i>	2.742	0.772	0.440
	<i>T1 * Session 3</i>	-1.359	-0.368	0.713
	<i>T1 * Session 4</i>	1.658	0.459	0.647
	<i>T1 * Session 5</i>	-1.081	-0.330	0.742
	<i>T1 * Session 7</i>	-3.576	-1.047	0.296
	<i>T1 * Session 8</i>	-5.286	-1.467	0.143
	<i>T1 * Session 9</i>	3.984	1.105	0.269
	<i>T1 * Session 10</i>	-3.202	-0.811	0.418

Table A4. Statistical results (parameter estimate [β], t-value and p-value) of sleep efficiency (total sleep time over total nap opportunity duration, %), from a generalised linear mixed model (GLMM) with Time (2-level factor: T0 vs. T1) and Session (10-level factor) as categorical fixed factors. T0 and Session 6 (mid-night, around 04:00) were used as references.

		Estimate (β)	t value	p-value
Time		-0.157	-8.833	$p < 0.001$
Session	<i>Session 2</i>	-0.044	-0.582	0.563
	<i>Session 3</i>	-0.249	-3.361	0.001
	<i>Session 4</i>	0.126	1.662	0.103
	<i>Session 5</i>	0.490	7.855	< 0.001
	<i>Session 7</i>	-0.059	-0.762	0.450
	<i>Session 8</i>	-0.428	-5.901	< 0.001
	<i>Session 9</i>	-0.445	-6.430	< 0.001
	<i>Session 10</i>	-0.279	-3.615	< 0.001
	<i>Session 11</i>	0.356	3.508	< 0.001
Time * Session	<i>T1 * Session 2</i>	-0.078	-1.589	0.112
	<i>T1 * Session 3</i>	0.018	0.379	0.705
	<i>T1 * Session 4</i>	-0.236	-4.848	< 0.001
	<i>T1 * Session 5</i>	-0.082	-1.715	0.086
	<i>T1 * Session 7</i>	0.363	7.509	< 0.001
	<i>T1 * Session 8</i>	0.205	4.218	< 0.001
	<i>T1 * Session 9</i>	-0.005	-0.103	0.918
	<i>T1 * Session 10</i>	-0.064	-1.338	0.181
	<i>T1 * Session 11</i>	-0.047	-0.613	0.540

Table A5. Statistical results (parameter estimate [β], t-value and p-value) of DPG, from a generalised linear mixed model (GLMM) with Time (2-level factor: T0 vs. T1) and Session (10-level factor) as categorical fixed factors. T0 and Session 6 (mid-night, around 04:00) were used as references. The first 130-minute session was removed from the analysis and graph to account for the potential carry-over effects of both cumulative sleep debt as well as night-time sleep (i.e. sleep inertia) on skin temperature. Every first 30 minutes of each wake episode was also discarded for nap-induced potential sleep inertia effects on skin temperature.

		Estimate (β)	t value	p-value
Time		-0.301	0.985	< 0.001
Harmonic	<i>Sin (24h)</i>	-0.339	-15.494	< 0.001
	<i>Cos (24h)</i>	0.104	4.649	< 0.001
	<i>Sin (12h)</i>	-0.063	-2.903	0.004
	<i>Cos (12h)</i>	-0.041	-1.776	0.075
Time * Harmonic	<i>T1 * Sin(24h)</i>	0.084	2.713	0.007
	<i>T1 * Cos(24h)</i>	0.151	4.745	< 0.001
	<i>T1 * Sin(12h)</i>	0.026	0.854	0.393
	<i>T1 * Cos(12h)</i>	0.034	1.030	0.303
Phase (° angle)	<i>T0</i>	- 72.9		
	<i>T1</i>	- 45.1		
Amplitude (°C)	<i>T0</i>	0.980		
	<i>T1</i>	0.698		

Table A6. Statistical results (parameter estimate [β], t-value and p-value) from harmonic regressions used to compare phase and amplitude of the 24-hour and 12-hour DPG modulation by Time. From the model parameter estimates, phase and amplitude were computed for each time.

		Estimate (β)	t value	p-value	
Distal skin temperature	Time	0.135	5.982	< 0.001	
	Session	Session 2	0.046	1.464	0.143
		Session 3	-0.103	-3.321	< 0.001
		Session 4	0.179	5.784	< 0.001
		Session 5	0.430	13.846	< 0.001
		Session 7	-0.162	-5.250	< 0.001
		Session 8	-0.626	-21.357	< 0.001
		Session 9	-0.486	-15.570	< 0.001
		Session 10	-0.212	-6.867	< 0.001
		Session 11	0.568	11.734	< 0.001
	Time * Session	T1 * Session 2	-0.131	-2.082	0.037
		T1 * Session 3	-0.046	-0.737	0.461
		T1 * Session 4	-0.254	-4.078	< 0.001
		T1 * Session 5	-0.179	-2.873	0.004
		T1 * Session 7	0.218	3.479	< 0.001
		T1 * Session 8	0.328	5.316	< 0.001
		T1 * Session 9	0.154	2.466	0.014
		T1 * Session 10	0.001	0.002	0.999
		T1 * Session 11	0.021	0.200	0.842
Proximal skin temperature	Time	0.050	2.224	0.026	
	Session	Session 2	0.107	3.451	< 0.001
		Session 3	0.155	5.046	< 0.001
		Session 4	0.056	1.847	0.064
		Session 5	-0.060	-1.953	0.051
		Session 7	-0.084	-2.767	0.006
		Session 8	-0.166	-5.728	< 0.001
		Session 9	-0.085	-2.757	0.006
		Session 10	0.081	2.645	0.008
		Session 11	0.152	3.190	0.001
	Time * Session	T1 * Session 2	-0.097	-1.558	0.119
		T1 * Session 3	-0.141	-2.286	0.022
		T1 * Session 4	-0.017	-0.276	0.783
		T1 * Session 5	-0.002	-0.025	0.980
		T1 * Session 7	-0.137	-2.211	0.027
		T1 * Session 8	0.097	1.585	0.113
		T1 * Session 9	0.037	0.593	0.553
		T1 * Session 10	0.020	0.331	0.741
		T1 * Session 11	0.216	2.139	0.032

Table A7. Statistical results (parameter estimate [β], t-value and p-value) of distal (up) and proximal skin temperature (bottom), from a generalised linear mixed model (GLMM) with Time (2-level factor: T0 vs. T1) and Session (10-level factor) as categorical fixed factors. T0 and Session 6 (mid-night, around 04:00) were used as references. The first 130-minute session was removed from the analysis and graph to account for the potential carry-over effects of both cumulative sleep debt as well as night-time sleep (i.e. sleep inertia) on skin temperature. Every first 30 minutes of each wake episode was also discarded for nap-induced potential sleep inertia effects on skin temperature.

Appendix 4 : LiNap Questionnaire

Questionnaire sur les siestes

[The « Liège-Naples NAP questionnaire »- LiNap]

This questionnaire was developed through a collaboration between the University of Naples and the University of Liège (V. Muto, C. Schmidt, M. Reyt, A. Lesoinne, R. Marcone and G. Ficca)

ID :

Date :

Heure :

Ce questionnaire vise à évaluer votre comportement de sieste. Les siestes, dans ce questionnaire, sont définies comme des périodes de sommeil, qui peuvent être prises à n'importe quel moment dans les 24 heures (i.e. une période de sommeil qui se situe en dehors de l'épisode de sommeil classique nocturne). Dans ce questionnaire une série de questions à choix multiples seront proposées. Veuillez cocher une seule case par question.

1) Faites-vous des siestes ?

- ☐ Oui
- ☐ Non

2) Depuis combien de temps faites-vous la sieste ?

- ☐ Moins d' 1 an
- ☐ 1 à 2 ans
- ☐ 2 à 3 ans
- ☐ 3 à 4 ans
- ☐ Plus de 10 ans
- ☐ Depuis toujours

3) A quelle fréquence faites-vous des siestes ?

- ☐ Moins d' 1 fois par semaine
- ☐ 1-2 fois par semaine
- ☐ 3-4 fois par semaine
- ☐ 4-5 fois par semaine
- ☐ 5-6 fois par semaine
- ☐ 1 fois par jour
- ☐ > 1 fois par jour

4) Quand ont lieu vos siestes ?

- ☐ Tous les jours de la semaine, week-end inclus
- ☐ Uniquement le week-end
- ☐ Uniquement la semaine
- ☐ Uniquement pendant les vacances
- ☐ Ca varie, il n'y a pas de régularité

5) A quel moment de la journée apparaissent habituellement vos siestes ?

- ☐ Matin (avant 12h)
- ☐ Après-midi (entre 12 et 17h)
- ☐ Soirée (après 17h)

6) De quelle durée, en moyenne, sont vos siestes ?

- ☐ Moins de 10 minutes
- ☐ Entre 10 et 30 minutes
- ☐ Entre 30 et 60 minutes
- ☐ Entre 1 et 2 heures
- ☐ Plus de 2 heures

7) Est-ce que faire la sieste est un besoin pour vous ?

- ☐ Pas du tout
- ☐ Un petit peu
- ☐ Moyennement
- ☐ Beaucoup
- ☐ Enormément

8) Est-ce que vos siestes sont apparues depuis un événement déclencheur ? (depuis la retraite, depuis le décès d'un proche, depuis la prise d'un traitement médicamenteux, depuis un problème de santé ...)

- ☐ Oui
- ☐ Non

Si oui, veuillez préciser depuis quand:

- ☐ Depuis la retraite
- ☐ Depuis le décès d'un proche
- ☐ Depuis la prise d'un traitement médicamenteux
- ☐ Depuis un problème de santé
- ☐ Autre :

9) Avez-vous remarqué des facteurs favorisant l'apparition de siestes (en fin de semaine, après une soirée avec vos proches, lors d'un changement de saison, ...) ?

- ☐ Oui

☐ Non

Si oui, veuillez préciser :

- ☐ En fin de semaine
- ☐ Après une soirée avec vos proches
- ☐ Lors d'un changement de saison
- ☐ Autre :

10) Pourquoi faites-vous des siestes?

- ☐ Je suis fatigué(e)
- ☐ Je ne dors pas bien la nuit
- ☐ Je suis fatigué(e) à cause de ma vie sociale
- ☐ J'ai besoin de récupérer parce que je ne dors pas assez la nuit
- ☐ J'ai besoin de récupérer parce que je ne dors pas bien la nuit
- ☐ Par plaisir, j'aime beaucoup faire des siestes
- ☐ Autre:

11) Est-ce que vous planifiez vos siestes ?

- ☐ Oui
- ☐ Non

12) Programmez-vous un réveil lorsque vous faites la sieste ?

- ☐ Oui
- ☐ Non

13) Est-ce qu'il vous arrive de faire des siestes involontairement (de vous endormir sans l'avoir planifié) ?

- ☐ Oui
- ☐ Non

Si oui, veuillez préciser dans quelles situations:

- ☐ En face de la télévision
- ☐ Après avoir mangé
- ☐ Après mon shift de nuit au travail

14) Quelle position choisissez-vous pour faire la sieste ?

- ☐ Position couchée
- ☐ Position assise

15) Lors de vos sieste, est-ce que la lumière vous dérange ?

- ☐ Oui
- ☐ Non

16) Lors de vos sieste, est-ce que vous créez l'obscurité dans la pièce où vous êtes ?

- ☐ Oui
- ☐ Non

Si oui, veuillez préciser de quelle façon :

- ☐ Vous fermez les rideaux
- ☐ Vous éteignez la lumière de la pièce

17) Sur une échelle de 1 à 10, à quel point votre sommeil pendant la sieste vous paraît réparateur ?

Sommeil non réparateur 1 2 3 4 5 6 7 8 9 10 Sommeil très réparateur

18) Est-ce que des rêves apparaissent lors de vos siestes ?

- ☐ Oui
- ☐ Non

19) Lors de vos siestes, combien de temps estimez-vous mettre pour vous endormir?

Temps en minute :

20) Lors de vos siestes, combien de temps estimez-vous dormir ?

Temps en minute :

21) Lors de vos siestes, sur une échelle de 1 à 10, à quel point votre sommeil pendant la sieste vous paraît profond ?

Sommeil pas profond 1 2 3 4 5 6 7 8 9 10 Sommeil très profond

22) Lors de vos siestes, combien de fois vous réveillez-vous ?

- ☐ Une seule fois, à la fin de votre sieste
- ☐ Deux fois
- ☐ Trois fois
- ☐ Plus de 3 fois

23) Après la sieste, combien de temps avez- vous besoin pour vous sentir complètement éveillé(e) ?

Temps en minute :

24) Après la sieste, combien de temps avez- vous besoin pour sentir que votre humeur revient à un état optimal ?

Temps en minute :

25) Comment évalueriez-vous globalement la qualité de votre sommeil durant la nuit suivant une journée au cours de laquelle vous avez fait une sieste ?

- ☐ Très bon
- ☐ Assez bon
- ☐ Assez mauvais
- ☐ Très mauvais

Bibliography

- Aber, R., & Webb, W. B. (1986). Effects of a limited nap on night sleep in older subjects. *Psychology and Aging*, 1(4), 300–302. <https://doi.org/10.1037/0882-7974.1.4.300>
- Adan, A., Archer, S. N., Hidalgo, M. P., Di Milia, L., Natale, V., & Randler, C. (2012). Circadian Typology: A Comprehensive Review. *Chronobiology International*, 29(9), 1153–1175. <https://doi.org/10.3109/07420528.2012.719971>
- Akerstedt, T., & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *Int J Neurosci*, 52(1–2), 29–37.
- Alessi, C. A., & Martin, J. L. (2018). Sleep in Older Adults: Challenges and Opportunities. *Sleep Medicine Clinics*, 13(1), xv–xviii. <https://doi.org/10.1016/j.jsmc.2017.12.002>
- Ali, D., Moga, D. C., Khouli, R. H. E., Martinez, A. I., Abner, E. L., & Jicha, G. A. (2020). Cognitive reserve for memory performance is mediated by preclinical frontotemporal and limbic amyloid deposition in subjects with normal cognition in early MCI. *Alzheimer's & Dementia*, 16(S5), e046569. <https://doi.org/10.1002/alz.046569>
- Allan Rechtschaffen, A. K. (1968). *A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects*. <http://archive.org/details/RKManual>
- Almklov, E. L., Drummond, S. P. A., Orff, H., & Alhassoon, O. M. (2015). The Effects of Sleep Deprivation on Brain Functioning in Older Adults. *Behavioral Sleep Medicine*, 13(4), 324–345. <https://doi.org/10.1080/15402002.2014.905474>
- Alqurashi, Y. D., AlHarkan, K., Aldhawyan, A., Bahamdan, A., Alabdulkader, A., Alotaibi, R., Alduailej, S., Alqahtani, M., & Ghamdi, K. A. (2022). Association Between Nap Duration and Cognitive Functions Among Saudi Older Adults. *Frontiers in Neuroscience*, 16. <https://doi.org/10.3389/fnins.2022.917987>
- Altamura, M., Elvevåg, B., Blasi, G., Bertolino, A., Callicott, J. H., Weinberger, D. R., Mattay, V. S., & Goldberg, T. E. (2007). Dissociating the effects of Sternberg working memory demands in prefrontal cortex. *Psychiatry Research: Neuroimaging*, 154(2), 103–114. <https://doi.org/10.1016/j.psychresns.2006.08.002>

- Álvarez-Bueno, C., Mesas, A. E., Reina-Gutierrez, S., Saz-Lara, A., Jimenez-Lopez, E., & Martinez-Vizcaino, V. (2022). Napping and cognitive decline: A systematic review and meta-analysis of observational studies. *BMC Geriatrics*, 22(1), 756. <https://doi.org/10.1186/s12877-022-03436-2>
- Ancoli-Israel, S., Cole, R., Alessi, C., Chambers, M., Moorcroft, W., & Pollak, C. P. (2003). The role of actigraphy in the study of sleep and circadian rhythms. *Sleep*, 26(3), 342–392. <https://doi.org/10.1093/sleep/26.3.342>
- Ancoli-Israel, S., & Martin, J. L. (2006). Insomnia and daytime napping in older adults. *Journal of Clinical Sleep Medicine: JCSM: Official Publication of the American Academy of Sleep Medicine*, 2(3), 333–342.
- Andersson, J. L. R., Hutton, C., Ashburner, J., Turner, R., & Friston, K. (2001). Modeling geometric deformations in EPI time series. *NeuroImage*, 13(5), 903–919. <https://doi.org/10.1006/nimg.2001.0746>
- Angel, L., Bastin, C., Genon, S., Balteau, E., Phillips, C., Luxen, A., Maquet, P., Salmon, E., & Collette, F. (2013). Differential effects of aging on the neural correlates of recollection and familiarity. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 49(6), 1585–1597. <https://doi.org/10.1016/j.cortex.2012.10.002>
- Angel, L., & Isingrini, M. (2015). Le vieillissement neurocognitif: Entre pertes et compensation. [Neurocognitive aging: Deficits and compensation.]. *L'Année Psychologique*, 115(2), 289–324. <https://doi.org/10.4074/S0003503314000104>
- Angevaren, M., Aufdemkampe, G., Verhaar, H. J. J., Aleman, A., & Vanhees, L. (2008). Physical activity and enhanced fitness to improve cognitive function in older people without known cognitive impairment. *The Cochrane Database of Systematic Reviews*, 3, CD005381. <https://doi.org/10.1002/14651858.CD005381.pub3>
- Arenaza-Urquijo, E. M., & Vemuri, P. (2018). Resistance vs resilience to Alzheimer disease. *Neurology*, 90(15), 695–703. <https://doi.org/10.1212/WNL.0000000000005303>
- Arenaza-Urquijo, E. M., & Vemuri, P. (2020). Improving the resistance and resilience framework for aging and dementia studies. *Alzheimer's Research & Therapy*, 12(1), 41. <https://doi.org/10.1186/s13195-020-00609-2>
- Arendt, J. (2005). Melatonin: Characteristics, concerns, and prospects. *Journal of Biological Rhythms*, 20(4), 291–303. <https://doi.org/10.1177/0748730405277492>

- Artuso, C., Cavallini, E., Bottiroli, S., & Palladino, P. (2017). Updating working memory: Memory load matters with aging. *Aging Clinical and Experimental Research*, 29(3), 371–377. <https://doi.org/10.1007/s40520-016-0581-y>
- Ashburner, J., & Friston, K. J. (2005). Unified segmentation. *NeuroImage*, 26(3), 839–851. <https://doi.org/10.1016/j.neuroimage.2005.02.018>
- Auyeung, T. W., Lee, J. S. W., Leung, J., Kwok, T., Leung, P. C., Woo, J., & Wing, Y. K. (2013). Cognitive deficit is associated with phase advance of sleep–wake rhythm, daily napping, and prolonged sleep duration—A cross-sectional study in 2,947 community-dwelling older adults. *AGE*, 35(2), 479–486. <https://doi.org/10.1007/s11357-011-9366-6>
- Azemachi, H., Oomae, T., Ito, T., Nagano, H., Shiratori, S., & Shimano, K. (2023). Analysis of gravity effect on human blood flow and skin temperature through postural change. *E3S Web of Conferences*, 396, 01088. <https://doi.org/10.1051/e3sconf/202339601088>
- Babcock, R. L., & Salthouse, T. A. (1990). Effects of increased processing demands on age differences in working memory. *Psychology and Aging*, 5(3), 421–428. <https://doi.org/10.1037/0882-7974.5.3.421>
- Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, 4(11), 417–423. [https://doi.org/10.1016/s1364-6613\(00\)01538-2](https://doi.org/10.1016/s1364-6613(00)01538-2)
- Baddeley, A. (2010). Working memory. *Current Biology*, 20(4), R136–R140. <https://doi.org/10.1016/j.cub.2009.12.014>
- Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology*, 63, 1–29. <https://doi.org/10.1146/annurev-psych-120710-100422>
- Baddeley, A., & Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 8, pp. 47–89). Academic Press. [https://doi.org/10.1016/S0079-7421\(08\)60452-1](https://doi.org/10.1016/S0079-7421(08)60452-1)
- Baker, F. C., & Driver, H. S. (2007). Circadian rhythms, sleep, and the menstrual cycle. *Sleep Medicine*, 8(6), 613–622. <https://doi.org/10.1016/j.sleep.2006.09.011>
- Baker, F. C., Sattari, N., de Zambotti, M., Goldstone, A., Alaynick, W. A., & Mednick, S. C. (2019). Impact of sex steroids and reproductive stage on sleep-dependent memory consolidation in women. *Neurobiology of Learning and Memory*, 160, 118–131. <https://doi.org/10.1016/j.nlm.2018.03.017>
- Baker, L. M., Laidlaw, D. H., Cabeen, R., Akbudak, E., Conturo, T. E., Correia, S., Tate, D. F., Heaps-Woodruff, J. M., Brier, M. R., Bolzenius, J., Salminen, L. E., Lane, E. M., McMichael, A. R., & Paul, R. H. (2017).

- Cognitive reserve moderates the relationship between neuropsychological performance and white matter fiber bundle length in healthy older adults. *Brain Imaging and Behavior*, 11(3), 632–639. <https://doi.org/10.1007/s11682-016-9540-7>
- Ballell, L., Ritchie, H. K., Knauer, O. A., Guerin, M. K., Stothard, E., & Wright, K. (2023). 0011 Daily verses circadian amplitude of the distal-proximal skin temperature gradient. *Sleep*, 46(Supplement_1), A5. <https://doi.org/10.1093/sleep/zsad077.0011>
- Barbey, A. K., Koenigs, M., & Grafman, J. (2013). Dorsolateral prefrontal contributions to human working memory. *Cortex*, 49(5), 1195–1205. <https://doi.org/10.1016/j.cortex.2012.05.022>
- Bartrés-Faz, D., Solé-Padullés, C., Junqué, C., Rami, L., Bosch, B., Bargalló, N., Falcón, C., Sánchez-Valle, R., & Molinuevo, J. L. (2009). Interactions of cognitive reserve with regional brain anatomy and brain function during a working memory task in healthy elders. *Biological Psychology*, 80(2), 256–259. <https://doi.org/10.1016/j.biopsycho.2008.10.005>
- Bassuk, S. S., Glass, T. A., & Berkman, L. F. (1999). Social disengagement and incident cognitive decline in community-dwelling elderly persons. *Annals of Internal Medicine*, 131(3), 165–173. <https://doi.org/10.7326/0003-4819-131-3-199908030-00002>
- Bastin, C., Simon, J., Kurth, S., Collette, F., & Salmon, É. (2013). Individual variability in episodic memory functioning in normal and pathological aging: The role of cognitive reserve. *Revue de Neuropsychologie*, 5(4), 235–242. <https://doi.org/10.1684/nrp.2013.0278>
- Bastin, C., Van der Linden, M., Michel, A.-P., & Friedman, W. J. (2004). The effects of aging on location-based and distance-based processes in memory for time. *Acta Psychologica*, 116(2), 145–171. <https://doi.org/10.1016/j.actpsy.2003.12.014>
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67, 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Batinga, H., Martinez-Nicolas, A., Zornoza-Moreno, M., Sánchez-Solis, M., Larqué, E., Mondéjar, M. T., Moreno-Casbas, M., García, F. J., Campos, M., Rol, M. A., & Madrid, J. A. (2015). Ontogeny and aging of the distal skin temperature rhythm in humans. *AGE*, 37(2), 29. <https://doi.org/10.1007/s11357-015-9768-y>
- Beck, A. T., & Beamesderfer, A. (1974). Assessment of depression: The depression inventory. *Mod Probl Pharmacopsychiatry*, 7(0), 151–169.

- Beck, A. T., Epstein, N., Brown, G., & Steer, R. A. (1988). An inventory for measuring clinical anxiety: Psychometric properties. *Journal of Consulting and Clinical Psychology*, 56(6), 893–897. <https://doi.org/10.1037//0022-006x.56.6.893>
- Beck, A. T., & Steer, R. A. (1984). Internal consistencies of the original and revised Beck Depression Inventory. *Journal of Clinical Psychology*, 40(6), 1365–1367. [https://doi.org/10.1002/1097-4679\(198411\)40:6%253C1365::aid-jclp2270400615%253E3.0.co;2-d](https://doi.org/10.1002/1097-4679(198411)40:6%253C1365::aid-jclp2270400615%253E3.0.co;2-d)
- Beck, A. T., Ward, C. H., Mendelson, M., Mock, J., & Erbaugh, J. (1961). An Inventory for Measuring Depression. *Arch Gen Psychiatry*, 4, 561–571.
- Benkirane, O., Delwiche, B., Mairesse, O., & Peigneux, P. (2022). Impact of Sleep Fragmentation on Cognition and Fatigue. *International Journal of Environmental Research and Public Health*, 19(23), 15485. <https://doi.org/10.3390/ijerph192315485>
- Bennett, I. J., Rivera, H. G., & Rypma, B. (2013). Isolating age-group differences in working memory load-related neural activity: Assessing the contribution of working memory capacity using a partial-trial fMRI method. *NeuroImage*, 72, 20–32. <https://doi.org/10.1016/j.neuroimage.2013.01.030>
- Ben-Shachar, M. S., Lüdtke, D., & Makowski, D. (2020). effectsize: Estimation of Effect Size Indices and Standardized Parameters. *Journal of Open Source Software*, 5(56), 2815. <https://doi.org/10.21105/joss.02815>
- Berardi, A., Parasuraman, R., & Haxby, J. V. (2001). Overall vigilance and sustained attention decrements in healthy aging. *Experimental Aging Research*, 27(1), 19–39. <https://doi.org/10.1080/03610730126014>
- Bernardi, G., Betta, M., Ricciardi, E., Pietrini, P., Tononi, G., & Siclari, F. (2019). Regional Delta Waves In Human Rapid Eye Movement Sleep. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 39(14), 2686–2697. <https://doi.org/10.1523/JNEUROSCI.2298-18.2019>
- Berry, R. B., Gamaldo, C. E., Harding, S. M., Brooks, R., Lloyd, R. M., Vaughn, B. V., & Marcus, C. L. (2015). AASM Scoring Manual Version 2.2 Updates: New Chapters for Scoring Infant Sleep Staging and Home Sleep Apnea Testing. *Journal of Clinical Sleep Medicine*, 11(11), 1253–1254. <https://doi.org/10.5664/jcsm.5176>
- Berthomier, C., Drouot, X., Herman-Stoica, M., Berthomier, P., Prado, J., Bokar-Thire, D., Benoit, O., Mattout, J., & d'Ortho, M.-P. (2007). Automatic analysis of single-channel sleep EEG: Validation in healthy individuals. *Sleep*, 30(11), 1587–1595. <https://doi.org/10.1093/sleep/30.11.1587>

- Berthomier, C., Muto, V., Schmidt, C., Vandewalle, G., Jaspar, M., Devillers, J., Gaggioni, G., Chellappa, S. L., Meyer, C., Phillips, C., Salmon, E., Berthomier, P., Prado, J., Benoit, O., Bouet, R., Brandewinder, M., Mattout, J., & Maquet, P. (2020). Exploring scoring methods for research studies: Accuracy and variability of visual and automated sleep scoring. *Journal of Sleep Research*, 29(5), e12994. <https://doi.org/10.1111/jsr.12994>
- Bethlehem, R. a. I., Seidlitz, J., White, S. R., Vogel, J. W., Anderson, K. M., Adamson, C., Adler, S., Alexopoulos, G. S., Anagnostou, E., Areces-Gonzalez, A., Astle, D. E., Auyeung, B., Ayub, M., Bae, J., Ball, G., Baron-Cohen, S., Beare, R., Bedford, S. A., Benegal, V., ... Alexander-Bloch, A. F. (2022). Brain charts for the human lifespan. *Nature*, 604(7906), 525–533. <https://doi.org/10.1038/s41586-022-04554-y>
- Biss, R. K., & Hasher, L. (2012). Happy as a lark: Morning-type younger and older adults are higher in positive affect. *Emotion*, 12(3), 437–441. <https://doi.org/10.1037/a0027071>
- Blackburn, H. L., & Benton, A. L. (1957). Revised administration and scoring of the Digit Span Test. *Journal of Consulting Psychology*, 21(2), 139–143. <https://doi.org/10.1037/h0047235>
- Blackwell, T., Figueiro, M. G., Tranah, G. J., Zeitzer, J. M., Yaffe, K., Ancoli-Israel, S., Kado, D. M., Ensrud, K. E., Lane, N. E., Leng, Y., Stone, K. L., & Osteoporotic Fractures in Men (MrOS) Study Group. (2023). Associations of 24-Hour Light Exposure and Activity Patterns and Risk of Cognitive Impairment and Decline in Older Men: The MrOS Sleep Study. *The Journals of Gerontology: Series A*, 78(10), 1834–1843. <https://doi.org/10.1093/gerona/glac187>
- Blackwell, T., Yaffe, K., Ancoli-Israel, S., Schneider, J. L., Cauley, J. A., Hillier, T. A., Fink, H. A., Stone, K. L., & for the Study of Osteoporotic Fractures Group. (2006). Poor Sleep Is Associated With Impaired Cognitive Function in Older Women: The Study of Osteoporotic Fractures. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 61(4), 405–410. <https://doi.org/10.1093/gerona/61.4.405>
- Blatter, K., & Cajochen, C. (2007). Circadian rhythms in cognitive performance: Methodological constraints, protocols, theoretical underpinnings. *Physiology & Behavior*, 90(2), 196–208. <https://doi.org/10.1016/j.physbeh.2006.09.009>
- Blatter, K., Graw, P., Münch, M., Knoblauch, V., Wirz-Justice, A., & Cajochen, C. (2006). Gender and age differences in psychomotor vigilance performance under differential sleep pressure conditions. *Behavioural Brain Research*, 168(2), 312–317. <https://doi.org/10.1016/j.bbr.2005.11.018>

- Blumenfeld, R. S., & Ranganath, C. (2006). Dorsolateral Prefrontal Cortex Promotes Long-Term Memory Formation through Its Role in Working Memory Organization. *Journal of Neuroscience*, 26(3), 916–925. <https://doi.org/10.1523/JNEUROSCI.2353-05.2006>
- Boivin, D. B., Boudreau, P., & Kosmadopoulos, A. (2022). Disturbance of the Circadian System in Shift Work and Its Health Impact. *Journal of Biological Rhythms*, 37(1), 3–28. <https://doi.org/10.1177/07487304211064218>
- Bolkan, S. S., Stujenske, J. M., Parnaudeau, S., Spellman, T. J., Rauffenbart, C., Abbas, A. I., Harris, A. Z., Gordon, J. A., & Kellendonk, C. (2017). Thalamic projections sustain prefrontal activity during working memory maintenance. *Nature Neuroscience*, 20(7), 987–996. <https://doi.org/10.1038/nn.4568>
- Boon, M. R., Bakker, L. E. H., Van Der Linden, R. A. D., Pereira Arias-Bouda, L., Smit, F., Verberne, H. J., Van Marken Lichtenbelt, W. D., Jazet, I. M., & Rensen, P. C. N. (2014). Supraclavicular Skin Temperature as a Measure of 18F-FDG Uptake by BAT in Human Subjects. *PLoS ONE*, 9(6), e98822. <https://doi.org/10.1371/journal.pone.0098822>
- Borbély, A. A. (1982). A two process model of sleep regulation. *Human Neurobiology*, 1(3), 195–204.
- Borbély, A. A., Daan, S., Wirz-Justice, A., & Deboer, T. (2016). The two-process model of sleep regulation: A reappraisal. *Journal of Sleep Research*, 25(2), 131–143. <https://doi.org/10.1111/jsr.12371>
- Bouchard, M., Lina, J.-M., Gaudreault, P.-O., Lafrenière, A., Dubé, J., Gosselin, N., & Carrier, J. (2021). Sleeping at the switch. *eLife*, 10, e64337. <https://doi.org/10.7554/eLife.64337>
- Bowling, A. (2007). Aspirations for older age in the 21st century: What is successful aging? *International Journal of Aging & Human Development*, 64(3), 263–297. <https://doi.org/10.2190/L0K1-87W4-9R01-7127>
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10(4), 433–436. <https://doi.org/10.1163/156856897X00357>
- Brickenkamp, R., & Zilmer, E. (2011). *D2 Test of Attention* [Data set]. American Psychological Association (APA). <https://doi.org/10.1037/t03299-000>
- Brooks, A., & Lack, L. (2006). A Brief Afternoon Nap Following Nocturnal Sleep Restriction: Which Nap Duration is Most Recuperative? *Sleep*, 29(6), 831–840. <https://doi.org/10.1093/sleep/29.6.831>
- Brooks, M. E., Kristensen, K., Benthem, K. J. van, Magnusson, A., Berg, C. W., Nielsen, A., Skaug, H. J., Mächler, M., & Bolker, B. M. (2017). glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *The R Journal*, 9(2), 378–400.

- Brown, R. E., Basheer, R., McKenna, J. T., Strecker, R. E., & McCarley, R. W. (2012). CONTROL OF SLEEP AND WAKEFULNESS. *Physiological Reviews*, 92(3), 1087–1187. <https://doi.org/10.1152/physrev.00032.2011>
- Buijs, F. N., León-Mercado, L., Guzmán-Ruiz, M., Guerrero-Vargas, N. N., Romo-Nava, F., & Buijs, R. M. (2016). The Circadian System: A Regulatory Feedback Network of Periphery and Brain. *Physiology*, 31(3), 170–181. <https://doi.org/10.1152/physiol.00037.2015>
- Burgess, H. J., & Eastman, C. I. (2005). The dim light melatonin onset following fixed and free sleep schedules. *Journal of Sleep Research*, 14(3), 229–237. <https://doi.org/10.1111/j.1365-2869.2005.00470.x>
- Burgess, H. J., Savic, N., Sletten, T., Roach, G., Gilbert, S. S., & Dawson, D. (2003). The relationship between the dim light melatonin onset and sleep on a regular schedule in young healthy adults. *Behavioral Sleep Medicine*, 1(2), 102–114. https://doi.org/10.1207/S15402010BSM0102_3
- Burgmans, S., van Boxtel, M. P. J., Vuurman, E. F. P. M., Smeets, F., Gronenschild, E. H. B. M., Uylings, H. B. M., & Jolles, J. (2009). The prevalence of cortical gray matter atrophy may be overestimated in the healthy aging brain. *Neuropsychology*, 23(5), 541–550. <https://doi.org/10.1037/a0016161>
- Burke, T. M., Scheer, F. A. J. L., Ronda, J. M., Czeisler, C. A., & Wright, K. P. (2015). Sleep inertia, sleep homeostatic and circadian influences on higher-order cognitive functions. *Journal of Sleep Research*, 24(4), 364–371. <https://doi.org/10.1111/jsr.12291>
- Burzynska, A. Z., Preuschhof, C., Bäckman, L., Nyberg, L., Li, S.-C., Lindenberger, U., & Heekeren, H. R. (2010). Age-related differences in white matter microstructure: Region-specific patterns of diffusivity. *NeuroImage*, 49(3), 2104–2112. <https://doi.org/10.1016/j.neuroimage.2009.09.041>
- Buyse, D. J., Kupfer, D. J., Frank, E., Monk, T. H., & Ritenour, A. (1992). Electroencephalographic sleep studies in depressed outpatients treated with interpersonal psychotherapy: II. Longitudinal studies at baseline and recovery. *Psychiatry Research*, 42(1), 27–40. [https://doi.org/10.1016/0165-1781\(92\)90036-3](https://doi.org/10.1016/0165-1781(92)90036-3)
- Buyse, D. J., Monk, T. H., Carrier, J., & Begley, A. (2005). Circadian Patterns of Sleep, Sleepiness, and Performance in Older and Younger Adults. *Sleep*, 28(11), 1365–1376. <https://doi.org/10.1093/sleep/28.11.1365>
- Buyse, D. J., Reynolds, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Psychiatry Research*, 28(2), 193–213. [https://doi.org/10.1016/0165-1781\(89\)90047-4](https://doi.org/10.1016/0165-1781(89)90047-4)

- Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging, 17*(1), 85–100. <https://doi.org/10.1037//0882-7974.17.1.85>
- Cabeza, R., Albert, M., Belleville, S., Craik, F. I. M., Duarte, A., Grady, C. L., Lindenberger, U., Nyberg, L., Park, D. C., Reuter-Lorenz, P. A., Rugg, M. D., Steffener, J., & Rajah, M. N. (2018). Maintenance, reserve and compensation: The cognitive neuroscience of healthy ageing. *Nature Reviews Neuroscience, 19*(11), 701–710. <https://doi.org/10.1038/s41583-018-0068-2>
- Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging Gracefully: Compensatory Brain Activity in High-Performing Older Adults. *NeuroImage, 17*(3), 1394–1402. <https://doi.org/10.1006/nimg.2002.1280>
- Cabeza, R., & Dennis, N. A. (2012). Frontal Lobes and Aging: Deterioration and Compensation. In D. T. Stuss & R. T. Knight (Eds), *Principles of Frontal Lobe Function* (pp. 628–652). Oxford University Press.
- Cabeza, R., & Dennis, N. A. (2013). Frontal Lobes and Aging: Deterioration and Compensation. In *Principles of Frontal Lobe Function*. Oxford University Press. <https://oxfordmedicine.com/view/10.1093/med/9780199837755.001.0001/med-9780199837755-chapter-44>
- Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience, 12*(1), 1–47. <https://doi.org/10.1162/08989290051137585>
- Cai, H., Su, N., Li, W., Li, X., Xiao, S., & Sun, L. (2021). Relationship between afternoon napping and cognitive function in the ageing Chinese population. *General Psychiatry, 34*(1), e100361. <https://doi.org/10.1136/gpsych-2020-100361>
- Cajochen, C. (2024). Circadian and sleep–wake homeostatic modulation of EEG activity during sleep and wakefulness. *Clinical Epileptology, 37*(4), 259–265. <https://doi.org/10.1007/s10309-024-00722-4>
- Cajochen, C., Brunner, D. P., Kräuchi, K., Graw, P., & Wirz-Justice, A. (1995). Power density in theta/alpha frequencies of the waking EEG progressively increases during sustained wakefulness. *Sleep, 18*(10), 890–894. <https://doi.org/10.1093/sleep/18.10.890>
- Cajochen, C., Knoblauch, V., Kräuchi, K., Renz, C., & Wirz-Justice, A. (2001). Dynamics of frontal EEG activity, sleepiness and body temperature under high and low sleep pressure. *Neuroreport, 12*(10), 2277–2281. <https://doi.org/10.1097/00001756-200107200-00046>

- Cajochen, C., Münch, M., Knoblauch, V., Blatter, K., & Wirz-Justice, A. (2006). Age-related Changes in the Circadian and Homeostatic Regulation of Human Sleep. *Chronobiology International*, 23(1–2), 461–474. <https://doi.org/10.1080/07420520500545813>
- Cajochen, C., Münch, M., Kobińska, S., Kräuchi, K., Steiner, R., Oelhafen, P., Orgül, S., & Wirz-Justice, A. (2005). High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light. *The Journal of Clinical Endocrinology and Metabolism*, 90(3), 1311–1316. <https://doi.org/10.1210/jc.2004-0957>
- Cajochen, C., & Schmidt, C. (2025). The Circadian Brain and Cognition. *Annual Review of Psychology*, 76(1), 115–141. <https://doi.org/10.1146/annurev-psych-022824-043825>
- Callaghan, M. F., Freund, P., Draganski, B., Anderson, E., Cappelletti, M., Chowdhury, R., Diedrichsen, J., Fitzgerald, T. H. B., Smittenaar, P., Helms, G., Lutti, A., & Weiskopf, N. (2014). Widespread age-related differences in the human brain microstructure revealed by quantitative magnetic resonance imaging. *Neurobiology of Aging*, 35(8), 1862–1872. <https://doi.org/10.1016/j.neurobiolaging.2014.02.008>
- Callow, D. D., Zipunnikov, V., Spira, A. P., Wanigatunga, S. K., Pettigrew, C., Albert, M., Soldan, A., & BIOCARD Research Team. (2024). Actigraphy Estimated Sleep Moderates the Relationship between Physical Activity and Cognition in Older Adults. *Mental Health and Physical Activity*, 26, 100573. <https://doi.org/10.1016/j.mhpa.2023.100573>
- Campbell, S. S., Dawson, D., & Zulley, J. (1993). When the Human Circadian System is Caught Napping: Evidence for Endogenous Rhythms Close to 24 Hours. *Sleep*, 16(7), 638–640. <https://doi.org/10.1093/sleep/16.7.638>
- Campbell, S. S., Murphy, P. J., & Stauble, T. N. (2005). Effects of a nap on nighttime sleep and waking function in older subjects. *Journal of the American Geriatrics Society*, 53(1), 48–53. <https://doi.org/10.1111/j.1532-5415.2005.53009.x>
- Cappell, K. A., Gmeindl, L., & Reuter-Lorenz, P. A. (2010). Age Differences in Prefrontal Recruitment During Verbal Working Memory Maintenance Depend on Memory Load. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, 46(4), 462–473. <https://doi.org/10.1016/j.cortex.2009.11.009>
- Carden, K. A. (2009). Recording Sleep: The Electrodes, 10/20 Recording System, and Sleep System Specifications. *Sleep Medicine Clinics*, 4(3), 333–341. <https://doi.org/10.1016/j.jsmc.2009.04.002>

- Carlson, E. J., Wilckens, K. A., & Wheeler, M. E. (2023). The Interactive Role of Sleep and Circadian Rhythms in Episodic Memory in Older Adults. *The Journals of Gerontology: Series A*, 78(10), 1844–1852. <https://doi.org/10.1093/gerona/glad112>
- Carp, J., Gmeindl, L., & Reuter-Lorenz, P. A. (2010). Age Differences in the Neural Representation of Working Memory Revealed by Multi-Voxel Pattern Analysis. *Frontiers in Human Neuroscience*, 4. <https://doi.org/10.3389/fnhum.2010.00217>
- Carrier, J., Monk, T. H., Buysse, D. J., & Kupfer, D. J. (1996). Amplitude Reduction of the Circadian Temperature and Sleep Rhythms in the Elderly. *Chronobiology International*, 13(5), 373–386. <https://doi.org/10.3109/07420529609012661>
- Carrier, J., Viens, I., Poirier, G., Robillard, R., Lafortune, M., Vandewalle, G., Martin, N., Barakat, M., Paquet, J., & Filipini, D. (2011). Sleep slow wave changes during the middle years of life. *The European Journal of Neuroscience*, 33(4), 758–766. <https://doi.org/10.1111/j.1460-9568.2010.07543.x>
- Carskadon, M. A., Brown, E. D., & Dement, W. C. (1982). Sleep fragmentation in the elderly: Relationship to daytime sleep tendency. *Neurobiology of Aging*, 3(4), 321–327. [https://doi.org/10.1016/0197-4580\(82\)90020-3](https://doi.org/10.1016/0197-4580(82)90020-3)
- Carvalho-Bos, S. S., Lek, R. F. R. der, Waterhouse, J., Reilly, T., & Someren, E. J. W. V. (2007). Strong Association of the Rest–Activity Rhythm With Well-Being in Demented Elderly Women. *The American Journal of Geriatric Psychiatry*, 15(2), 92–100. <https://doi.org/10.1097/01.JGP.0000236584.03432.dc>
- Cash, E., Rebholz, W., Albert, C., Fields, O., Zimmaro, L., Siwik, C., Phillips, K., Kloecker, G., & Sephton, S. E. (2017). Associations between the prognostic indicators rest/activity rhythm and diurnal cortisol profiles in patients with lung cancer. *Brain, Behavior, and Immunity*, 66, e31–e32. <https://doi.org/10.1016/j.bbi.2017.07.117>
- Cash, S. S., Halgren, E., Dehghani, N., Rossetti, A. O., Thesen, T., Wang, C., Devinsky, O., Kuzniecky, R., Doyle, W., Madsen, J. R., Bromfield, E., Erőss, L., Halász, P., Karmos, G., Csercsa, R., Wittner, L., & Ulbert, I. (2009). The Human K-Complex Represents an Isolated Cortical Down-State. *Science*, 324(5930), 1084–1087. <https://doi.org/10.1126/science.1169626>
- Castro-Lionard, K., Thomas-Antérion, C., Crawford-Achour, E., Rouch, I., Trombert-Paviot, B., Barthélémy, J.-C., Laurent, B., Roche, F., & Gonthier, R. (2011). Can maintaining cognitive function at 65 years old predict successful ageing 6 years later? The PROOF study. *Age and Ageing*, 40(2), 259–265. <https://doi.org/10.1093/ageing/afq174>

- Cellini, N., Buman, M. P., McDevitt, E. A., Ricker, A. A., & Mednick, S. C. (2013). Direct comparison of two actigraphy devices with polysomnographically recorded naps in healthy young adults. *Chronobiology International*, 30(5), 691–698. <https://doi.org/10.3109/07420528.2013.782312>
- Cerri, M., Luppi, M., Tupone, D., Zamboni, G., & Amici, R. (2017). REM Sleep and Endothermy: Potential Sites and Mechanism of a Reciprocal Interference. *Frontiers in Physiology*, 8. <https://doi.org/10.3389/fphys.2017.00624>
- Chamberlain, J. D., Sprague, B. N., & Ross, L. A. (2022). Age- and Time-Varying Associations Between Subjective Health and Episodic Memory in Older Adults. *The Journals of Gerontology: Series B*, 77(4), 673–682. <https://doi.org/10.1093/geronb/gbab142>
- Chan, J. K. M., & Nicholas, C. L. (2018). EEG changes between sleeping and wakefulness: Characteristics and neural generation. In *The Routledge International Handbook of Psychobiology*. Routledge.
- Chang, H. J., Yang, K. I., Chu, M. K., Yun, C.-H., & Kim, D. (2022). Association Between Nap and Reported Cognitive Function and Role of Sleep Debt: A Population-Based Study. *Journal of Clinical Neurology*, 18(4), 470–477. <https://doi.org/10.3988/jcn.2022.18.4.470>
- Chapman, T. W., & Hill, R. A. (2020). Myelin plasticity in adulthood and aging. *Neuroscience Letters*, 715, 134645. <https://doi.org/10.1016/j.neulet.2019.134645>
- Chatfield, M. D., Brayne, C. E., & Matthews, F. E. (2005). A systematic literature review of attrition between waves in longitudinal studies in the elderly shows a consistent pattern of dropout between differing studies. *Journal of Clinical Epidemiology*, 58(1), 13–19. <https://doi.org/10.1016/j.jclinepi.2004.05.006>
- Chee, M. W. L., & Choo, W. C. (2004). Functional imaging of working memory after 24 hr of total sleep deprivation. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 24(19), 4560–4567. <https://doi.org/10.1523/JNEUROSCI.0007-04.2004>
- Chen, J.-C., Espeland, M. A., Brunner, R. L., Lovato, L. C., Wallace, R. B., Leng, X., Phillips, L. S., Robinson, J. G., Kotchen, J. M., Johnson, K. C., Manson, J. E., Stefanick, M. L., Sarto, G. E., & Mysiw, W. J. (2016). Sleep duration, cognitive decline, and dementia risk in older women. *Alzheimer's & Dementia*, 12(1), 21–33. <https://doi.org/10.1016/j.jalz.2015.03.004>
- Chen, Y., Pan, L., & Ma, N. (2022). Altered effective connectivity of thalamus with vigilance impairments after sleep deprivation. *Journal of Sleep Research*, 31(6), e13693. <https://doi.org/10.1111/jsr.13693>

- Chevalier, V., Mormont, M.-C., Curé, H., & Chollet, P. (2003). Assessment of circadian rhythms by actimetry in healthy subjects and patients with advanced colorectal cancer. *Oncology Reports*, 10(3), 733–737.
- Chinoy, E. D., Frey, D. J., Kaslovsky, D. N., Meyer, F. G., & Wright, K. P. (2014). Age-related changes in slow wave activity rise time and NREM sleep EEG with and without zolpidem in healthy young and older adults. *Sleep Medicine*, 15(9), 1037–1045. <https://doi.org/10.1016/j.sleep.2014.05.007>
- Chung, S. (2009). How to measure the circadian rhythm in human being? *Journal of Korean Sleep Research Society*, 6(2), 63–68. <https://doi.org/10.13078/jksrs09013>
- Chylinski, D., Van Egroo, M., Narbutas, J., Muto, V., Bahri, M. A., Berthomier, C., Salmon, E., Bastin, C., Phillips, C., Collette, F., Maquet, P., Carrier, J., Lina, J.-M., & Vandewalle, G. (2022). Timely coupling of sleep spindles and slow waves linked to early amyloid- β burden and predicts memory decline. *eLife*, 11, e78191. <https://doi.org/10.7554/eLife.78191>
- Cipolla-Neto, J., & Amaral, F. G. do. (2018). Melatonin as a Hormone: New Physiological and Clinical Insights. *Endocrine Reviews*, 39(6), 990–1028. <https://doi.org/10.1210/er.2018-00084>
- Cirelli, C., & Tononi, G. (2008). Is Sleep Essential? *PLOS Biology*, 6(8), e216. <https://doi.org/10.1371/journal.pbio.0060216>
- Cochrane, A., Robertson, I. H., & Coogan, A. N. (2012). Association between circadian rhythms, sleep and cognitive impairment in healthy older adults: An actigraphic study. *Journal of Neural Transmission*, 119(10), 1233–1239. <https://doi.org/10.1007/s00702-012-0802-2>
- Cohen, J. (2013). *Statistical Power Analysis for the Behavioral Sciences* (2nd edn). Routledge. <https://doi.org/10.4324/9780203771587>
- Cohen, M. X. (2017). Where Does EEG Come From and What Does It Mean? *Trends in Neurosciences*, 40(4), 208–218. <https://doi.org/10.1016/j.tins.2017.02.004>
- Colcombe, S. J., Erickson, K. I., Scalf, P. E., Kim, J. S., Prakash, R., McAuley, E., Elavsky, S., Marquez, D. X., Hu, L., & Kramer, A. F. (2006). Aerobic exercise training increases brain volume in aging humans. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, 61(11), 1166–1170. <https://doi.org/10.1093/gerona/61.11.1166>
- Coletta, N. A., Mallette, M. M., Gabriel, D. A., Tyler, C. J., & Cheung, S. S. (2018). Core and skin temperature influences on the surface electromyographic responses to an isometric force and position task. *PLOS ONE*, 13(3), e0195219. <https://doi.org/10.1371/journal.pone.0195219>

- Collet, J., Ftouni, S., Clough, M., Cain, S., Fielding, J., & Anderson, C. (2020). Differential Impact of Sleep Deprivation and Circadian Timing on Reflexive Versus Inhibitory Control of Attention. *Scientific Reports*, 10, 7270. <https://doi.org/10.1038/s41598-020-63144-y>
- Colrain, I. M. (2005). The K-Complex: A 7-Decade History. *Sleep*, 28(2), 255–273. <https://doi.org/10.1093/sleep/28.2.255>
- Copinschi, G., & Van Cauter, E. (2008). Effects of Ageing on Modulation of Hormonal Secretions by Sleep and Circadian Rhythmicity. *Hormone Research*, 43(1–3), 20–24. <https://doi.org/10.1159/000184232>
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, 3(3), 201–215. <https://doi.org/10.1038/nrn755>
- Corbin, N., Todd, N., Friston, K. J., & Callaghan, M. F. (2018). Accurate modeling of temporal correlations in rapidly sampled fMRI time series. *Human Brain Mapping*, 39(10), 3884–3897. <https://doi.org/10.1002/hbm.24218>
- Cosco, T. D., Matthew Prina, A., Perales, J., Stephan, B. C., & Brayne, C. (2014). Whose ‘successful ageing’?: Lay- and researcher-driven conceptualisations of ageing well. *The European Journal of Psychiatry*, 28(2), 124–130. <https://doi.org/10.4321/S0213-61632014000200006>
- Cowan, N. (1995). *Attention and memory: An integrated framework* (pp. xv, 321). Oxford University Press.
- Craik, F. I. M., & Byrd, M. (1982). Aging and Cognitive Deficits. In F. I. M. Craik & S. Trehub (Eds), *Aging and Cognitive Processes* (pp. 191–211). Springer US. https://doi.org/10.1007/978-1-4684-4178-9_11
- Craik, F. I. M., & Rose, N. S. (2012). Memory encoding and aging: A neurocognitive perspective. *Neuroscience & Biobehavioral Reviews*, 36(7), 1729–1739. <https://doi.org/10.1016/j.neubiorev.2011.11.007>
- Crespo, C., Fernández, J. R., Aboy, M., & Mojón, A. (2013). Clinical application of a novel automatic algorithm for actigraphy-based activity and rest period identification to accurately determine awake and asleep ambulatory blood pressure parameters and cardiovascular risk. *Chronobiology International*, 30(1–2), 43–54. <https://doi.org/10.3109/07420528.2012.701147>
- Cross, N., Terpening, Z., Rogers, N. L., Duffy, S. L., Hickie, I. B., Lewis, S. J. G., & Naismith, S. L. (2015). Napping in older people ‘at risk’ of dementia: Relationships with depression, cognition, medical burden and sleep quality. *Journal of Sleep Research*, 24(5), 494–502. <https://doi.org/10.1111/jsr.12313>
- Czeisler, C. A., & Buxton, O. M. (2017). Chapter 35—Human Circadian Timing System and Sleep-Wake Regulation. In M. Kryger, T. Roth, & W. C. Dement (Eds), *Principles and Practice of Sleep Medicine (Sixth Edition)* (pp. 362-376.e5). Elsevier. <https://doi.org/10.1016/B978-0-323-24288-2.00035-0>

- Czeisler, C. A., Duffy, J. F., Shanahan, T. L., Brown, E. N., Mitchell, J. F., Rimmer, D. W., Ronda, J. M., Silva, E. J., Allan, J. S., Emens, J. S., Dijk, D., & Kronauer, R. E. (1999). Stability, precision, and near-24-hour period of the human circadian pacemaker. *Science (New York, N.Y.)*, 284(5423), 2177–2181. <https://doi.org/10.1126/science.284.5423.2177>
- Czeisler, C. A., Dumont, M., Duffy, J. F., Steinberg, J. D., Richardson, G. S., Brown, E. N., Sánchez, R., Ríos, C. D., & Ronda, J. M. (1992). Association of sleep-wake habits in older people with changes in output of circadian pacemaker. *Lancet (London, England)*, 340(8825), 933–936. [https://doi.org/10.1016/0140-6736\(92\)92817-y](https://doi.org/10.1016/0140-6736(92)92817-y)
- Czeisler, C. A., Zimmerman, C., Ronda, M., Moore-Ede, C., & Weitzman, D. (1980). Timing of REM Sleep is Coupled to the Circadian Rhythm of Body Temperature in Man. *Sleep*, 2(3), 329–346. <https://doi.org/10.1093/sleep/2.3.329>
- Daan, S., Beersma, D. G., & Borbély, A. A. (1984). Timing of human sleep: Recovery process gated by a circadian pacemaker. *The American Journal of Physiology*, 246(2 Pt 2), R161–183. <https://doi.org/10.1152/ajpregu.1984.246.2.R161>
- D'Aurizio, G., Festucci, F., Di Pompeo, I., Tempesta, D., & Curcio, G. (2023). Effects of Physical Activity on Cognitive Functioning: The Role of Cognitive Reserve and Active Aging. *Brain Sciences*, 13(11), 1581. <https://doi.org/10.3390/brainsci13111581>
- Dautovich, N. D., McCrae, C. S., & Rowe, M. (2008). Subjective and Objective Napping and Sleep in Older Adults: Are Evening Naps 'Bad' for Nighttime Sleep? *Journal of the American Geriatrics Society*, 56(9), 1681–1686. <https://doi.org/10.1111/j.1532-5415.2008.01822.x>
- Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2008). Que PASA? The posterior-anterior shift in aging. *Cerebral Cortex (New York, N.Y.: 1991)*, 18(5), 1201–1209. <https://doi.org/10.1093/cercor/bhm155>
- de Andrés, I., Garzón, M., & Reinoso-Suárez, F. (2011). Functional Anatomy of Non-REM Sleep. *Frontiers in Neurology*, 2, 70. <https://doi.org/10.3389/fneur.2011.00070>
- de Haan, S., Dourte, M., Deantoni, M., Rey, M., Baillet, M., Berthomier, C., Muto, V., Hammad, G., Cajochen, C., Reichert, C. F., Maire, M., Schmidt, C., & Postnova, S. (2025). Impact of Varying Sleep Pressure on Daytime Sleep Propensity in Healthy Young and Older Adults. *Clocks & Sleep*, 7(1), Article 1. <https://doi.org/10.3390/clockssleep7010002>

- Deantoni, M., Baillet, M., Hammad, G., Berthomier, C., Rey, M., Jaspard, M., Meyer, C., Van Egroo, M., Talwar, P., Lambot, E., Chellappa, S. L., Degueldre, C., Luxen, A., Salmon, E., Balteau, E., Phillips, C., Dijk, D., Vandewalle, G., Collette, F., ... Schmidt, C. (2023). Association between sleep slow-wave activity and in-vivo estimates of myelin in healthy young men. *NeuroImage*, 272, 120045. <https://doi.org/10.1016/j.neuroimage.2023.120045>
- Deantoni, M., Rey, M., Baillet, M., Dourte, M., De Haan, S., Lesoinne, A., Vandewalle, G., Maquet, P., Berthomier, C., Muto, V., Hammad, G., & Schmidt, C. (2024). Napping and circadian sleep–wake regulation during healthy aging. *Sleep*, 47(5), zsad287. <https://doi.org/10.1093/sleep/zsad287>
- Deantoni, M., Rey, M., Berthomier, C., Muto, V., Hammad, G., De Haan, S., Dourte, M., Taillard, J., Lambot, E., Cajochen, C., Reichert, C. F., Maire, M., Baillet, M., & Schmidt, C. (2023). Association between circadian sleep regulation and cortical gyrification in young and older adults. *Sleep*, 46(9), zsad094. <https://doi.org/10.1093/sleep/zsad094>
- Deboer, T. (2018). Sleep homeostasis and the circadian clock: Do the circadian pacemaker and the sleep homeostat influence each other's functioning? *Neurobiology of Sleep and Circadian Rhythms*, 5, 68. <https://doi.org/10.1016/j.nbscr.2018.02.003>
- Degroot, D. W., & Kenney, W. L. (2007). Impaired defense of core temperature in aged humans during mild cold stress. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, 292(1), R103-108. <https://doi.org/10.1152/ajpregu.00074.2006>
- Della Sala, S., Parra, M. A., Fabi, K., Luzzi, S., & Abrahams, S. (2012). Short-term memory binding is impaired in AD but not in non-AD dementias. *Neuropsychologia*, 50(5), 833–840. <https://doi.org/10.1016/j.neuropsychologia.2012.01.018>
- Dement, W., & Kleitman, N. (1957). Cyclic variations in EEG during sleep and their relation to eye movements, body motility, and dreaming. *Electroencephalography and Clinical Neurophysiology*, 9(4), 673–690. [https://doi.org/10.1016/0013-4694\(57\)90088-3](https://doi.org/10.1016/0013-4694(57)90088-3)
- Depp, C. A., & Jeste, D. V. (2006). Definitions and Predictors of Successful Aging: A Comprehensive Review of Larger Quantitative Studies. *The American Journal of Geriatric Psychiatry*, 14(1), 6–20. <https://doi.org/10.1097/01.JGP.0000192501.03069.bc>
- Devore, E. E., Grodstein, F., & Schernhammer, E. S. (2016). Sleep Duration in Relation to Cognitive Function among Older Adults: A Systematic Review of Observational Studies. *Neuroepidemiology*, 46(1), 57–78. <https://doi.org/10.1159/000442418>

- Dhand, R., & Sohal, H. (2007). Good sleep, bad sleep! The role of daytime naps in healthy adults: *Current Opinion in Internal Medicine*, 6(1), 91–94. <https://doi.org/10.1097/01.mcp.0000245703.92311.d0>
- Di Rosa, E., Schiff, S., Cagnolati, F., & Mapelli, D. (2015). Motivation–cognition interaction: How feedback processing changes in healthy ageing and in Parkinson’s disease. *Aging Clinical and Experimental Research*, 27(6), 911–920. <https://doi.org/10.1007/s40520-015-0358-8>
- Dickstein, D. L., Kabaso, D., Rocher, A. B., Luebke, J. I., Wearne, S. L., & Hof, P. R. (2007). Changes in the structural complexity of the aged brain. *Aging Cell*, 6(3), 275–284. <https://doi.org/10.1111/j.1474-9726.2007.00289.x>
- Didikoglu, A., Maharani ,Asri, Payton ,Antony, Pendleton ,Neil, & and Canal, M. M. (2019). Longitudinal change of sleep timing: Association between chronotype and longevity in older adults. *Chronobiology International*, 36(9), 1285–1300. <https://doi.org/10.1080/07420528.2019.1641111>
- Diekelmann, S., & Born, J. (2010). The memory function of sleep. *Nature Reviews. Neuroscience*, 11(2), 114–126. <https://doi.org/10.1038/nrn2762>
- Dijk, D., & Archer, S. N. (2009). Light, Sleep, and Circadian Rhythms: Together Again. *PLoS Biology*, 7(6), e1000145. <https://doi.org/10.1371/journal.pbio.1000145>
- Dijk, D., Brunner, D. P., Beersma, D. G., & Borbély, A. A. (1990). Electroencephalogram power density and slow wave sleep as a function of prior waking and circadian phase. *Sleep*, 13(5), 430–440. <https://doi.org/10.1093/sleep/13.5.430>
- Dijk, D., & Czeisler, C. A. (1994). Paradoxical timing of the circadian rhythm of sleep propensity serves to consolidate sleep and wakefulness in humans. *Neuroscience Letters*, 166(1), 63–68. [https://doi.org/10.1016/0304-3940\(94\)90841-9](https://doi.org/10.1016/0304-3940(94)90841-9)
- Dijk, D., & Czeisler, C. A. (1995). Contribution of the circadian pacemaker and the sleep homeostat to sleep propensity, sleep structure, electroencephalographic slow waves, and sleep spindle activity in humans. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 15(5 Pt 1), 3526–3538. <https://doi.org/10.1523/JNEUROSCI.15-05-03526.1995>
- Dijk, D., & Duffy, J. F. (1999). Circadian regulation of human sleep and age-related changes in its timing, consolidation and EEG characteristics. *Annals of Medicine*, 31(2), 130–140. <https://doi.org/10.3109/07853899908998789>

- Dijk, D., & Duffy, J. F. (2020). Novel Approaches for Assessing Circadian Rhythmicity in Humans: A Review. *Journal of Biological Rhythms*, 35(5), 421–438. <https://doi.org/10.1177/0748730420940483>
- Dijk, D., Duffy, J. F., & Czeisler, C. A. (1992). Circadian and sleep/wake dependent aspects of subjective alertness and cognitive performance. *Journal of Sleep Research*, 1(2), 112–117. <https://doi.org/10.1111/j.1365-2869.1992.tb00021.x>
- Dijk, D., Duffy, J. F., & Czeisler, C. A. (2000). CONTRIBUTION OF CIRCADIAN PHYSIOLOGY AND SLEEP HOMEOSTASIS TO AGE-RELATED CHANGES IN HUMAN SLEEP. *Chronobiology International*, 17(3), 285–311. <https://doi.org/10.1081/CBI-100101049>
- Dijk, D., Duffy, J. F., Riel, E., Shanahan, T. L., & Czeisler, C. A. (1999). Ageing and the circadian and homeostatic regulation of human sleep during forced desynchrony of rest, melatonin and temperature rhythms. *The Journal of Physiology*, 516 (Pt 2)(Pt 2), 611–627. <https://doi.org/10.1111/j.1469-7793.1999.0611v.x>
- Dijk, D., Groeger, J. A., Stanley, N., & Deacon, S. (2010). Age-related reduction in daytime sleep propensity and nocturnal slow wave sleep. *Sleep*, 33(2), 211–223. <https://doi.org/10.1093/sleep/33.2.211>
- Dijk, D., & von Schantz, M. (2005). Timing and consolidation of human sleep, wakefulness, and performance by a symphony of oscillators. *Journal of Biological Rhythms*, 20(4), 279–290. <https://doi.org/10.1177/0748730405278292>
- Dijk, D.-J. (2012). Sleep and health: Beyond sleep duration and sleepiness? *Journal of Sleep Research*, 21(4), 355–356. <https://doi.org/10.1111/j.1365-2869.2012.01036.x>
- Ding, Y., Zheng, Y., Liu, T., Chen, T., Wang, C., Sun, Q., Hua, M., & Hua, T. (2017). Changes in GABAergic markers accompany degradation of neuronal function in the primary visual cortex of senescent rats. *Scientific Reports*, 7(1), 14897. <https://doi.org/10.1038/s41598-017-15006-3>
- Dinges, D. F., & Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments, & Computers*, 17(6), 652–655. <https://doi.org/10.3758/BF03200977>
- Dittmar, M., Stark, T., & Wedell, S. (2024). Circadian Rhythm of Distal Skin Temperature in Healthy Older and Young Women and Its Relationship with Sleep–Wake Rhythm and Environmental Factors under Natural Living Conditions. *Geriatrics*, 9(4), 102. <https://doi.org/10.3390/geriatrics9040102>
- Dixon, R. A., & Lachman, M. E. (2019). Risk and protective factors in cognitive aging: Advances in assessment, prevention, and promotion of alternative pathways. In *The aging brain: Functional adaptation*

- across adulthood. (pp. 217–263). American Psychological Association.
<https://doi.org/10.1037/0000143-009>
- Djonlagic, I., Mariani, S., Fitzpatrick, A. L., Van Der Klei, V. M. G. T. H., Johnson, D., Wood, A. C., Seeman, T., Nguyen, H. T., Prerau, M. J., Luchsinger, J. A., Dzierzewski, J. M., Rapp, S. R., Tranah, G. J., Yaffe, K., Burdick, K. E., Stone, K. L., Redline, S., & Purcell, S. M. (2021). Macro and micro sleep architecture and cognitive performance in older adults. *Nature Human Behaviour*, 5(1), 123–145.
<https://doi.org/10.1038/s41562-020-00964-y>
- Dolcos, F., Rice, H. J., & Cabeza, R. (2002). Hemispheric asymmetry and aging: Right hemisphere decline or asymmetry reduction. *Neuroscience and Biobehavioral Reviews*, 26(7), 819–825.
[https://doi.org/10.1016/s0149-7634\(02\)00068-4](https://doi.org/10.1016/s0149-7634(02)00068-4)
- Donohue, M. C., Sperling, R. A., Salmon, D. P., Rentz, D. M., Raman, R., Thomas, R. G., Weiner, M., Aisen, P. S., Australian Imaging, Biomarkers, and Lifestyle Flagship Study of Ageing, Alzheimer’s Disease Neuroimaging Initiative, & Alzheimer’s Disease Cooperative Study. (2014). The preclinical Alzheimer cognitive composite: Measuring amyloid-related decline. *JAMA Neurology*, 71(8), 961–970. <https://doi.org/10.1001/jamaneurol.2014.803>
- Drag, L. L., & Bieliauskas, L. A. (2010). Contemporary review 2009: Cognitive aging. *Journal of Geriatric Psychiatry and Neurology*, 23(2), 75–93. <https://doi.org/10.1177/0891988709358590>
- Druiven, S. J. M., Riese, H., Kamphuis, J., Haarman, B. C. M., Antypa, N., Penninx, B. W. J. H., Schoevers, R. A., & Meesters, Y. (2021). Chronotype changes with age; seven-year follow-up from the Netherlands study of depression and anxiety cohort. *Journal of Affective Disorders*, 295, 1118–1121.
<https://doi.org/10.1016/j.jad.2021.08.095>
- Duarte, A., & Dulas, M. R. (2020). Episodic memory decline in aging. In *The Cambridge handbook of cognitive aging: A life course perspective* (pp. 200–217). Cambridge University Press.
<https://doi.org/10.1017/9781108552684.013>
- Duffy, J. F., Dijk, D., Klerman, E. B., & Czeisler, C. A. (1998). Later endogenous circadian temperature nadir relative to an earlier wake time in older people. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 275(5), R1478–R1487.
<https://doi.org/10.1152/ajpregu.1998.275.5.R1478>
- Duffy, J. F., & Dijk, D.-J. (2002). Getting Through to Circadian Oscillators: Why Use Constant Routines? *Journal of Biological Rhythms*, 17(1), 4–13. <https://doi.org/10.1177/074873002129002294>

- Duffy, J. F., & Wright, K. P. (2005). Entrainment of the human circadian system by light. *Journal of Biological Rhythms*, 20(4), 326–338. <https://doi.org/10.1177/0748730405277983>
- Duffy, J. F., Zitting, K.-M., & Chinoy, E. D. (2015). Aging and Circadian Rhythms. *Sleep Medicine Clinics*, 10(4), 423–434. <https://doi.org/10.1016/j.jsmc.2015.08.002>
- Duggan, K. A., McDevitt, Elizabeth A., Whitehurst, Lauren N., & Mednick, S. C. (2018). To Nap, Perchance to DREAM: A Factor Analysis of College Students' Self-Reported Reasons for Napping. *Behavioral Sleep Medicine*, 16(2), 135–153. <https://doi.org/10.1080/15402002.2016.1178115>
- Dwivedi, M., Dubey, N., Pansari, A. J., Bapi, R. S., Das, M., Guha, M., Banerjee, R., Pramanick, G., Basu, J., & Ghosh, A. (2021). Effects of Meditation on Structural Changes of the Brain in Patients With Mild Cognitive Impairment or Alzheimer's Disease Dementia. *Frontiers in Human Neuroscience*, 15, 728993. <https://doi.org/10.3389/fnhum.2021.728993>
- Dzierzewski, J. M., Donovan, E. K., & Sabet, S. M. (2021). The Sleep Regularity Questionnaire: Development and initial validation. *Sleep Medicine*, 85, 45–53. <https://doi.org/10.1016/j.sleep.2021.06.028>
- Edwards, S., Clow, A., Evans, P., & Hucklebridge, F. (2001). Exploration of the awakening cortisol response in relation to diurnal cortisol secretory activity. *Life Sciences*, 68(18), 2093–2103. [https://doi.org/10.1016/s0024-3205\(01\)00996-1](https://doi.org/10.1016/s0024-3205(01)00996-1)
- Engels-Domínguez, N., Koops, E. A., Prokopiou, P. C., Van Egroo, M., Schneider, C., Riphagen, J. M., Singhal, T., & Jacobs, H. I. L. (2023). State-of-the-art imaging of neuromodulatory subcortical systems in aging and Alzheimer's Disease: Challenges and opportunities. *Neuroscience and Biobehavioral Reviews*, 144, 104998. <https://doi.org/10.1016/j.neubiorev.2022.104998>
- Eyler, L. T., Sherzai, A., Kaup, A. R., & Jeste, D. V. (2011). A review of functional brain imaging correlates of successful cognitive aging. *Biological Psychiatry*, 70(2), 115–122. <https://doi.org/10.1016/j.biopsych.2010.12.032>
- Ezzati, A., Katz, M. J., Zammit, A. R., Lipton, M. L., Zimmerman, M. E., Sliwinski, M. J., & Lipton, R. B. (2016). Differential association of left and right hippocampal volumes with verbal episodic and spatial memory in older adults. *Neuropsychologia*, 93, 380–385. <https://doi.org/10.1016/j.neuropsychologia.2016.08.016>
- Farokhian, F., Yang, C., Beheshti, I., Matsuda, H., & Wu, S. (2017). Age-Related Gray and White Matter Changes in Normal Adult Brains. *Aging and Disease*, 8(6), Article 6. <https://doi.org/10.14336/AD.2017.0502>

- Festini, S. B., Zahodne, L., & Reuter-Lorenz, P. A. (2018). Theoretical Perspectives on Age Differences in Brain Activation: HAROLD, PASA, CRUNCH—How Do They STAC Up? In *Oxford Research Encyclopedia of Psychology*. <https://doi.org/10.1093/acrefore/9780190236557.013.400>
- Ficca, G., Axelsson, J., Mollicone, D. J., Muto, V., & Vitiello, M. V. (2010). Naps, cognition and performance. *Sleep Medicine Reviews*, 14(4), 249–258. <https://doi.org/10.1016/j.smr.2009.09.005>
- Filippini, N., Nickerson, L. D., Beckmann, C. F., Ebmeier, K. P., Frisoni, G. B., Matthews, P. M., Smith, S. M., & Mackay, C. E. (2012). Age-related adaptations of brain function during a memory task are also present at rest. *NeuroImage*, 59(4), 3821–3828. <https://doi.org/10.1016/j.neuroimage.2011.11.063>
- Finelli, L. A., Baumann, H., Borbély, A. A., & Achermann, P. (2000). Dual electroencephalogram markers of human sleep homeostasis: Correlation between theta activity in waking and slow-wave activity in sleep. *Neuroscience*, 101(3), 523–529. [https://doi.org/10.1016/S0306-4522\(00\)00409-7](https://doi.org/10.1016/S0306-4522(00)00409-7)
- Fjell, A. M., & Walhovd, K. B. (2010). Structural brain changes in aging: Courses, causes and cognitive consequences. *Reviews in the Neurosciences*, 21(3), 187–221. <https://doi.org/10.1515/REVNEURO.2010.21.3.187>
- Floyd, J., Janisse, J., Jenuwine, E., & Ager, J. (2007). Changes in REM-Sleep Percentage Over the Adult Lifespan. *Sleep*, 30, 829–836. <https://doi.org/10.1093/sleep/30.7.829>
- Foley, D., Ancoli-Israel, S., Britz, P., & Walsh, J. (2004). Sleep disturbances and chronic disease in older adults. *Journal of Psychosomatic Research*, 56(5), 497–502. <https://doi.org/10.1016/j.jpsychores.2004.02.010>
- Foley, D., Vitiello, M. V., Bliwise, D. L., Ancoli-Israel, S., Monjan, A. A., & Walsh, J. K. (2007). Frequent Napping Is Associated With Excessive Daytime Sleepiness, Depression, Pain, and Nocturia in Older Adults: Findings From the National Sleep Foundation '2003 Sleep in America' Poll. *The American Journal of Geriatric Psychiatry*, 15(4), 344–350. <https://doi.org/10.1097/01.JGP.0000249385.50101.67>
- Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). 'Mini-mental state'. A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, 12(3), 189–198. [https://doi.org/10.1016/0022-3956\(75\)90026-6](https://doi.org/10.1016/0022-3956(75)90026-6)
- Ford, C. G., Vowles, K. E., Smith, B. W., & Kinney, A. Y. (2020). Mindfulness and Meditative Movement Interventions for Men Living With Cancer: A Meta-analysis. *Annals of Behavioral Medicine: A*

- Publication of the Society of Behavioral Medicine*, 54(5), 360–373.
<https://doi.org/10.1093/abm/kaz053>
- Forstmann, B. U., Dutilh, G., Brown, S., Neumann, J., von Cramon, D. Y., Ridderinkhof, K. R., & Wagenmakers, E.-J. (2008). Striatum and pre-SMA facilitate decision-making under time pressure. *Proceedings of the National Academy of Sciences of the United States of America*, 105(45), 17538–17542.
<https://doi.org/10.1073/pnas.0805903105>
- Fraigne, J. J., Luppi, P. H., Mahoney, C. E., De Luca, R., Shiromani, P. J., Weber, F., Adamantidis, A., & Peever, J. (2023). Dopamine neurons in the ventral tegmental area modulate rapid eye movement sleep. *Sleep*, 46(8), zsad024. <https://doi.org/10.1093/sleep/zsad024>
- Franken, P., & Dijk, D. (2024). Sleep and circadian rhythmicity as entangled processes serving homeostasis. *Nature Reviews. Neuroscience*, 25(1), 43–59. <https://doi.org/10.1038/s41583-023-00764-z>
- Fronczek, R., Overeem, S., Lammers, G. J., van Dijk, J. G., & van Someren, E. J. W. (2006). Altered Skin-Temperature Regulation in Narcolepsy Relates to Sleep Propensity. *Sleep*, 29(11), 1444–1449.
<https://doi.org/10.1093/sleep/29.11.1444>
- Gaggioni, G., Maquet, P., Schmidt, C., Dijk, D., & Vandewalle, G. (2014). Neuroimaging, cognition, light and circadian rhythms. *Frontiers in Systems Neuroscience*, 8.
<https://www.frontiersin.org/article/10.3389/fnsys.2014.00126>
- Galea, S., & Tracy, M. (2007). Participation rates in epidemiologic studies. *Annals of Epidemiology*, 17(9), 643–653. <https://doi.org/10.1016/j.annepidem.2007.03.013>
- Gao, C., Zheng, X., Cai, R., Yu, L., Schneider, J. A., Buchman, A. S., Bennett, D. A., Leng, Y., Ibáñez, A., Gao, L., Hu, K., & Li, P. (2025). Timing and intraindividual variability of daytime napping and Alzheimer's disease in older adults. *Communications Medicine*, 5(1), 1–9. <https://doi.org/10.1038/s43856-025-00936-1>
- Gazzaley, A., Cooney, J. W., Rissman, J., & D'Esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature Neuroscience*, 8(10), 1298–1300.
<https://doi.org/10.1038/nn1543>
- Geerligs, L., Renken, R. J., Saliassi, E., Maurits, N. M., & Lorist, M. M. (2015). A Brain-Wide Study of Age-Related Changes in Functional Connectivity. *Cerebral Cortex (New York, N.Y.: 1991)*, 25(7), 1987–1999.
<https://doi.org/10.1093/cercor/bhu012>

- Gislason, T., Reynisdóttir, H., Kristbjarnarson, H., & Benediktsdóttir, B. (1993). Sleep habits and sleep disturbances among the elderly—An epidemiological survey. *Journal of Internal Medicine*, 234(1), 31–39. <https://doi.org/10.1111/j.1365-2796.1993.tb00701.x>
- Glisky, E. L. (2007). Changes in Cognitive Function in Human Aging. In D. R. Riddle (Ed.), *Brain Aging: Models, Methods, and Mechanisms*. CRC Press/Taylor & Francis. <http://www.ncbi.nlm.nih.gov/books/NBK3885/>
- Godfrey, S., Iversen, Helle K., & West, A. S. (2022). Melatonin profile in healthy, elderly subjects—A systematic literature review. *Chronobiology International*, 39(4), 476–492. <https://doi.org/10.1080/07420528.2021.2016794>
- Goldman, S. E., Hall, M., Boudreau, R., Matthews, K. A., Cauley, J. A., Ancoli-Israel, S., Stone, K. L., Rubin, S. M., Satterfield, S., Simonsick, E. M., & Newman, A. B. (2008). Association between Nighttime Sleep and Napping in Older Adults. *Sleep*, 31(5), 733–740. <https://doi.org/10.1093/sleep/31.5.733>
- Gomes, B. A., Plaska, C. R., Ortega, J., & Ellmore, T. M. (2023). A simultaneous EEG-fMRI study of thalamic load-dependent working memory delay period activity. *Frontiers in Behavioral Neuroscience*, 17. <https://doi.org/10.3389/fnbeh.2023.1132061>
- Gonçalves, B. S. B., Adamowicz, T., Louzada, F. M., Moreno, C. R., & Araujo, J. F. (2015). A fresh look at the use of nonparametric analysis in actimetry. *Sleep Medicine Reviews*, 20, 84–91. <https://doi.org/10.1016/j.smr.2014.06.002>
- Gooley, J. J., Schomer, A., & Saper, C. B. (2006). The dorsomedial hypothalamic nucleus is critical for the expression of food-entrainable circadian rhythms. *Nature Neuroscience*, 9(3), 398–407. <https://doi.org/10.1038/nn1651>
- Gradisar, M., & Lack, L. (2004). Relationships between the Circadian Rhythms of Finger Temperature, Core Temperature, Sleep Latency, and Subjective Sleepiness. *Journal of Biological Rhythms*, 19(2), 157–163. <https://doi.org/10.1177/0748730403261560>
- Grady, C. (2012). The cognitive neuroscience of ageing. *Nature Reviews Neuroscience*, 13(7), 491–505. <https://doi.org/10.1038/nrn3256>
- Grant, A., Dennis, N., & Li, P. (2014). Cognitive control, cognitive reserve, and memory in the aging bilingual brain. *Frontiers in Psychology*, 5. <https://doi.org/10.3389/fpsyg.2014.01401>

- Greene, R. W., & Frank, M. G. (2010). Slow wave activity during sleep: Functional and therapeutic implications. *The Neuroscientist: A Review Journal Bringing Neurobiology, Neurology and Psychiatry*, 16(6), 618–633. <https://doi.org/10.1177/1073858410377064>
- Grober, E., & Buschke, H. (1987). Genuine memory deficits in dementia. *Developmental Neuropsychology*, 3(1), 13–36. <https://doi.org/10.1080/87565648709540361>
- Gunning-Dixon, F. M., Brickman, A. M., Cheng, J. C., & Alexopoulos, G. S. (2009). Aging of Cerebral White Matter: A Review of MRI Findings. *International Journal of Geriatric Psychiatry*, 24(2), 109–117. <https://doi.org/10.1002/gps.2087>
- Gutchess, A. H., Welsh, R. C., Hedden, T., Bangert, A., Minear, M., Liu, L. L., & Park, D. C. (2005). Aging and the neural correlates of successful picture encoding: Frontal activations compensate for decreased medial-temporal activity. *Journal of Cognitive Neuroscience*, 17(1), 84–96. <https://doi.org/10.1162/0898929052880048>
- Guttmann, C. R., Jolesz, F. A., Kikinis, R., Killiany, R. J., Moss, M. B., Sandor, T., & Albert, M. S. (1998). White matter changes with normal aging. *Neurology*, 50(4), 972–978. <https://doi.org/10.1212/wnl.50.4.972>
- Hahn, M. A., Heib, D., Schabus, M., Hoedlmoser, K., & Helfrich, R. F. (2020). Slow oscillation-spindle coupling predicts enhanced memory formation from childhood to adolescence. *eLife*, 9. <https://doi.org/10.7554/elife.53730>
- Hammad, G., Reyt, M., Beliy, N., Baillet, M., Deantoni, M., Lesoinne, A., Muto, V., & Schmidt, C. (2021). pyActigraphy: Open-source python package for actigraphy data visualization and analysis. *PLOS Computational Biology*, 17(10), e1009514. <https://doi.org/10.1371/journal.pcbi.1009514>
- Haque, Z. Z., Samandra, R., & Mansouri, F. A. (2021). Neural substrate and underlying mechanisms of working memory: Insights from brain stimulation studies. *Journal of Neurophysiology*, 125(6), 2038–2053. <https://doi.org/10.1152/jn.00041.2021>
- Harada, C. N., Love, M. C. N., & Triebel, K. L. (2013). Normal Cognitive Aging. *Clinics in Geriatric Medicine*, 29(4), 737–752. <https://doi.org/10.1016/j.cger.2013.07.002>
- Harper, D. G., Volicer, L., Stopa, E. G., McKee, A. C., Nitta, M., & Satlin, A. (2005). Disturbance of endogenous circadian rhythm in aging and Alzheimer disease. *The American Journal of Geriatric Psychiatry: Official Journal of the American Association for Geriatric Psychiatry*, 13(5), 359–368. <https://doi.org/10.1176/appi.ajgp.13.5.359>

- Harrison, Y., & Horne, J. A. (1998). Sleep loss impairs short and novel language tasks having a prefrontal focus. *Journal of Sleep Research*, 7(2), 95–100. <https://doi.org/10.1046/j.1365-2869.1998.00104.x>
- Hashizume, Y. (1997). Fluctuations of rectal and tympanic temperatures with changes of ambient temperature during night sleep. *Psychiatry and Clinical Neurosciences*, 51(3), 129–133. <https://doi.org/10.1111/j.1440-1819.1997.tb02374.x>
- Hasselberg, M. J., McMahon, J., & Parker, K. (2013). The validity, reliability, and utility of the iButton® for measurement of body temperature circadian rhythms in sleep/wake research. *Sleep Medicine*, 14(1), 5–11. <https://doi.org/10.1016/j.sleep.2010.12.011>
- Hastings, M. H., Maywood, E. S., & Brancaccio, M. (2018). Generation of circadian rhythms in the suprachiasmatic nucleus. *Nature Reviews Neuroscience*, 19(8), 453–469. <https://doi.org/10.1038/s41583-018-0026-z>
- Hawker, G. A., French, M. R., Waugh, E. J., Gignac, M. a. M., Cheung, C., & Murray, B. J. (2010). The multidimensionality of sleep quality and its relationship to fatigue in older adults with painful osteoarthritis. *Osteoarthritis and Cartilage*, 18(11), 1365–1371. <https://doi.org/10.1016/j.joca.2010.08.002>
- Heinzel, S., Lorenz, R. C., Brockhaus, W.-R., Wüstenberg, T., Kathmann, N., Heinz, A., & Rapp, M. A. (2014). Working memory load-dependent brain response predicts behavioral training gains in older adults. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 34(4), 1224–1233. <https://doi.org/10.1523/JNEUROSCI.2463-13.2014>
- Helfrich, R. F., Mander, B. A., Jagust, W. J., Knight, R. T., & Walker, M. P. (2018). Old Brains Come Uncoupled in Sleep: Slow Wave-Spindle Synchrony, Brain Atrophy, and Forgetting. *Neuron*, 97(1), 221–230.e4. <https://doi.org/10.1016/j.neuron.2017.11.020>
- Hess, T. M., Emery, L., & Neupert, S. D. (2012). Longitudinal Relationships Between Resources, Motivation, and Functioning. *The Journals of Gerontology: Series B*, 67B(3), 299–308. <https://doi.org/10.1093/geronb/gbr100>
- Heyde, I., Kiehn, J.-T., & Oster, H. (2018). Mutual influence of sleep and circadian clocks on physiology and cognition. *Free Radical Biology and Medicine*, 119, 8–16. <https://doi.org/10.1016/j.freeradbiomed.2017.11.003>

- Hicks, H., Meyer, K., & Watts, A. (2023). Differential effects of chronotype on physical activity and cognitive performance in older adults. *Frontiers in Epidemiology*, 3, 1029221. <https://doi.org/10.3389/fepid.2023.1029221>
- Hirshkowitz, M., Whiton, K., Albert, S. M., Alessi, C., Bruni, O., DonCarlos, L., Hazen, N., Herman, J., Katz, E. S., Kheirandish-Gozal, L., Neubauer, D. N., O'Donnell, A. E., Ohayon, M., Peever, J., Rawding, R., Sachdeva, R. C., Setters, B., Vitiello, M. V., Ware, J. C., & Adams Hillard, P. J. (2015). National Sleep Foundation's sleep time duration recommendations: Methodology and results summary. *Sleep Health*, 1(1), 40–43. <https://doi.org/10.1016/j.sleh.2014.12.010>
- Hoedlmoser, K., Peigneux, P., & Rauchs, G. (2022). Recent advances in memory consolidation and information processing during sleep. *Journal of Sleep Research*, 31(4), e13607. <https://doi.org/10.1111/jsr.13607>
- Hofman, M. A., & Swaab, D. F. (2006). Living by the clock: The circadian pacemaker in older people. *Ageing Research Reviews*, 5(1), 33–51. <https://doi.org/10.1016/j.arr.2005.07.001>
- Hofstra, W. A., & Weerd, A. W. de. (2008). How to assess circadian rhythm in humans: A review of literature. *Epilepsy & Behavior*, 13(3), 438–444. <https://doi.org/10.1016/j.yebeh.2008.06.002>
- Höller-Wallscheid, M. S., Thier, P., Pomper, J. K., & Lindner, A. (2017). Bilateral recruitment of prefrontal cortex in working memory is associated with task demand but not with age. *Proceedings of the National Academy of Sciences*, 114(5), E830–E839. <https://doi.org/10.1073/pnas.1601983114>
- Hood, S., & Amir, S. (2017). The aging clock: Circadian rhythms and later life. *Journal of Clinical Investigation*, 127(2), 437–446. <https://doi.org/10.1172/JCI90328>
- Hoof, J. V., & Hensen, J. L. M. (2006). Thermal comfort and older adults. *Gerontechnology*, 4(4), 223–228. <https://doi.org/10.4017/gt.2006.04.04.006.00>
- Horne, J. A., & Ostberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology*, 4(2), 97–110.
- Horne, J. A., & Östberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology*, 4, 97–110.
- Hua, T., Li, X., He, L., Zhou, Y., Wang, Y., & Leventhal, A. G. (2006). Functional degradation of visual cortical cells in old cats. *Neurobiology of Aging*, 27(1), 155–162. <https://doi.org/10.1016/j.neurobiolaging.2004.11.012>

- Huang, Y.-L., Liu, R.-Y., Wang, Q.-S., Van Someren, E. J. W., Xu, H., & Zhou, J.-N. (2002). Age-associated difference in circadian sleep-wake and rest-activity rhythms. *Physiology & Behavior*, 76(4), 597-603. [https://doi.org/10.1016/S0031-9384\(02\)00733-3](https://doi.org/10.1016/S0031-9384(02)00733-3)
- Hubbard, J., Gent, T. C., Hoekstra, M. M. B., Emmenegger, Y., Mongrain, V., Landolt, H.-P., Adamantidis, A. R., & Franken, P. (2020). Rapid fast-delta decay following prolonged wakefulness marks a phase of wake-inertia in NREM sleep. *Nature Communications*, 11(1), 3130. <https://doi.org/10.1038/s41467-020-16915-0>
- Hülür, G., Hertzog, C., Pearman, A. M., & Gerstorf, D. (2015). Correlates and Moderators of Change in Subjective Memory and Memory Performance: Findings from the Health and Retirement Study. *Gerontology*, 61(3), 232-240. <https://doi.org/10.1159/000369010>
- Hutton, C., Bork, A., Josephs, O., Deichmann, R., Ashburner, J., & Turner, R. (2002). Image distortion correction in fMRI: A quantitative evaluation. *NeuroImage*, 16(1), 217-240. <https://doi.org/10.1006/nimg.2001.1054>
- Hutton, C., Josephs, O., Stadler, J., Featherstone, E., Reid, A., Speck, O., Bernarding, J., & Weiskopf, N. (2011). The impact of physiological noise correction on fMRI at 7 T. *NeuroImage*, 57(1), 101-112. <https://doi.org/10.1016/j.neuroimage.2011.04.018>
- Iber, C. (2007). The AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology, and Technical Specification. (*No Title*). <https://cir.nii.ac.jp/crid/1370004237604151044>
- Iglesias, J. E., Augustinack, J. C., Nguyen, K., Player, C. M., Player, A., Wright, M., Roy, N., Frosch, M. P., McKee, A. C., Wald, L. L., Fischl, B., Van Leemput, K., & Alzheimer's Disease Neuroimaging Initiative. (2015). A computational atlas of the hippocampal formation using ex vivo, ultra-high resolution MRI: Application to adaptive segmentation of in vivo MRI. *NeuroImage*, 115, 117-137. <https://doi.org/10.1016/j.neuroimage.2015.04.042>
- Introzzi, I., Zamora, E., Aydmune, Y., Richard's, M. M., Comesaña, A., & Canet-Juric, L. (2020). The Change Processes in Selective Attention during Adulthood. Inhibition or Processing Speed? *The Spanish Journal of Psychology*, 23, e37. <https://doi.org/10.1017/SJP.2020.41>
- Inui, T. S. (2003). The Need for an Integrated Biopsychosocial Approach to Research on Successful Aging. *Annals of Internal Medicine*, 139(5_Part_2), 391-394. https://doi.org/10.7326/0003-4819-139-5_Part_2-200309021-00002

- Jordan, A. D., Cooke, K. A., Moored, K. D., Katz, B., Buschkuehl, M., Jaeggi, S. M., Polk, T. A., Peltier, S. J., Jonides, J., & Reuter-Lorenz, P. A. (2020). Neural correlates of working memory training: Evidence for plasticity in older adults. *NeuroImage*, 217, 116887. <https://doi.org/10.1016/j.neuroimage.2020.116887>
- J. Albaret, M. Migliore, "Manuel du test de Stroop, " Editions du Centre de Psychologie Appliquée, Paris, 1999. - References—Scientific Research Publishing. (n.d.). Retrieved 25 July 2025, from <https://www.scirp.org/reference/referencespapers?referenceid=141483>
- Jan Długosz University in Częstochowa, & Kozerska, A. (2022). The Concept of Successful Ageing from the Perspectives of Older Adults: An Empirical Typology. *Kultura i Edukacja*, 136(2), 215–233. <https://doi.org/10.15804/kie.2022.02.13>
- Jansma, J. M., Ramsey, N. F., de Zwart, J. A., van Gelderen, P., & Duyn, J. H. (2006). fMRI study of effort and information processing in a working memory task. *Human Brain Mapping*, 28(5), 431–440. <https://doi.org/10.1002/hbm.20297>
- Jean-Louis, G., Kripke, D. F., & Ancoli-Israel, S. (2000). Sleep and quality of well-being. *Sleep*, 23(8), 1115–1121.
- Jennings, J. R., Reynolds Iii, C. F., Bryant, D. S., Berman, S. R., Buysse, D. J., Dahl, R. E., Hoch, C. C., & Monk, T. H. (1993). Peripheral thermal responsivity to facial cooling during sleep. *Psychophysiology*, 30(4), 374–382. <https://doi.org/10.1111/j.1469-8986.1993.tb02059.x>
- Jessen, F., Amariglio, R. E., van Boxtel, M., Breteler, M., Ceccaldi, M., Chételat, G., Dubois, B., Dufouil, C., Ellis, K. A., van der Flier, W. M., Glodzik, L., van Harten, A. C., de Leon, M. J., McHugh, P., Mielke, M. M., Molinuevo, J. L., Mosconi, L., Osorio, R. S., Perrotin, A., ... Wagner, M. (2014). A conceptual framework for research on subjective cognitive decline in preclinical Alzheimer's disease. *Alzheimer's & Dementia: The Journal of the Alzheimer's Association*, 10(6), 844–852. <https://doi.org/10.1016/j.jalz.2014.01.001>
- Johns, M. W. (1991). A new method for measuring daytime sleepiness: The Epworth sleepiness scale. *Sleep*, 14(6), 540–545. <https://doi.org/10.1093/sleep/14.6.540>
- Johnson, M. P., Duffy, J. F., Dijk, D.-J., Ronda, J. M., Dyal, C. M., & Czeisler, C. A. (1992). Short-term memory, alertness and performance: A reappraisal of their relationship to body temperature. *Journal of Sleep Research*, 1(1), 24–29. <https://doi.org/10.1111/j.1365-2869.1992.tb00004.x>

- Johnson, W., Logie, R. H., & Brockmole, J. R. (2010). Working memory tasks differ in factor structure across age cohorts: Implications for dedifferentiation. *Intelligence*, 38(5), 513–528. <https://doi.org/10.1016/j.intell.2010.06.005>
- Jost, K., Bryck, R. L., Vogel, E. K., & Mayr, U. (2011). Are old adults just like low working memory young adults? Filtering efficiency and age differences in visual working memory. *Cerebral Cortex (New York, N.Y.: 1991)*, 21(5), 1147–1154. <https://doi.org/10.1093/cercor/bhq185>
- Ju, Y.-E. S., Lucey, B. P., & Holtzman, D. M. (2014). Sleep and Alzheimer disease pathology—A bidirectional relationship. *Nature Reviews Neurology*, 10(2), 115–119. <https://doi.org/10.1038/nrneurol.2013.269>
- Jung, K.-I., Song, C.-H., Ancoli-Israel, S., & Barrett-Connor, E. (2013). Gender differences in nighttime sleep and daytime napping as predictors of mortality in older adults: The Rancho Bernardo Study. *Sleep Medicine*, 14(1), 12–19. <https://doi.org/10.1016/j.sleep.2012.06.004>
- Kales, A., Wilson, T., Kales, J. D., Jacobson, A., Paulson, M. J., Kollar, E., & Walter, R. D. (1967). Measurements of all-night sleep in normal elderly persons: Effects of aging. *Journal of the American Geriatrics Society*, 15(5), 405–414. <https://doi.org/10.1111/j.1532-5415.1967.tb02072.x>
- Kalpouzos, G., Chételat, G., Baron, J.-C., Landeau, B., Mevel, K., Godeau, C., Barré, L., Constans, J.-M., Viader, F., Eustache, F., & Desgranges, B. (2009). Voxel-based mapping of brain gray matter volume and glucose metabolism profiles in normal aging. *Neurobiology of Aging*, 30(1), 112–124. <https://doi.org/10.1016/j.neurobiolaging.2007.05.019>
- Kanady, J. C., Drummond, S. P. A., & Mednick, S. C. (2011). Actigraphic assessment of a polysomnographic-recorded nap: A validation study. *Journal of Sleep Research*, 20(1 Pt 2), 214–222. <https://doi.org/10.1111/j.1365-2869.2010.00858.x>
- Kaneshwaran, K., Olah, M., Tasaki, S., Yu, L., Bradshaw, E. M., Schneider, J. A., Buchman, A. S., Bennett, D. A., De Jager, P. L., & Lim, A. S. P. (2019). Sleep fragmentation, microglial aging, and cognitive impairment in adults with and without Alzheimer's dementia. *Science Advances*, 5(12), eaax7331. <https://doi.org/10.1126/sciadv.aax7331>
- Kassambara, A. (2023). *rstatix: Pipe-Friendly Framework for Basic Statistical Tests* (Version 0.7.2) [Computer software]. <https://cran.r-project.org/web/packages/rstatix/index.html>
- Kaup, A. R., Drummond, S. P. A., & Eyler, L. T. (2014). Brain functional correlates of working memory: Reduced load-modulated activation and deactivation in aging without hyperactivation or functional

- reorganization. *Journal of the International Neuropsychological Society: JINS*, 20(9), 945–950.
<https://doi.org/10.1017/S1355617714000824>
- Keage, H. A. D., Banks, S., Yang, K. L., Morgan, K., Brayne, C., & Matthews, F. E. (2012). What sleep characteristics predict cognitive decline in the elderly? *Sleep Medicine*, 13(7), 886–892.
<https://doi.org/10.1016/j.sleep.2012.02.003>
- Kennedy, K. M., Boylan, M. A., Rieck, J. R., Foster, C. M., & Rodrigue, K. M. (2017). Dynamic range in BOLD modulation: Lifespan aging trajectories and association with performance. *Neurobiology of Aging*, 60, 153–163. <https://doi.org/10.1016/j.neurobiolaging.2017.08.027>
- Kim, J. H., Ahn, J. H., Min, C. Y., Yoo, D. M., & Choi, H. G. (2021). Association between sleep quality and subjective cognitive decline: Evidence from a community health survey. *Sleep Medicine*, 83, 123–131. <https://doi.org/10.1016/j.sleep.2021.04.031>
- Kim, S. J., Benloucif, S., Reid, K. J., Weintraub, S., Kennedy, N., Wolfe, L. F., & Zee, P. C. (2014). Phase-shifting response to light in older adults. *The Journal of Physiology*, 592(1), 189–202.
<https://doi.org/10.1113/jphysiol.2013.262899>
- Kirchner, W. (1958). Age Differences in Short-Term Retention of Rapidly Changing Information. *Journal of Experimental Psychology*, 55, 352–358. <https://doi.org/10.1037/h0043688>
- Kirschstein, T., & Köhling, R. (2009). What is the Source of the EEG? *Clinical EEG and Neuroscience*, 40(3), 146–149. <https://doi.org/10.1177/155005940904000305>
- Kitamura, K., Watanabe, Y., Nakamura, K., Takano, C., Hayashi, N., Sato, H., & Someya, T. (2021). Short daytime napping reduces the risk of cognitive decline in community-dwelling older adults: A 5-year longitudinal study. *BMC Geriatrics*, 21(1), 474. <https://doi.org/10.1186/s12877-021-02418-0>
- Kleiner, M., Brainard, D. H., & Pelli, D. G. (2007). What's new in Psychtoolbox-3? *Perception*, 36, 1–16.
- Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., & Broussard, C. (2007). What's new in psychtoolbox-3. *Perception*, 36(14), 1–16.
- Kleitman, N. (1987). *Sleep and Wakefulness* (Revised & enlarged edition, Eds). University of Chicago Press.
<https://press.uchicago.edu/ucp/books/book/chicago/S/bo27408234.html>
- Klerman, E. B., & Dijk, D. (2008). Age-related reduction in the maximal capacity for sleep—Implications for insomnia. *Current Biology: CB*, 18(15), 1118–1123. <https://doi.org/10.1016/j.cub.2008.06.047>
- Klinzing, J. G., Niethard, N., & Born, J. (2019). Mechanisms of systems memory consolidation during sleep. *Nature Neuroscience*, 22(10), 1598–1610. <https://doi.org/10.1038/s41593-019-0467-3>

- Knights, E., Morcom, A. M., & Henson, R. N. (2021). Does Hemispheric Asymmetry Reduction in Older Adults in Motor Cortex Reflect Compensation? *The Journal of Neuroscience*, 41(45), 9361–9373. <https://doi.org/10.1523/JNEUROSCI.1111-21.2021>
- Koen, J. D., & Rugg, M. D. (2019). Neural Dedifferentiation in the Aging Brain. *Trends in Cognitive Sciences*, 23(7), 547–559. <https://doi.org/10.1016/j.tics.2019.04.012>
- Koen, J. D., & Yonelinas, A. P. (2014). The Effects of Healthy Aging, Amnesic Mild Cognitive Impairment, and Alzheimer's Disease on Recollection and Familiarity: A Meta-Analytic Review. *Neuropsychology Review*, 24(3), 332–354. <https://doi.org/10.1007/s11065-014-9266-5>
- Kokošová, V., Filip, P., Kec, D., & Baláž, M. (2021). Bidirectional Association Between Sleep and Brain Atrophy in Aging. *Frontiers in Aging Neuroscience*, 13. <https://doi.org/10.3389/fnagi.2021.726662>
- Kondratova, A. A., & Kondratov, R. V. (2012). The circadian clock and pathology of the ageing brain. *Nature Reviews. Neuroscience*, 13(5), 325–335. <https://doi.org/10.1038/nrn3208>
- Korkki, S. M., Richter, F. R., Jeyarathnarajah, P., & Simons, J. S. (2020). Healthy ageing reduces the precision of episodic memory retrieval. *Psychology and Aging*, 35(1), 124–142. <https://doi.org/10.1037/pag0000432>
- Kramer, J. H., Schuff, N., Reed, B. R., Mungas, D., Du, A.-T., Rosen, H. J., Jagust, W. J., Miller, B. L., Weiner, M. W., & Chui, H. C. (2004). Hippocampal volume and retention in Alzheimer's disease. *Journal of the International Neuropsychological Society*, 10(4), 639–643. <https://doi.org/10.1017/S1355617704104050>
- Kräuchi, K. (2002). How is the circadian rhythm of core body temperature regulated? *Clinical Autonomic Research*, 12(3), 147–149. <https://doi.org/10.1007/s10286-002-0043-9>
- Kräuchi, K. (2007a). The human sleep–wake cycle reconsidered from a thermoregulatory point of view. *Physiology & Behavior*, 90(2–3), 236–245. <https://doi.org/10.1016/j.physbeh.2006.09.005>
- Kräuchi, K. (2007b). The thermophysiological cascade leading to sleep initiation in relation to phase of entrainment. *Sleep Medicine Reviews*, 11(6), 439–451. <https://doi.org/10.1016/j.smr.2007.07.001>
- Kräuchi, K. (2010). The interrelationship between sleep regulation and thermoregulation. *Frontiers in Bioscience*, 15(1), 604. <https://doi.org/10.2741/3636>
- Kräuchi, K., Cajochen, C., Pache, M., Flammer, J., & Wirz-Justice, A. (2006). Thermoregulatory effects of melatonin in relation to sleepiness. *Chronobiology International*, 23(1–2), 475–484. <https://doi.org/10.1080/07420520500545854>

- Kräuchi, K., Cajochen, C., Werth, E., & Wirz-Justice, A. (1999). Warm feet promote the rapid onset of sleep. *Nature*, 401(6748), 36–37. <https://doi.org/10.1038/43366>
- Kräuchi, K., Cajochen, C., Werth, E., & Wirz-Justice, A. (2000). Functional link between distal vasodilation and sleep-onset latency? *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 278(3), R741–R748. <https://doi.org/10.1152/ajpregu.2000.278.3.R741>
- Kräuchi, K., Cajochen, C., & Wirz-Justice, A. (1997). A relationship between heat loss and sleepiness: Effects of postural change and melatonin administration. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, 83(1), 134–139. <https://doi.org/10.1152/jappl.1997.83.1.134>
- Kräuchi, K., Cajochen, C., & Wirz-Justice, A. (2005). Thermophysiologic Aspects of the Three-Process-Model of Sleepiness Regulation. *Clinics in Sports Medicine*, 24(2), 287–300. <https://doi.org/10.1016/j.csm.2004.12.009>
- Kräuchi, K., Knoblauch, V., Wirz-Justice, A., & Cajochen, C. (2006). Challenging the sleep homeostat does not influence the thermoregulatory system in men: Evidence from a nap vs. sleep-deprivation study. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 290(4), R1052–R1061. <https://doi.org/10.1152/ajpregu.00381.2005>
- Kräuchi, K., & Wirz-Justice, A. (1994). Circadian rhythm of heat production, heart rate, and skin and core temperature under unmasking conditions in men. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 267(3), R819–R829. <https://doi.org/10.1152/ajpregu.1994.267.3.R819>
- Kräuchi, K., & Wirz-Justice, A. (2001). Circadian Clues to Sleep Onset Mechanisms. *Neuropsychopharmacology*, 25(1), S92–S96. [https://doi.org/10.1016/S0893-133X\(01\)00315-3](https://doi.org/10.1016/S0893-133X(01)00315-3)
- Kudielka, B. M., Buchtal, J., Uhde, A., & Wüst, S. (2007). Circadian cortisol profiles and psychological self-reports in shift workers with and without recent change in the shift rotation system. *Biological Psychology*, 74(1), 92–103. <https://doi.org/10.1016/j.biopsycho.2006.08.008>
- Kumar, D., Kumar, V. M., & Mallick, H. N. (2011). Warm sensitive neurons of the preoptic area regulate ambient temperature related changes in sleep in the rat. *Indian Journal of Physiology and Pharmacology*, 55(3), 262–271.
- Kumar, S., Rai, S., Hsieh, K.-C., McGinty, D., Alam, Md. N., & Szymusiak, R. (2013). Adenosine A2A receptors regulate the activity of sleep regulatory GABAergic neurons in the preoptic hypothalamus. *American*

- Journal of Physiology - Regulatory, Integrative and Comparative Physiology*, 305(1), R31–R41.
<https://doi.org/10.1152/ajpregu.00402.2012>
- Kurth, S., Jenni, O. G., Riedner, B. A., Tononi, G., Carskadon, M. A., & Huber, R. (2010). Characteristics of sleep slow waves in children and adolescents. *Sleep*, 33(4), 475–480.
<https://doi.org/10.1093/sleep/33.4.475>
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). **lmerTest** Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, 82(13). <https://doi.org/10.18637/jss.v082.i13>
- Lack, L., Bailey, M., Lovato, N., & Wright, H. (2009). Chronotype differences in circadian rhythms of temperature, melatonin, and sleepiness as measured in a modified constant routine protocol. *Nature and Science of Sleep*, 1, 1–8. <https://doi.org/10.2147/nss.s6234>
- Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology*, 4. <https://doi.org/10.3389/fpsyg.2013.00863>
- Lamia, K. A., Storch, K.-F., & Weitz, C. J. (2008). Physiological significance of a peripheral tissue circadian clock. *Proceedings of the National Academy of Sciences*, 105(39), 15172–15177.
<https://doi.org/10.1073/pnas.0806717105>
- Landolt, H.-P. (2008). Sleep homeostasis: A role for adenosine in humans? *Biochemical Pharmacology*, 75(11), 2070–2079. <https://doi.org/10.1016/j.bcp.2008.02.024>
- Langner, R., & Eickhoff, S. B. (2013). Sustaining attention to simple tasks: A meta-analytic review of the neural mechanisms of vigilant attention. *Psychological Bulletin*, 139(4), 870–900.
<https://doi.org/10.1037/a0030694>
- Lautenschlager, N. T., Cox, K. L., Flicker, L., Foster, J. K., van Bockxmeer, F. M., Xiao, J., Greenop, K. R., & Almeida, O. P. (2008). Effect of physical activity on cognitive function in older adults at risk for Alzheimer disease: A randomized trial. *JAMA*, 300(9), 1027–1037. <https://doi.org/10.1001/jama.300.9.1027>
- Lazar, A. S., Lazar, Z. I., & Dijk, D. (2015). Circadian regulation of slow waves in human sleep: Topographical aspects. *NeuroImage*, 116, 123–134. <https://doi.org/10.1016/j.neuroimage.2015.05.012>
- Leal, S. L., & Yassa, M. A. (2015). Neurocognitive Aging and the Hippocampus across Species. *Trends in Neurosciences*, 38(12), 800–812. <https://doi.org/10.1016/j.tins.2015.10.003>
- Leclercq, M., & Zimmermann, P. (2014). Chapitre 9. L'évaluation des fonctions attentionnelles. In *Traité de neuropsychologie clinique de l'adulte* (Vol. 2, pp. 143–162). De Boeck Supérieur.
<https://doi.org/10.3917/dbu.seron.2014.01.0143>

- LeDoux, J. E. (2000). Emotion circuits in the brain. *Annual Review of Neuroscience*, 23, 155–184.
<https://doi.org/10.1146/annurev.neuro.23.1.155>
- Leng, Y., Redline, S., Stone, K. L., Ancoli-Israel, S., & Yaffe, K. (2019). Objective napping, cognitive decline, and risk of cognitive impairment in older men. *Alzheimer's & Dementia*, 15(8), 1039–1047.
<https://doi.org/10.1016/j.jalz.2019.04.009>
- Leng, Y., Stone, K., Ancoli-Israel, S., Covinsky, K., & Yaffe, K. (2018). Who Take Naps? Self-Reported and Objectively Measured Napping in Very Old Women. *The Journals of Gerontology: Series A*, 73(3), 374–379. <https://doi.org/10.1093/gerona/glx014>
- Leong, R. L. F., Lo, J. C., & Chee, M. W. L. (2022). Systematic review and meta-analyses on the effects of afternoon napping on cognition. *Sleep Medicine Reviews*, 65, 101666.
<https://doi.org/10.1016/j.smr.2022.101666>
- Lew, C. H., Petersen, C., Neylan, T. C., & Grinberg, L. T. (2021). Tau-driven degeneration of sleep- and wake-regulating neurons in Alzheimer's disease. *Sleep Medicine Reviews*, 60, 101541.
<https://doi.org/10.1016/j.smr.2021.101541>
- Lewandowska, K., Wachowicz, B., Marek, T., Oginska, H., & Fafrowicz, M. (2018). Would you say 'yes' in the evening? Time-of-day effect on response bias in four types of working memory recognition tasks. *Chronobiology International*, 35(1), 80–89. <https://doi.org/10.1080/07420528.2017.1386666>
- Li, J., Cacchione, P. Z., Hodgson, N., Riegel, B., Keenan, B. T., Scharf, M. T., Richards, K. C., & Gooneratne, N. S. (2017). Afternoon Napping and Cognition in Chinese Older Adults: Findings from the China Health and Retirement Longitudinal Study Baseline Assessment. *Journal of the American Geriatrics Society*, 65(2), 373–380. <https://doi.org/10.1111/jgs.14368>
- Li, J., Chang, Y.-P., Riegel, B., Keenan, B. T., Varrasse, M., Pack, A. I., & Gooneratne, N. S. (2018). Intermediate, But Not Extended, Afternoon Naps May Preserve Cognition in Chinese Older Adults. *The Journals of Gerontology: Series A*, 73(3), 360–366. <https://doi.org/10.1093/gerona/glx069>
- Li, J., McPhillips, M. V., Deng, Z., Fan, F., & Spira, A. (2022). Daytime Napping and Cognitive Health in Older Adults: A Systematic Review. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 78(10), 1853–1860. <https://doi.org/10.1093/gerona/glac239>
- Li, J., Vitiello, M. V., & Gooneratne, N. S. (2018). Sleep in Normal Aging. *Sleep Medicine Clinics*, 13(1), 1–11.
<https://doi.org/10.1016/j.jsmc.2017.09.001>

- Li, P., Gao, L., Yu, L., Zheng, X., Ulsa, M. C., Yang, H., Gaba, A., Yaffe, K., Bennett, D. A., Buchman, A. S., Hu, K., & Leng, Y. (2023). Daytime napping and Alzheimer's dementia: A potential bidirectional relationship. *Alzheimer's & Dementia*, 19(1), 158–168. <https://doi.org/10.1002/alz.12636>
- Lim, A. S. P., Ellison, B. A., Wang, J. L., Yu, L., Schneider, J. A., Buchman, A. S., Bennett, D. A., & Saper, C. B. (2014). Sleep is related to neuron numbers in the ventrolateral preoptic/intermediate nucleus in older adults with and without Alzheimer's disease. *Brain*, 137(10), 2847–2861. <https://doi.org/10.1093/brain/awu222>
- Lim, A. S. P., Kowgier, M., Yu, L., Buchman, A. S., & Bennett, D. A. (2013). Sleep Fragmentation and the Risk of Incident Alzheimer's Disease and Cognitive Decline in Older Persons. *Sleep*, 36(7), 1027–1032. <https://doi.org/10.5665/sleep.2802>
- Lim, A. S. P., Yu, L., Costa, M. D., Buchman, A. S., Bennett, D. A., Leurgans, S. E., & Saper, C. B. (2011). Quantification of the Fragmentation of Rest-Activity Patterns in Elderly Individuals Using a State Transition Analysis. *Sleep*, 34(11), 1569–1581. <https://doi.org/10.5665/sleep.1400>
- Lim, A. S. P., Yu, L., Costa, M. D., Leurgans, S. E., Buchman, A. S., Bennett, D. A., & Saper, C. B. (2012). Increased Fragmentation of Rest-Activity Patterns Is Associated With a Characteristic Pattern of Cognitive Impairment in Older Individuals. *Sleep*, 35(5), 633–640. <https://doi.org/10.5665/sleep.1820>
- Lim, J., & Dinges, D. F. (2008). Sleep Deprivation and Vigilant Attention. *Annals of the New York Academy of Sciences*, 1129(1), 305–322. <https://doi.org/10.1196/annals.1417.002>
- Lin, L., Jin, Y., Xiong, M., Wu, S., & Sun, S. (2023). The Protective Power of Cognitive Reserve: Examining White Matter Integrity and Cognitive Function in the Aging Brain for Sustainable Cognitive Health. *Sustainability*, 15(14), Article 14. <https://doi.org/10.3390/su151411336>
- Lindenberger, U. (2014). Human cognitive aging: Corriger la fortune? *Science (New York, N.Y.)*, 346(6209), 572–578. <https://doi.org/10.1126/science.1254403>
- Liu, D., Johnson, H. J., Long, J. D., Magnotta, V. A., & Paulsen, J. S. (2014). The power-proportion method for intracranial volume correction in volumetric imaging analysis. *Frontiers in Neuroscience*, 8. <https://doi.org/10.3389/fnins.2014.00356>
- Lo, E. B. L., Laferriere, L. J. C., Stewart, M. R., Milanovic, M., Kinney, M., Bowie, C. R., & Dringenberg, H. C. (2021). Does Napping Enhance the Consolidation of Clinically Relevant Information? A Comparison of Individuals with Low and Elevated Depressive Symptoms. *Nature and Science of Sleep*, 13, 141–152. <https://doi.org/10.2147/NSS.S297872>

- Lo, J. C., Groeger, J. A., Cheng, G. H., Dijk, D., & Chee, M. W. L. (2016). Self-reported sleep duration and cognitive performance in older adults: A systematic review and meta-analysis. *Sleep Medicine*, 17, 87–98. <https://doi.org/10.1016/j.sleep.2015.08.021>
- Lo, J. C., Groeger, J. A., Santhi, N., Arbon, E. L., Lazar, A. S., Hasan, S., Schantz, M. von, Archer, S. N., & Dijk, D. (2012). Effects of Partial and Acute Total Sleep Deprivation on Performance across Cognitive Domains, Individuals and Circadian Phase. *PLOS ONE*, 7(9), e45987. <https://doi.org/10.1371/journal.pone.0045987>
- Lo, J. C., Ong, J. L., Leong, R. L. F., Gooley, J. J., & Chee, M. W. L. (2016). Cognitive Performance, Sleepiness, and Mood in Partially Sleep Deprived Adolescents: The Need for Sleep Study. *Sleep*, 39(3), 687–698. <https://doi.org/10.5665/sleep.5552>
- Lockhart, S. N., & DeCarli, C. (2014). Structural Imaging Measures of Brain Aging. *Neuropsychology Review*, 24(3), 271–289. <https://doi.org/10.1007/s11065-014-9268-3>
- Long, X., Liao, W., Jiang, C., Liang, D., Qiu, B., & Zhang, L. (2012). Healthy Aging: An Automatic Analysis of Global and Regional Morphological Alterations of Human Brain. *Academic Radiology*, 19(7), 785–793. <https://doi.org/10.1016/j.acra.2012.03.006>
- Longato, E., Garrido, M., Saccardo, D., Montesinos Guevara, C., Mani, A. R., Bolognesi, M., Amodio, P., Facchinetti, A., Sparacino, G., & Montagnese, S. (2017). Expected accuracy of proximal and distal temperature estimated by wireless sensors, in relation to their number and position on the skin. *PLOS ONE*, 12(6), e0180315. <https://doi.org/10.1371/journal.pone.0180315>
- Loock, A., Khan Sullivan, A., Reis, C., Paiva, T., Ghotbi, N., Pilz, L. K., Biller, A. M., Molenda, C., Vuori-Brodowski, M. T., Roenneberg, T., & Winnebeck, E. C. (2021). Validation of the Munich Actimetry Sleep Detection Algorithm for estimating sleep–wake patterns from activity recordings. *Journal of Sleep Research*, 30(6), e13371. <https://doi.org/10.1111/jsr.13371>
- López-Otín, C., Blasco, M. A., Partridge, L., Serrano, M., & Kroemer, G. (2013). The Hallmarks of Aging. *Cell*, 153(6), 1194–1217. <https://doi.org/10.1016/j.cell.2013.05.039>
- Lovato, N., & Lack, L. (2010). The effects of napping on cognitive functioning. In G. A. Kerkhof & H. P. A. van Dongen (Eds), *Progress in Brain Research* (Vol. 185, pp. 155–166). Elsevier. <https://doi.org/10.1016/B978-0-444-53702-7.00009-9>

- Lucas, J. A., Ivnik, R. J., Smith, G. E., Bohac, D. L., Tangalos, E. G., Kokmen, E., Graff-Radford, N. R., & Petersen, R. C. (1998). Normative data for the Mattis Dementia Rating Scale. *Journal of Clinical and Experimental Neuropsychology*, 20(4), 536–547. <https://doi.org/10.1076/jcen.20.4.536.1469>
- Lüdecke, D., Makowski, D., Ben-Shachar, M. S., Patil, I., Højsgaard, S., Wiernik, B. M., Lau, Z. J., Arel-Bundock, V., Girard, J., Maimone, C., Ohlsen, N., Morrison, D. E., & Luchman, J. (2025). *parameters: Processing of Model Parameters* (Version 0.26.0) [Computer software]. <https://cran.r-project.org/web/packages/parameters/index.html>
- Luik, A. I., Zuurbier, L. A., Hofman, A., Van Someren, E. J. W., Ikram, M. A., & Tiemeier, H. (2015). Associations of the 24-h activity rhythm and sleep with cognition: A population-based study of middle-aged and elderly persons. *Sleep Medicine*, 16(7), 850–855. <https://doi.org/10.1016/j.sleep.2015.03.012>
- Luik, A. I., Zuurbier, L. A., Hofman, A., Van Someren, E. J. W., & Tiemeier, H. (2013). Stability and Fragmentation of the Activity Rhythm Across the Sleep-Wake Cycle: The Importance of Age, Lifestyle, and Mental Health. *Chronobiology International*, 30(10), 1223–1230. <https://doi.org/10.3109/07420528.2013.813528>
- Lunsford-Avery, J. R., Engelhard, M. M., Navar, A. M., & Kollins, S. H. (2018). Validation of the Sleep Regularity Index in Older Adults and Associations with Cardiometabolic Risk. *Scientific Reports*, 8(1), 14158. <https://doi.org/10.1038/s41598-018-32402-5>
- Lupien, S. J., McEwen, B. S., Gunnar, M. R., & Heim, C. (2009). Effects of stress throughout the lifespan on the brain, behaviour and cognition. *Nature Reviews. Neuroscience*, 10(6), 434–445. <https://doi.org/10.1038/nrn2639>
- Lupien, S. J., & Wan, N. (2004). Successful ageing: From cell to self. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 359(1449), 1413–1426. <https://doi.org/10.1098/rstb.2004.1516>
- Lushington, K., Greeneklee, H., Veltmeyer, M., Gilbert, S. S., & van den Heuvel, C. (2004). Biofeedback training in hand temperature raising promotes sleep onset in young normals. *J Sleep Res*, 13.
- Lustig, C., Shah, P., Seidler, R., & Reuter-Lorenz, P. A. (2009). Aging, training, and the brain: A review and future directions. *Neuropsychology Review*, 19(4), 504–522. <https://doi.org/10.1007/s11065-009-9119-9>
- Ly, J. Q. M., Gaggioni, G., Chellappa, S. L., Papachilleos, S., Brzozowski, A., Borsu, C., Rosanova, M., Sarasso, S., Middleton, B., Luxen, A., Archer, S. N., Phillips, C., Dijk, D., Maquet, P., Massimini, M., & Vandewalle, G.

- (2016). Circadian regulation of human cortical excitability. *Nature Communications*, 7, 11828. <https://doi.org/10.1038/ncomms11828>
- Macpherson, H. N., White, D. J., Ellis, K. A., Stough, C., Camfield, D., Silberstein, R., & Pipingas, A. (2014). Age-related changes to the neural correlates of working memory which emerge after midlife. *Frontiers in Aging Neuroscience*, 6, 70. <https://doi.org/10.3389/fnagi.2014.00070>
- Mahoney, J. R., Verghese, J., Dumas, K., Wang, C., & Holtzer, R. (2012). The effect of multisensory cues on attention in aging. *Brain Research*, 1472, 63–73. <https://doi.org/10.1016/j.brainres.2012.07.014>
- Maillet, D., & Rajah, M. N. (2013). Association between prefrontal activity and volume change in prefrontal and medial temporal lobes in aging and dementia: A review. *Ageing Research Reviews*, 12(2), 479–489. <https://doi.org/10.1016/j.arr.2012.11.001>
- Mairesse, O., De Valck, E., Quanten, S., Neu, D., Cortoos, A., Pattyn, N., Theuns, P., Cluydts, R., & Hofmans, J. (2014). Sleepiness phenomics: Modeling individual differences in subjective sleepiness profiles. *International Journal of Psychophysiology*, 93(1), 150–161. <https://doi.org/10.1016/j.ijpsycho.2013.03.021>
- Mairesse, O., Hofmans, J., Neu, D., Dinis, A. L., de Oliveira, M., Cluydts, R., & Theuns, P. (2010). *The algebra of sleepiness: Investigating the interaction of homeostatic (S) and circadian (C) processes in sleepiness using linear metrics*.
- Majerus, S. (2010). Les multiples déterminants de la mémoire à court terme verbale: Implications théoriques et évaluatives. *Développements*, 4(1), 5–15. <https://doi.org/10.3917/devel.004.0005>
- Majerus, S. (2014). Chapitre 11. L'évaluation de la mémoire à court terme. In *Traité de neuropsychologie clinique de l'adulte* (Vol. 2, pp. 167–177). De Boeck Supérieur. <https://doi.org/10.3917/dbu.seron.2014.01.0167>
- Majerus, S., Attout, L., D'Argembeau, A., Degueldre, C., Fias, W., Maquet, P., Martinez Perez, T., Stawarczyk, D., Salmon, E., Van Der Linden, M., Phillips, C., & Baetens, E. (2012). Attention Supports Verbal Short-Term Memory via Competition between Dorsal and Ventral Attention Networks. *Cerebral Cortex*, 22(5), 1086–1097. <https://doi.org/10.1093/cercor/bhr174>
- Majerus, S., Cowan, N., Péters, F., Van Calster, L., Phillips, C., & Schrouff, J. (2016). Cross-Modal Decoding of Neural Patterns Associated with Working Memory: Evidence for Attention-Based Accounts of Working Memory. *Cerebral Cortex (New York, N.Y.: 1991)*, 26(1), 166–179. <https://doi.org/10.1093/cercor/bhu189>

- Majerus, S., Péters, F., Bouffier, M., Cowan, N., & Phillips, C. (2018). The Dorsal Attention Network Reflects Both Encoding Load and Top-down Control during Working Memory. *Journal of Cognitive Neuroscience*, 30(2), 144–159. https://doi.org/10.1162/jocn_a_01195
- Mak-McCully, R. A., Deiss, S. R., Rosen, B. Q., Jung, K.-Y., Sejnowski, T. J., Bastuji, H., Rey, M., Cash, S. S., Bazhenov, M., & Halgren, E. (2014). Synchronization of Isolated Downstates (K-Complexes) May Be Caused by Cortically-Induced Disruption of Thalamic Spindling. *PLOS Computational Biology*, 10(9), e1003855. <https://doi.org/10.1371/journal.pcbi.1003855>
- Maldonado, T., Orr, J. M., Goen, J. R. M., & Bernard, J. A. (2020). Age Differences in the Subcomponents of Executive Functioning. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, 75(6), e31–e55. <https://doi.org/10.1093/geronb/gbaa005>
- Manard, M., Bahri, M. A., Salmon, E., & Collette, F. (2016). Relationship between grey matter integrity and executive abilities in aging. *Brain Research*, 1642, 562–580. <https://doi.org/10.1016/j.brainres.2016.04.045>
- Mander, B. A., Rao, V., Lu, B., Saletin, J. M., Lindquist, J. R., Ancoli-Israel, S., Jagust, W., & Walker, M. P. (2013). Prefrontal atrophy, disrupted NREM slow waves and impaired hippocampal-dependent memory in aging. *Nature Neuroscience*, 16(3), 357–364. <https://doi.org/10.1038/nn.3324>
- Mander, B. A., Winer, J. R., Jagust, W. J., & Walker, M. P. (2016). Sleep: A Novel Mechanistic Pathway, Biomarker, and Treatment Target in the Pathology of Alzheimer’s Disease? *Trends in Neurosciences*, 39(8), 552–566. <https://doi.org/10.1016/j.tins.2016.05.002>
- Mander, B. A., Winer, J. R., & Walker, M. P. (2017). Sleep and Human Aging. *Neuron*, 94(1), 19–36. <https://doi.org/10.1016/j.neuron.2017.02.004>
- Marmot, M. (2005). Social determinants of health inequalities. *Lancet (London, England)*, 365(9464), 1099–1104. [https://doi.org/10.1016/S0140-6736\(05\)71146-6](https://doi.org/10.1016/S0140-6736(05)71146-6)
- Martinez-Nicolas, A., Guaita, M., Santamaría, J., Montserrat, J. M., Rol, M. Á., & Madrid, J. A. (2017). Circadian Impairment of Distal Skin Temperature Rhythm in Patients With Sleep-Disordered Breathing: The Effect of CPAP. *Sleep*, 40(6). <https://doi.org/10.1093/sleep/zsx067>
- Martinez-Nicolas, A., Madrid, J. A., García, F. J., Campos, M., Moreno-Casbas, M. T., Almada-Pagán, P. F., Lucas-Sánchez, A., & Rol, M. A. (2018). Circadian monitoring as an aging predictor. *Scientific Reports*, 8(1), 15027. <https://doi.org/10.1038/s41598-018-33195-3>

- Martinez-Nicolas, A., Madrid, J. A., & Rol, M. A. (2014). Day–night contrast as source of health for the human circadian system. *Chronobiology International*, 31(3), 382–393. <https://doi.org/10.3109/07420528.2013.861845>
- Martinez-Nicolas, A., Ortiz-Tudela, E., Rol, M. A., & Madrid, J. A. (2013). Uncovering Different Masking Factors on Wrist Skin Temperature Rhythm in Free-Living Subjects. *PLoS ONE*, 8(4), e61142. <https://doi.org/10.1371/journal.pone.0061142>
- Mattay, V. S., Fera, F., Tessitore, A., Hariri, A. R., Berman, K. F., Das, S., Meyer-Lindenberg, A., Goldberg, T. E., Callicott, J. H., & Weinberger, D. R. (2006). Neurophysiological correlates of age-related changes in working memory capacity. *Neuroscience Letters*, 392(1–2), 32–37. <https://doi.org/10.1016/j.neulet.2005.09.025>
- Mattis, S. (1976). Mental Status Examination of Organic Mental Syndrome in the Elderly Patient. In L. Bellack & T. B. Karusu (Eds), *Geriatric Psychiatry* (pp. 77–121). Grune and Stratton.
- Mayerson, H. S., & Toth, L. A. (1938). Influence of Posture on Skin and Subcutaneous Temperatures. *Experimental Biology and Medicine*, 38(5), 879–881. <https://doi.org/10.3181/00379727-38-10048>
- McCarrey, A. C., An, Y., Kitner-Triolo, M. H., Ferrucci, L., & Resnick, S. M. (2016). Sex differences in cognitive trajectories in clinically normal older adults. *Psychology and Aging*, 31(2), 166–175. <https://doi.org/10.1037/pag0000070>
- McDevitt, E. A., Sattari, N., Duggan, K. A., Cellini, N., Whitehurst, L. N., Perera, C., Reihanabad, N., Granados, S., Hernandez, L., & Mednick, S. C. (2018). The impact of frequent napping and nap practice on sleep-dependent memory in humans. *Scientific Reports*, 8(1), 15053. <https://doi.org/10.1038/s41598-018-33209-0>
- McDonough, I. M., Wong, J. T., & Gallo, D. A. (2013). Age-related differences in prefrontal cortex activity during retrieval monitoring: Testing the compensation and dysfunction accounts. *Cerebral Cortex*, 23(5), 1049–1060. <https://doi.org/10.1093/cercor/bhs064>
- Mednick, S. C. (2024). Is napping in older adults problematic or productive? The answer may lie in the reason they nap. *Sleep*, 47(5), zsae056. <https://doi.org/10.1093/sleep/zsae056>
- Mednick, S., Nakayama, K., & Stickgold, R. (2003). Sleep-dependent learning: A nap is as good as a night. *Nature Neuroscience*, 6(7), 697–698. <https://doi.org/10.1038/nn1078>

- Mella, N., Fagot, D., Renaud, O., Kliegel, M., & De Ribaupierre, A. (2018). Individual Differences in Developmental Change: Quantifying the Amplitude and Heterogeneity in Cognitive Change across Old Age. *Journal of Intelligence*, 6(1), Article 1. <https://doi.org/10.3390/jintelligence6010010>
- Merlino, G., Piani, A., Gigli, G. L., Cancelli, I., Rinaldi, A., Baroselli, A., Serafini, A., Zanchettin, B., & Valente, M. (2010). Daytime sleepiness is associated with dementia and cognitive decline in older Italian adults: A population-based study. *Sleep Medicine*, 11(4), 372–377. <https://doi.org/10.1016/j.sleep.2009.07.018>
- Meyer, N., Harvey, A. G., Lockley, S. W., & Dijk, D. (2022). Circadian rhythms and disorders of the timing of sleep. *Lancet (London, England)*, 400(10357), 1061–1078. [https://doi.org/10.1016/S0140-6736\(22\)00877-7](https://doi.org/10.1016/S0140-6736(22)00877-7)
- Mian, M., Tahiri, J., Habbal, S., Aftan, F., & Reddy, P. H. (2025). The impact of sleep and exercise on brain atrophy in mild cognitive impairment. *Mechanisms of Ageing and Development*, 223, 112023. <https://doi.org/10.1016/j.mad.2024.112023>
- Milner, C., & Cote, K. (2009). Benefits of napping in healthy adults: Rmpact of nap length, time of day, age, and experience with napping. *Journal of Sleep Research*, 18, 272–281. <https://doi.org/10.1111/j.1365-2869.2008.00718.x>
- Milner, C. E., Fogel, S. M., & Cote, K. A. (2006). Habitual napping moderates motor performance improvements following a short daytime nap. *Biological Psychology*, 73(2), 141–156. <https://doi.org/10.1016/j.biopsycho.2006.01.015>
- Minors, D. S., & and Waterhouse, J. M. (1984). The use of Constant Routines in Unmasking the Endogenous Component of Human Circadian Rhythms. *Chronobiology International*, 1(3), 205–216. <https://doi.org/10.3109/07420528409063897>
- Mirino, P., Quagliari, A., Scozia, G., Mercuri, S., Alessi, A., Guariglia, C., Giannini, A. M., Doricchi, F., & Pecchinenda, A. (2024). Role of the dorsolateral prefrontal cortex in processing temporal anomalies retained in working memory. *Frontiers in Behavioral Neuroscience*, 18. <https://doi.org/10.3389/fnbeh.2024.1494227>
- Mitchell, A. S., Sherman, S. M., Sommer, M. A., Mair, R. G., Vertes, R. P., & Chudasama, Y. (2014). Advances in understanding mechanisms of thalamic relays in cognition and behavior. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 34(46), 15340–15346. <https://doi.org/10.1523/JNEUROSCI.3289-14.2014>

- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex 'Frontal Lobe' tasks: A latent variable analysis. *Cognitive Psychology*, 41(1), 49–100. <https://doi.org/10.1006/cogp.1999.0734>
- Miyata, S., Noda, A., Iwamoto, K., Kawano, N., Okuda, M., & Ozaki, N. (2013). Poor sleep quality impairs cognitive performance in older adults. *Journal of Sleep Research*, 22(5), 535–541. <https://doi.org/10.1111/jsr.12054>
- Molloy, C. J., Nugent, S., & Bokde, A. L. W. (2021). Alterations in Diffusion Measures of White Matter Integrity Associated with Healthy Aging. *The Journals of Gerontology: Series A*, 76(6), 945–954. <https://doi.org/10.1093/gerona/glz289>
- Monk, T. H. (2005). Aging human circadian rhythms: Conventional wisdom may not always be right. *Journal of Biological Rhythms*, 20(4), 366–374. <https://doi.org/10.1177/0748730405277378>
- Monk, T. H., Buysse, D. J., Carrier, J., Billy, B. D., & Rose, L. R. (2001). Effects of afternoon 'siesta' naps on sleep, alertness, performance, and circadian rhythms in the elderly. *Sleep*, 24(6), 680–687. <https://doi.org/10.1093/sleep/24.6.680>
- Monk, T. H., Buysse, D. J., Carrier, J., & Kupfer, D. J. (2000). Inducing jet-lag in older people: Directional asymmetry. *Journal of Sleep Research*, 9(2), 101–116. <https://doi.org/10.1046/j.1365-2869.2000.00184.x>
- Montembeault, M., Joubert, S., Doyon, J., Carrier, J., Gagnon, J.-F., Monchi, O., Lungu, O., Belleville, S., & Brambati, S. M. (2012). The impact of aging on gray matter structural covariance networks. *NeuroImage*, 63(2), 754–759. <https://doi.org/10.1016/j.neuroimage.2012.06.052>
- Moon, C., Cole, R. A., Xiao, Q., & Voss, M. W. (2020). 0417 Associations Between Rest-Activity Patterns and Resting-State Networks in Older Adults. *Sleep*, 43(Supplement_1), A159–A160. <https://doi.org/10.1093/sleep/zsaa056.414>
- Morcom, A. M., & Henson, R. N. A. (2018). Increased Prefrontal Activity with Aging Reflects Nonspecific Neural Responses Rather than Compensation. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 38(33), 7303–7313. <https://doi.org/10.1523/JNEUROSCI.1701-17.2018>
- Morris, B. J., Willcox, B. J., & Donlon, T. A. (2019). Genetic and epigenetic regulation of human aging and longevity. *Biochimica et Biophysica Acta - Molecular Basis of Disease*, 1865(7), 1718–1744. <https://doi.org/10.1016/j.bbadis.2018.08.039>

- Morris, C. J., Aeschbach, D., & Scheer, F. A. J. L. (2012). Circadian system, sleep and endocrinology. *Molecular and Cellular Endocrinology*, 349(1), 91–104. <https://doi.org/10.1016/j.mce.2011.09.003>
- Morrison, C., & Oliver, M. D. (2023). Subjective Cognitive Decline Is Associated With Lower Baseline Cognition and Increased Rate of Cognitive Decline. *The Journals of Gerontology: Series B*, 78(4), 573–584. <https://doi.org/10.1093/geronb/gbac178>
- Morrison, R. (2005). *Thinking in Working Memory*.
- Most, E. I. S., Scheltens, P., & Van Someren, E. J. W. (2012). Increased skin temperature in Alzheimer's disease is associated with sleepiness. *Journal of Neural Transmission*, 119(10), 1185–1194. <https://doi.org/10.1007/s00702-012-0864-1>
- Muehlroth, B. E., Sander, M. C., Fandakova, Y., Grandy, T. H., Rasch, B., Shing, Y. L., & Werkle-Bergner, M. (2019). Precise Slow Oscillation–Spindle Coupling Promotes Memory Consolidation in Younger and Older Adults. *Scientific Reports*, 9(1), 1940. <https://doi.org/10.1038/s41598-018-36557-z>
- Müller, M. J., & Haag, A. (2018). The concept of chronotypes and its clinical importance for depressive disorders. *The International Journal of Psychiatry in Medicine*, 53(3), 224–240. <https://doi.org/10.1177/0091217417749787>
- Münch, M. (2014). [Sleep and biological clock in the elderly]. *Therapeutische Umschau. Revue Therapeutique*, 71(11), 657–662. <https://doi.org/10.1024/0040-5930/a000606>
- Münch, M., Knoblauch, V., Blatter, K., Schröder, C., Schnitzler, C., Kräuchi, K., Wirz-Justice, A., & Cajochen, C. (2005). Age-related attenuation of the evening circadian arousal signal in humans. *Neurobiology of Aging*, 26(9), 1307–1319. <https://doi.org/10.1016/j.neurobiolaging.2005.03.004>
- Munro, C. A., Winicki, J. M., Schretlen, D. J., Gower, E. W., Turano, K. A., Muñoz, B., Keay, L., Bandeen-Roche, K., & West, S. K. (2012). Sex differences in cognition in healthy elderly individuals. *Aging, Neuropsychology, and Cognition*, 19(6), 759–768. <https://doi.org/10.1080/13825585.2012.690366>
- Murman, D. L. (2015). The Impact of Age on Cognition. *Seminars in Hearing*, 36(3), 111–121. <https://doi.org/10.1055/s-0035-1555115>
- Musiek, E. S., Bhimasani, M., Zangrilli, M. A., Morris, J. C., Holtzman, D. M., & Ju, Y.-E. S. (2018). Circadian Rest-Activity Pattern Changes in Aging and Preclinical Alzheimer Disease. *JAMA Neurology*, 75(5), 582–590. <https://doi.org/10.1001/jamaneurol.2017.4719>

- Musiek, E. S., & Holtzman, D. M. (2016). Mechanisms linking circadian clocks, sleep, and neurodegeneration. *Science*, 354(6315), 1004–1008. <https://doi.org/10.1126/science.aah4968>
- Muto, V., Jaspar, M., Meyer, C., Kussé, C., Chellappa, S. L., Degueldre, C., Balteau, E., Shaffii-Le Bourdieu, A., Luxen, A., Middleton, B., Archer, S. N., Phillips, C., Collette, F., Vandewalle, G., Dijk, D., & Maquet, P. (2016). Local modulation of human brain responses by circadian rhythmicity and sleep debt. *Science (New York, N.Y.)*, 353(6300), 687–690. <https://doi.org/10.1126/science.aad2993>
- Nagel, I. E., Preuschhof, C., Li, S.-C., Nyberg, L., Bäckman, L., Lindenberger, U., & Heekeren, H. R. (2009). Performance level modulates adult age differences in brain activation during spatial working memory. *Proceedings of the National Academy of Sciences of the United States of America*, 106(52), 22552–22557. <https://doi.org/10.1073/pnas.0908238106>
- Naumczyk, P., Sawicka, A. K., Brzeska, B., Sabisz, A., Jodzio, K., Radkowski, M., Czachowska, K., Winklewski, P. J., Finc, K., Szurowska, E., Demkow, U., & Szarmach, A. (2018). *Cognitive Predictors of Cortical Thickness in Healthy Aging*. 1116, 51–62. https://doi.org/10.1007/5584_2018_265
- Neu, D., Mairesse, O., Newell, J., Verbanck, P., Peigneux, P., & Deliens, G. (2015). Does more sleep matter? Differential effects of NREM- and REM-dominant sleep on sleepiness and vigilance. *Neurophysiologie Clinique/Clinical Neurophysiology*, 45(2), 167–175. <https://doi.org/10.1016/j.neucli.2014.10.004>
- Neubauer, A. C., & Fink, A. (2009). Intelligence and neural efficiency. *Neuroscience and Biobehavioral Reviews*, 33(7), 1004–1023. <https://doi.org/10.1016/j.neubiorev.2009.04.001>
- Newman, A. B., Arnold, A. M., Naydeck, B. L., Fried, L. P., Burke, G. L., Enright, P., Gottdiener, J., Hirsch, C., O’Leary, D., Tracy, R., & for the Cardiovascular Health Study Research Group. (2003). ‘Successful Aging’: Effect of Subclinical Cardiovascular Disease. *Archives of Internal Medicine*, 163(19), 2315–2322. <https://doi.org/10.1001/archinte.163.19.2315>
- Nyberg, L., Dahlin, E., Stigsdotter Neely, A., & Bäckman, L. (2009). Neural correlates of variable working memory load across adult age and skill: Dissociative patterns within the fronto-parietal network. *Scandinavian Journal of Psychology*, 50(1), 41–46. <https://doi.org/10.1111/j.1467-9450.2008.00678.x>
- Nyberg, L., Lövdén, M., Riklund, K., Lindenberger, U., & Bäckman, L. (2012). Memory aging and brain maintenance. *Trends in Cognitive Sciences*, 16(5), 292–305. <https://doi.org/10.1016/j.tics.2012.04.005>

- O'Connell, M. A., & Basak, C. (2018). Effects of task complexity and age-differences on task-related functional connectivity of attentional networks. *Neuropsychologia*, 114, 50–64. <https://doi.org/10.1016/j.neuropsychologia.2018.04.013>
- Oh, H., Habeck, C., Madison, C., & Jagust, W. (2014). Covarying alterations in A β deposition, glucose metabolism, and gray matter volume in cognitively normal elderly. *Human Brain Mapping*, 35(1), 297–308. <https://doi.org/10.1002/hbm.22173>
- Ohayon, M. M., Carskadon, M. A., Guilleminault, C., & Vitiello, M. V. (2004). Meta-Analysis of Quantitative Sleep Parameters From Childhood to Old Age in Healthy Individuals: Developing Normative Sleep Values Across the Human Lifespan. *Sleep*, 27(7), 1255–1273. <https://doi.org/10.1093/sleep/27.7.1255>
- Oken, B. S., Salinsky, M. C., & Elsas, S. M. (2006). Vigilance, alertness, or sustained attention: Physiological basis and measurement. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, 117(9), 1885–1901. <https://doi.org/10.1016/j.clinph.2006.01.017>
- Okuda, M., Noda, A., Mabuchi, S., Iwamoto, K., Banno, M., Miyata, S., Yasuma, F., & Ozaki, N. (2021). Sleep fragmentation and working memory in healthy adults. *Sleep Science (Sao Paulo, Brazil)*, 14(Spec 2), 111–117. <https://doi.org/10.5935/1984-0063.20200088>
- Oosterman, J. M., van Someren, E. J. W., Vogels, R. L. C., Van Harten, B., & Scherder, E. J. A. (2009). Fragmentation of the rest-activity rhythm correlates with age-related cognitive deficits. *Journal of Sleep Research*, 18(1), 129–135. <https://doi.org/10.1111/j.1365-2869.2008.00704.x>
- Ortiz-Tudela, E., Martinez-Nicolas, A., Campos, M., Rol, M. Á., & Madrid, J. A. (2010). A New Integrated Variable Based on Thermometry, Actimetry and Body Position (TAP) to Evaluate Circadian System Status in Humans. *PLOS Computational Biology*, 6(11), e1000996. <https://doi.org/10.1371/journal.pcbi.1000996>
- Overton, M., Skoog, J., Laukka, E. J., Bodin, T. H., Mattsson, A. D., Sjöberg, L., Hofer, S. M., Johansson, L., Kulmala, J., Kivipelto, M., Solomon, A., Skoog, I., Kåreholt, I., & Sindi, S. (2024). Sleep disturbances and change in multiple cognitive domains among older adults: A multicenter study of five Nordic cohorts. *SLEEP*, 47(3), zsad244. <https://doi.org/10.1093/sleep/zsad244>
- Owens, J. F., Buysse, D. J., Hall, M., Kamarck, T. W., Lee, L., Strollo, P. J., Reis, S. E., & Matthews, K. A. (2010). Napping, Nighttime Sleep, and Cardiovascular Risk Factors in Mid-Life Adults. *Journal of Clinical Sleep Medicine*, 06(04), 330–335. <https://doi.org/10.5664/jcsm.27873>

- Owusu, J. T., Rabinowitz, J. A., Tzuang, M., An, Y., Kitner-Triolo, M., Zipunnikov, V., Wu, M. N., Wanigatunga, S. K., Schrack, J. A., Thorpe, R. J., Jr., Simonsick, E. M., Ferrucci, L., Resnick, S. M., & Spira, A. P. (2023). Associations Between Objectively Measured Sleep and Cognition: Main Effects and Interactions With Race in Adults Aged ≥ 50 Years. *The Journals of Gerontology: Series A*, 78(3), 454–462. <https://doi.org/10.1093/gerona/glac180>
- Owusu, J. T., Wennberg, A. M. V., Holingue, C. B., Tzuang, M., Abeson, K. D., & Spira, A. P. (2019). Napping characteristics and cognitive performance in older adults. *International Journal of Geriatric Psychiatry*, 34(1), 87–96. <https://doi.org/10.1002/gps.4991>
- Pandya, S. P. (2019). Meditation Program Enhances Self-efficacy and Resilience of Home-based Caregivers of Older Adults with Alzheimer's: A Five-year Follow-up Study in Two South Asian Cities. *Journal of Gerontological Social Work*, 62(6), 663–681. <https://doi.org/10.1080/01634372.2019.1642278>
- Papatsimpa, C., Schlangen, L. J. M., Smolders, K. C. H. J., Linnartz, J.-P. M. G., & de Kort, Y. a. W. (2021). The interindividual variability of sleep timing and circadian phase in humans is influenced by daytime and evening light conditions. *Scientific Reports*, 11(1), 13709. <https://doi.org/10.1038/s41598-021-92863-z>
- Papp, K. V., Rentz, D. M., Orlovsky, I., Sperling, R. A., & Mormino, E. C. (2017). Optimizing the preclinical Alzheimer's cognitive composite with semantic processing: The PACC5. *Alzheimer's & Dementia (New York, N. Y.)*, 3(4), 668–677. <https://doi.org/10.1016/j.trci.2017.10.004>
- Pappaletta, C., Carrarini, C., Miraglia, F., Vecchio, F., & Rossini, P. M. (2024). Cognitive resilience/reserve: Myth or reality? A review of definitions and measurement methods. *Alzheimer's & Dementia: The Journal of the Alzheimer's Association*, 20(5), 3567–3586. <https://doi.org/10.1002/alz.13744>
- Park, D. C., Polk, T. A., Park, R., Minear, M., Savage, A., & Smith, M. R. (2004). Aging reduces neural specialization in ventral visual cortex. *Proceedings of the National Academy of Sciences*, 101(35), 13091–13095. <https://doi.org/10.1073/pnas.0405148101>
- Park, D. C., & Reuter-Lorenz, P. (2009). The Adaptive Brain: Aging and Neurocognitive Scaffolding. *Annual Review of Psychology*, 60(Volume 60, 2009), 173–196. <https://doi.org/10.1146/annurev.psych.59.103006.093656>
- Park, J., Carp, J., Hebrank, A., Park, D. C., & Polk, T. A. (2010). Neural Specificity Predicts Fluid Processing Ability in Older Adults. *Journal of Neuroscience*, 30(27), 9253–9259. <https://doi.org/10.1523/JNEUROSCI.0853-10.2010>

- Park, J. E., Lee, Y. J., Byun, M. S., Yi, D., Lee, J. H., Jeon, S. Y., Hwang, J. Y., Yoon, H., Choe, Y. M., Kim, Y. K., Shin, S. A., Suk, H. W., & Lee, D. Y. (2021). Differential associations of age and Alzheimer's disease with sleep and rest-activity rhythms across the adult lifespan. *Neurobiology of Aging*, *101*, 141–149. <https://doi.org/10.1016/j.neurobiolaging.2021.01.006>
- Parker, J. L., Appleton, S. L., Melaku, Y. A., D'Rozario, A. L., Wittert, G. A., Martin, S. A., Toson, B., Catcheside, P. G., Lechat, B., Teare, A. J., Adams, R. J., & Vakulin, A. (2022). The association between sleep microarchitecture and cognitive function in middle-aged and older men: A community-based cohort study. *Journal of Clinical Sleep Medicine : JCSM : Official Publication of the American Academy of Sleep Medicine*, *18*(6), 1593–1608. <https://doi.org/10.5664/jcsm.9934>
- Parmeggiani, P. L. (2003). Thermoregulation and sleep. *Frontiers in Bioscience: A Journal and Virtual Library*, *8*, s557-567. <https://doi.org/10.2741/1054>
- Parra, M. A., Abrahams, S., Logie, R. H., Méndez, L. G., Lopera, F., & Della Sala, S. (2010). Visual short-term memory binding deficits in familial Alzheimer's disease. *Brain: A Journal of Neurology*, *133*(9), 2702–2713. <https://doi.org/10.1093/brain/awq148>
- Parra, M., Abrahams, S., Fabi, K., Logie, R., Luzzi, S., & Sala, S. (2009). Short-term memory binding deficits in Alzheimers disease. *Brain : A Journal of Neurology*, *132*, 1057–1066. <https://doi.org/10.1093/brain/awp036>
- Partington, J. E., & Leiter, R. G. (1949). Partington's Pathways Test. *Psychological Service Center Journal*, *1*, 11–20.
- Pascual-Leone, A., & Bartres-Faz, D. (2021). Human Brain Resilience: A Call to Action. *Annals of Neurology*, *90*(3), 336–349. <https://doi.org/10.1002/ana.26157>
- Pataky, T. C. (2012). One-dimensional statistical parametric mapping in Python. *Computer Methods in Biomechanics and Biomedical Engineering*, *15*(3), 295–301. <https://doi.org/10.1080/10255842.2010.527837>
- Pataky, T. C., Vanrenterghem, J., & Robinson, M. A. (2015). Zero- vs. One-dimensional, parametric vs. Non-parametric, and confidence interval vs. Hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. *Journal of Biomechanics*, *48*(7), 1277–1285. <https://doi.org/10.1016/j.jbiomech.2015.02.051>
- Patel, R., Mackay, C. E., Jansen, M. G., Devenyi, G. A., O'Donoghue, M. C., Kivimäki, M., Singh-Manoux, A., Zsoldos, E., Ebmeier, K. P., Chakravarty, M. M., & Suri, S. (2022). Inter- and intra-individual variation

- in brain structural-cognition relationships in aging. *NeuroImage*, 257, 119254.
<https://doi.org/10.1016/j.neuroimage.2022.119254>
- Payer, D., Marshuetz, C., Sutton, B., Hebrank, A., Welsh, R. C., & Park, D. C. (2006). Decreased neural specialization in old adults on a working memory task. *NeuroReport*, 17(5), 487.
<https://doi.org/10.1097/01.wnr.0000209005.40481.31>
- Paz, V., Dashti, H. S., & Garfield, V. (2023). Is there an association between daytime napping, cognitive function, and brain volume? A Mendelian randomization study in the UK Biobank. *Sleep Health: Journal of the National Sleep Foundation*, 9(5), 786–793.
<https://doi.org/10.1016/j.sleh.2023.05.002>
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spat Vis.*, 10(4), 437–442.
- Perani, D., Farsad, M., Ballarini, T., Lubian, F., Malpetti, M., Fracchetti, A., Magnani, G., March, A., & Abutalebi, J. (2017). The impact of bilingualism on brain reserve and metabolic connectivity in Alzheimer's dementia. *Proceedings of the National Academy of Sciences of the United States of America*, 114(7), 1690–1695. <https://doi.org/10.1073/pnas.1610909114>
- Pereira Franco, V. H., Vasquez-Bonilla, A. A., & Sillero-Quintana, M. (2025). Influence of body position on skin temperature, heart rate, and blood pressure in active men. *Journal of Thermal Biology*, 127, 104009.
<https://doi.org/10.1016/j.jtherbio.2024.104009>
- Pergola, G., Ranft, A., Mathias, K., & Suchan, B. (2013). The role of the thalamic nuclei in recognition memory accompanied by recall during encoding and retrieval: An fMRI study. *NeuroImage*, 74, 195–208.
<https://doi.org/10.1016/j.neuroimage.2013.02.017>
- Persson, J., & Nyberg, L. (2006). Altered brain activity in healthy seniors: What does it mean? In A. R. Møller (Ed.), *Progress in Brain Research* (Vol. 157, pp. 45–385). Elsevier. [https://doi.org/10.1016/S0079-6123\(06\)57004-9](https://doi.org/10.1016/S0079-6123(06)57004-9)
- Pertsov, Y., Dong, M. Y., Peich, M.-C., & Husain, M. (2012). Forgetting what was where: The fragility of object-location binding. *PloS One*, 7(10), e48214. <https://doi.org/10.1371/journal.pone.0048214>
- Pertsov, Y., Heider, M., Liang, Y., & Husain, M. (2015). Effects of healthy ageing on precision and binding of object location in visual short term memory. *Psychology and Aging*, 30(1), 26–35.
<https://doi.org/10.1037/a0038396>

- Phillips, A. J. K., Clerx, W. M., O'Brien, C. S., Sano, A., Barger, L. K., Picard, R. W., Lockley, S. W., Klerman, E. B., & Czeisler, C. A. (2017). Irregular sleep/wake patterns are associated with poorer academic performance and delayed circadian and sleep/wake timing. *Scientific Reports*, 7(1), 3216. <https://doi.org/10.1038/s41598-017-03171-4>
- Pilcher, J. J., Michalowski, K. R., & Carrigan, R. D. (2001). The Prevalence of Daytime Napping and Its Relationship to Nighttime Sleep. *Behavioral Medicine*, 27(2), 71–76. <https://doi.org/10.1080/08964280109595773>
- Popa-Wagner, A., Buga, A.-M., Dumitrascu, D. I., Uzoni, A., Thome, J., & Coogan, A. N. (2017). How does healthy aging impact on the circadian clock? *Journal of Neural Transmission*, 124(S1), 89–97. <https://doi.org/10.1007/s00702-015-1424-2>
- Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, 13, 25–42. <https://doi.org/10.1146/annurev.ne.13.030190.000325>
- Potvin, O., Lorrain, D., Forget, H., Dubé, M., Grenier, S., Prévile, M., & Hudon, C. (2012). Sleep Quality and 1-Year Incident Cognitive Impairment in Community-Dwelling Older Adults. *Sleep*, 35(4), 491–499. <https://doi.org/10.5665/sleep.1732>
- Prince, J. B., Davis, H. L., Tan, J., Muller-Townsend, K., Markovic, S., Lewis, D. M. G., Hastie, B., Thompson, M. B., Drummond, P. D., Fujiyama, H., & Sohrabi, H. R. (2024). Cognitive and neuroscientific perspectives of healthy ageing. *Neuroscience and Biobehavioral Reviews*, 161, 105649. <https://doi.org/10.1016/j.neubiorev.2024.105649>
- Puttaert, D., Adam, S., & Peigneux, P. (2019). Subjectively-defined optimal/non-optimal time of day modulates controlled but not automatic retrieval processes in verbal memory. *Journal of Sleep Research*, 28(4), e12798. <https://doi.org/10.1111/jsr.12798>
- R Core Team. (2020). *R: A language and environment for statistical computing* (No. 3.6.3; p. R.). R Foundation for Statistical Computing.
- Rahman, S. A., Gathungu, R. M., Marur, V. R., St. Hilaire, M. A., Scheuermaier, K., Belenky, M., Struble, J. S., Czeisler, C. A., Lockley, S. W., Klerman, E. B., Duffy, J. F., & Kristal, B. S. (2023). Age-related changes in circadian regulation of the human plasma lipidome. *Communications Biology*, 6(1), 1–14. <https://doi.org/10.1038/s42003-023-05102-8>

- Rajah, M. N., & D'Esposito, M. (2005). Region-specific changes in prefrontal function with age: A review of PET and fMRI studies on working and episodic memory. *Brain*, 128(9), 1964–1983.
<https://doi.org/10.1093/brain/awh608>
- Ramanoël, S., Hoyau, E., Kauffmann, L., Renard, F., Pichat, C., Boudiaf, N., Krainik, A., Jaillard, A., & Baciou, M. (2018). Gray Matter Volume and Cognitive Performance During Normal Aging. A Voxel-Based Morphometry Study. *Frontiers in Aging Neuroscience*, 10, 235.
<https://doi.org/10.3389/fnagi.2018.00235>
- Rasch, B., & Born, J. (2013). About Sleep's Role in Memory. *Physiological Reviews*, 93(2), 681–766.
<https://doi.org/10.1152/physrev.00032.2012>
- Raymann, R. J. E. M., Swaab, D. F., & Van Someren, E. J. W. (2005). Cutaneous warming promotes sleep onset. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 288(6), R1589–R1597. <https://doi.org/10.1152/ajpregu.00492.2004>
- Raymann, R. J. E. M., Swaab, D. F., & Van Someren, E. J. W. (2007). Skin temperature and sleep-onset latency: Changes with age and insomnia. *Physiology & Behavior*, 90(2–3), 257–266.
<https://doi.org/10.1016/j.physbeh.2006.09.008>
- Raz, N., & Lindenberger, U. (2011). Only time will tell: Cross-sectional studies offer no solution to the age–brain–cognition triangle: Comment on Salthouse (2011). *Psychological Bulletin*, 137(5), 790–795.
<https://doi.org/10.1037/a0024503>
- Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., Dahle, C., Gerstorf, D., & Acker, J. D. (2005). Regional brain changes in aging healthy adults: General trends, individual differences and modifiers. *Cerebral Cortex (New York, N.Y.: 1991)*, 15(11), 1676–1689.
<https://doi.org/10.1093/cercor/bhi044>
- Raz, N., & Rodrigue, K. M. (2006). Differential aging of the brain: Patterns, cognitive correlates and modifiers. *Neuroscience and Biobehavioral Reviews*, 30(6), 730–748.
<https://doi.org/10.1016/j.neubiorev.2006.07.001>
- Reagh, Z. M., Noche, J. A., Tustison, N. J., Delisle, D., Murray, E. A., & Yassa, M. A. (2018). Functional Imbalance of Anterolateral Entorhinal Cortex and Hippocampal Dentate/CA3 Underlies Age-Related Object Pattern Separation Deficits. *Neuron*, 97(5), 1187–1198.e4.
<https://doi.org/10.1016/j.neuron.2018.01.039>

- Recordati, G. (2003). A thermodynamic model of the sympathetic and parasympathetic nervous systems. *Autonomic Neuroscience: Basic & Clinical*, 103(1–2), 1–12. [https://doi.org/10.1016/s1566-0702\(02\)00260-6](https://doi.org/10.1016/s1566-0702(02)00260-6)
- Refinetti, R. (2020). Circadian rhythmicity of body temperature and metabolism. *Temperature*, 7(4), 321–362. <https://doi.org/10.1080/23328940.2020.1743605>
- Refinetti, R., & Manaker, M. (1992). The circadian rhythm of body temperature of normal and tau-mutant golden hamsters. *Journal of Thermal Biology*, 17(2), 129–133. [https://doi.org/10.1016/0306-4565\(92\)90011-4](https://doi.org/10.1016/0306-4565(92)90011-4)
- Reichert, C. F., Maire, M., Gabel, V., Viola, A. U., Götz, T., Scheffler, K., Klarhöfer, M., Berthomier, C., Strobel, W., Phillips, C., Salmon, E., Cajochen, C., & Schmidt, C. (2017). Cognitive brain responses during circadian wake-promotion: Evidence for sleep-pressure-dependent hypothalamic activations. *Scientific Reports*, 7(1), Article 1. <https://doi.org/10.1038/s41598-017-05695-1>
- Requier, F., Demnitz-King, H., Whitfield, T., Klimecki, O., Marchant, N., & Collette, F. (2023). The Effect of Meditation-Based Interventions on Patients with Fatigue Symptoms: A Systematic Review and Meta-Analysis. *Psychologica Belgica*, 63. <https://doi.org/10.5334/pb.1182>
- Resnick, S. M., Pham, D. L., Kraut, M. A., Zonderman, A. B., & Davatzikos, C. (2003). Longitudinal magnetic resonance imaging studies of older adults: A shrinking brain. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, 23(8), 3295–3301. <https://doi.org/10.1523/JNEUROSCI.23-08-03295.2003>
- Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive Aging and the Compensation Hypothesis. *Current Directions in Psychological Science*, 17(3), 177–182. <https://doi.org/10.1111/j.1467-8721.2008.00570.x>
- Reuter-Lorenz, P. A., Jonides, J., Smith, E. E., Hartley, A., Miller, A., Marshuetz, C., & Koeppel, R. A. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience*, 12(1), 174–187. <https://doi.org/10.1162/089892900561814>
- Reuter-Lorenz, P. A., Marshuetz, C., Jonides, J., Smith, E. E., Hartley, A., & Koeppel, R. (2001). Neurocognitive ageing of storage and executive processes. *European Journal of Cognitive Psychology*, 13(1–2), 257–278. <https://doi.org/10.1080/09541440125972>

- Reuter-Lorenz, P. A., & Park, D. C. (2010). Human Neuroscience and the Aging Mind: A New Look at Old Problems. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 65B(4), 405–415. <https://doi.org/10.1093/geronb/gbq035>
- Reuter-Lorenz, P. A., & Park, D. C. (2014). How does it STAC up? Revisiting the scaffolding theory of aging and cognition. *Neuropsychology Review*, 24(3), 355–370. <https://doi.org/10.1007/s11065-014-9270-9>
- Reuter-Lorenz, P. A., & Sylvester, C.-Y. C. (2005). The Cognitive Neuroscience of Working Memory and Aging. In *Cognitive neuroscience of aging: Linking cognitive and cerebral aging* (pp. 186–217). Oxford University Press.
- Reyt, M., Deantoni, M., Baillet, M., Lesoinne, A., Laloux, S., Lambot, E., Demeuse, J., Calaprice, C., LeGoff, C., Collette, F., Vandewalle, G., Maquet, P., Muto, V., Hammad, G., & Schmidt, C. (2022). Daytime rest: Association with 24-h rest-activity cycles, circadian timing and cognition in older adults. *Journal of Pineal Research*, 73(3), e12820. <https://doi.org/10.1111/jpi.12820>
- Reyt, M., Dourte, M., DeHaan, S., Deantoni, M., Baillet, M., Lesoinne, A., Laloux, S., Hammad, G., Collette, F., Peigneux, P., Muto, V., Vandewalle, G., Bahri, M. A., Phillips, C., & Schmidt, C. (2025). *Napping alters Functional Brain Responses in the Aged* (p. 2025.06.10.657597). bioRxiv. <https://doi.org/10.1101/2025.06.10.657597>
- Rienäcker, F., Jacobs, H. I. L., Van Heugten, C. M., & Van Gerven, P. W. M. (2018). Practice makes perfect: High performance gains in older adults engaged in selective attention within and across sensory modalities. *Acta Psychologica*, 191, 101–111. <https://doi.org/10.1016/j.actpsy.2018.09.005>
- Rikhye, R. V., Gilra, A., & Halassa, M. M. (2018). Thalamic regulation of switching between cortical representations enables cognitive flexibility. *Nature Neuroscience*, 21(12), 1753–1763. <https://doi.org/10.1038/s41593-018-0269-z>
- Robillard, R., Naismith, S. L., Smith, K. L., Rogers, N. L., White, D., Terpening, Z., Ip, T. K. C., Hermens, D. F., Whitwell, B., Scott, E. M., & Hickie, I. B. (2014). Sleep-Wake Cycle in Young and Older Persons with a Lifetime History of Mood Disorders. *PLoS ONE*, 9(2), e87763. <https://doi.org/10.1371/journal.pone.0087763>
- Roe, J. M., Vidal-Piñeiro, Di., Sneve, M. H., Kompus, K., Greve, D. N., Walhovd, K. B., Fjell, A. M., & Westerhausen, R. (2020). Age-Related Differences in Functional Asymmetry during Memory Retrieval Revisited:

- No Evidence for Contralateral Overactivation or Compensation. *Cerebral Cortex*, 30(3), 1129–1147.
<https://doi.org/10.1093/cercor/bhz153>
- Roenneberg, T., Keller, L. K., Fischer, D., Matera, J. L., Vetter, C., & Winnebeck, E. C. (2015). Human activity and rest in situ. *Methods in Enzymology*, 552, 257–283. <https://doi.org/10.1016/bs.mie.2014.11.028>
- Roenneberg, T., Kuehnle, T., Juda, M., Kantermann, T., Allebrandt, K., Gordijn, M., & Mellow, M. (2007). Epidemiology of the human circadian clock. *Sleep Medicine Reviews*, 11(6), 429–438.
<https://doi.org/10.1016/j.smr.2007.07.005>
- Rogers-Soeder, T. S., Blackwell, T., Yaffe, K., Ancoli-Israel, S., Redline, S., Cauley, J. A., Ensrud, K. E., Paudel, M., Barrett-Connor, E., LeBlanc, E., Stone, K., Lane, N. E., Tranah, G., & Group, for the O. F. in M. S. R. (2018). Rest-Activity Rhythms and Cognitive Decline in Older Men: The Osteoporotic Fractures in Men Sleep Study. *Journal of the American Geriatrics Society*, 66(11), 2136–2143.
<https://doi.org/10.1111/jgs.15555>
- Roh, H. W., Choi, J., Kim, N.-R., Choe, Y. S., Choi, J. W., Cho, S.-M., Seo, S. W., Park, B., Hong, C. H., Yoon, D., Son, S. J., & Kim, E. Y. (2020). Associations of rest-activity patterns with amyloid burden, medial temporal lobe atrophy, and cognitive impairment. *eBioMedicine*, 58.
<https://doi.org/10.1016/j.ebiom.2020.102881>
- Roh, J. H., Jiang, H., Finn, M. B., Stewart, F. R., Mahan, T. E., Cirrito, J. R., Heda, A., Snider, B. J., Li, M., Yanagisawa, M., de Lecea, L., & Holtzman, D. M. (2014). Potential role of orexin and sleep modulation in the pathogenesis of Alzheimer's disease. *Journal of Experimental Medicine*, 211(13), 2487–2496.
<https://doi.org/10.1084/jem.20141788>
- Rönnlund, M., Nyberg, L., Bäckman, L., & Nilsson, L.-G. (2005). Stability, growth, and decline in adult life span development of declarative memory: Cross-sectional and longitudinal data from a population-based study. *Psychology and Aging*, 20(1), 3–18. <https://doi.org/10.1037/0882-7974.20.1.3>
- Rosinvil, T., Bouvier, J., Dubé, J., Lafrenière, A., Bouchard, M., Cyr-Cronier, J., Gosselin, N., Carrier, J., & Lina, J.-M. (2021). Are age and sex effects on sleep slow waves only a matter of electroencephalogram amplitude? *Sleep*, 44(3), zsaa186. <https://doi.org/10.1093/sleep/zsaa186>
- Rothhaas, R., & Chung, S. (2021). Role of the Preoptic Area in Sleep and Thermoregulation. *Frontiers in Neuroscience*, 15, 664781. <https://doi.org/10.3389/fnins.2021.664781>
- Rowe, J. W., & Kahn, R. L. (1987). Human aging: Usual and successful. *Science (New York, N.Y.)*, 237(4811), 143–149. <https://doi.org/10.1126/science.3299702>

- Sadeh, A. (2011). The role and validity of actigraphy in sleep medicine: An update. *Sleep Medicine Reviews*, 15(4), 259–267. <https://doi.org/10.1016/j.smr.2010.10.001>
- Sakurai, T. (2007). The neural circuit of orexin (hypocretin): Maintaining sleep and wakefulness. *Nature Reviews Neuroscience*, 8(3), 171–181. <https://doi.org/10.1038/nrn2092>
- Sala, J. B., & Courtney, S. M. (2009). Flexible working memory representation of the relationship between an object and its location as revealed by interactions with attention. *Attention, Perception & Psychophysics*, 71(7), 1525–1533. <https://doi.org/10.3758/APP.71.7.1525>
- Salat, D. H., Kaye, J. A., & Janowsky, J. S. (1999). Prefrontal Gray and White Matter Volumes in Healthy Aging and Alzheimer Disease. *Archives of Neurology*, 56(3), 338–344. <https://doi.org/10.1001/archneur.56.3.338>
- Salat, D. H., Tuch, D. S., Greve, D. N., van der Kouwe, A. J. W., Hevelone, N. D., Zaleta, A. K., Rosen, B. R., Fischl, B., Corkin, S., Rosas, H. D., & Dale, A. M. (2005). Age-related alterations in white matter microstructure measured by diffusion tensor imaging. *Neurobiology of Aging*, 26(8), 1215–1227. <https://doi.org/10.1016/j.neurobiolaging.2004.09.017>
- Saliasi, E., Geerligs, L., Lorist, M. M., & Maurits, N. M. (2014). Neural Correlates Associated with Successful Working Memory Performance in Older Adults as Revealed by Spatial ICA. *PLoS ONE*, 9(6), e99250. <https://doi.org/10.1371/journal.pone.0099250>
- Salthouse, T. A. (1990). Working memory as a processing resource in cognitive aging. *Developmental Review*, 10(1), 101–124. [https://doi.org/10.1016/0273-2297\(90\)90006-P](https://doi.org/10.1016/0273-2297(90)90006-P)
- Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, 103(3), 403–428. <https://doi.org/10.1037/0033-295x.103.3.403>
- Salthouse, T. A. (2010). Selective review of cognitive aging. *Journal of the International Neuropsychological Society: JINS*, 16(5), 754–760. <https://doi.org/10.1017/S1355617710000706>
- Salthouse, T. A. (2017). Contributions of the Individual Differences Approach to Cognitive Aging. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, 72(1), 7–15. <https://doi.org/10.1093/geronb/gbw069>
- Sanchis-Segura, C., Ibañez-Gual, M. V., Aguirre, N., Cruz-Gómez, Á. J., & Forn, C. (2020). Effects of different intracranial volume correction methods on univariate sex differences in grey matter volume and multivariate sex prediction. *Scientific Reports*, 10(1), 12953. <https://doi.org/10.1038/s41598-020-69361-9>

- Santhi, N., Lazar, A. S., McCabe, P. J., Lo, J. C., Groeger, J. A., & Dijk, D. (2016). Sex differences in the circadian regulation of sleep and waking cognition in humans. *Proceedings of the National Academy of Sciences*, 113(19). <https://doi.org/10.1073/pnas.1521637113>
- Saper, C. B., Chou, T. C., & Scammell, T. E. (2001). The sleep switch: Hypothalamic control of sleep and wakefulness. *Trends in Neurosciences*, 24(12), 726–731. [https://doi.org/10.1016/s0166-2236\(00\)02002-6](https://doi.org/10.1016/s0166-2236(00)02002-6)
- Saper, C. B., & Fuller, P. M. (2017). Wake-sleep circuitry: An overview. *Current Opinion in Neurobiology*, 44, 186–192. <https://doi.org/10.1016/j.conb.2017.03.021>
- Saper, C. B., Fuller, P. M., Pedersen, N. P., Lu, J., & Scammell, T. E. (2010). Sleep state switching. *Neuron*, 68(6), 1023–1042. <https://doi.org/10.1016/j.neuron.2010.11.032>
- Saper, C. B., Scammell, T. E., & Lu, J. (2005). Hypothalamic regulation of sleep and circadian rhythms. *Nature*, 437(7063), 1257–1263. <https://doi.org/10.1038/nature04284>
- Scammell, T. E., Arrigoni, E., & Lipton, J. O. (2017). Neural Circuitry of Wakefulness and Sleep. *Neuron*, 93(4), 747–765. <https://doi.org/10.1016/j.neuron.2017.01.014>
- Schacter, D. L., & Tulving, E. (1994). *Memory Systems 1994*. MIT Press.
- Schaefferbeke, J. M., Gabel, S., Meersmans, K., Luckett, E. S., De Meyer, S., Adamczuk, K., Nelissen, N., Goovaerts, V., Radwan, A., Sunaert, S., Dupont, P., Van Laere, K., & Vandenberghe, R. (2021). Baseline cognition is the best predictor of 4-year cognitive change in cognitively intact older adults. *Alzheimer's Research & Therapy*, 13(1), 75. <https://doi.org/10.1186/s13195-021-00798-4>
- Scharfen, J., Peters, J. M., & Holling, H. (2018). Retest effects in cognitive ability tests: A meta-analysis. *Intelligence*, 67, 44–66. <https://doi.org/10.1016/j.intell.2018.01.003>
- Schiff, N. D. (2008). Central thalamic contributions to arousal regulation and neurological disorders of consciousness. *Annals of the New York Academy of Sciences*, 1129, 105–118. <https://doi.org/10.1196/annals.1417.029>
- Schiff, N. D., & Pfaff, D. W. (2009). Neural Perspectives on Activation and Arousal. In *Handbook of Neuroscience for the Behavioral Sciences*. John Wiley & Sons, Ltd. <https://doi.org/10.1002/9780470478509.neubb001024>
- Schmidt, C., & Collette, F. (2016). Impact of time-of-day and sleep-wake cycles on cognitive performance. *Revue de neuropsychologie*, 8(3), 173–181.

- Schmidt, C., Collette, F., Cajochen, C., & Peigneux, P. (2007). A time to think: Circadian rhythms in human cognition. *Cognitive Neuropsychology*, 24(7), 755–789. <https://doi.org/10.1080/02643290701754158>
- Schmidt, C., Peigneux, P., & Cajochen, C. (2012). Age-Related Changes in Sleep and Circadian Rhythms: Impact on Cognitive Performance and Underlying Neuroanatomical Networks. *Frontiers in Neurology*, 3. <https://doi.org/10.3389/fneur.2012.00118>
- Schmidt, C., Peigneux, P., Cajochen, C., & Collette, F. (2012). Adapting Test Timing to the Sleep-Wake Schedule: Effects on Diurnal Neurobehavioral Performance Changes in Young Evening and Older Morning Chronotypes. *Chronobiology International*, 29(4), 482–490. <https://doi.org/10.3109/07420528.2012.658984>
- Schmolesky, M. T., Wang, Y., Pu, M., & Leventhal, A. G. (2000). Degradation of stimulus selectivity of visual cortical cells in senescent rhesus monkeys. *Nature Neuroscience*, 3(4), 384–390. <https://doi.org/10.1038/73957>
- Schneider-Garces, N. J., Gordon, B. A., Brumback-Peltz, C. R., Shin, E., Lee, Y., Sutton, B. P., Maclin, E. L., Gratton, G., & Fabiani, M. (2010). Span, CRUNCH, and beyond: Working memory capacity and the aging brain. *Journal of Cognitive Neuroscience*, 22(4), 655–669. <https://doi.org/10.1162/jocn.2009.21230>
- Scholtens, R. M., van Munster, B. C., van Kempen, M. F., & de Rooij, S. E. J. A. (2016). Physiological melatonin levels in healthy older people: A systematic review. *Journal of Psychosomatic Research*, 86, 20–27. <https://doi.org/10.1016/j.jpsychores.2016.05.005>
- Schott, J. M. (2025). Lifestyle Interventions to Improve Cognition in Later Life: When Is Enough Enough? *JAMA*. <https://doi.org/10.1001/jama.2025.12500>
- Scullin, M. K. (2013). Sleep, memory, and aging: The link between slow-wave sleep and episodic memory changes from younger to older adults. *Psychology and Aging*, 28(1), 105–114. <https://doi.org/10.1037/a0028830>
- Scullin, M. K., & Bliwise, D. L. (2015). Sleep, Cognition, and Normal Aging: Integrating a Half Century of Multidisciplinary Research. *Perspectives on Psychological Science*, 10(1), 97–137. <https://doi.org/10.1177/1745691614556680>
- Scullin, M. K., Fairley, J., Decker, M. J., & Bliwise, D. L. (2017). The Effects of an Afternoon Nap on Episodic Memory in Young and Older Adults. *Sleep*, 40(5), zsx035. <https://doi.org/10.1093/sleep/zsx035>

- Shekleton, J. A., Rajaratnam, S. M. W., Gooley, J. J., Van Reen, E., Czeisler, C. A., & Lockley, S. W. (2013). Improved Neurobehavioral Performance during the Wake Maintenance Zone. *Journal of Clinical Sleep Medicine : JCSM : Official Publication of the American Academy of Sleep Medicine*, 9(4), 353–362. <https://doi.org/10.5664/jcsm.2588>
- Sherin, J. E., Elmquist, J. K., Torrealba, F., & Saper, C. B. (1998). *Innervation of Histaminergic Tuberonmammillary Neurons by GABAergic and Galaninergic Neurons in the Ventrolateral Preoptic Nucleus of the Rat*.
- Sherin, J. E., Shiromani, P. J., McCarley, R. W., & Saper, C. B. (1996). Activation of ventrolateral preoptic neurons during sleep. *Science (New York, N.Y.)*, 271(5246), 216–219. <https://doi.org/10.1126/science.271.5246.216>
- Sherman, B., Wysham, W., & Pfoh, B. (1985). Age-Related Changes in the Circadian Rhythm of Plasma Cortisol in Man*. *The Journal of Clinical Endocrinology & Metabolism*, 61(3), 439–443. <https://doi.org/10.1210/jcem-61-3-439>
- Shine, J. M., Lewis, L. D., Garrett, D. D., & Hwang, K. (2023). The impact of the human thalamus on brain-wide information processing. *Nature Reviews Neuroscience*, 24(7), 416–430. <https://doi.org/10.1038/s41583-023-00701-0>
- Silva, E. J., Wang, W., Ronda, J. M., Wyatt, J. K., & Duffy, J. F. (2010). Circadian and Wake-Dependent Influences on Subjective Sleepiness, Cognitive Throughput, and Reaction Time Performance in Older and Young Adults. *Sleep*, 33(4), 481–490. <https://doi.org/10.1093/sleep/33.4.481>
- Simmons, S. E., Saxby, B. K., McGlone, F. P., & Jones, D. A. (2008). The effect of passive heating and head cooling on perception, cardiovascular function and cognitive performance in the heat. *European Journal of Applied Physiology*, 104(2), 271–280. <https://doi.org/10.1007/s00421-008-0677-y>
- Skeldon, A. C., Derks, G., & Dijk, D. (2016). Modelling changes in sleep timing and duration across the lifespan: Changes in circadian rhythmicity or sleep homeostasis? *Sleep Medicine Reviews*, 28, 96–107. <https://doi.org/10.1016/j.smr.2015.05.011>
- Słomko, J., & Zalewski, P. (2016). The circadian rhythm of core body temperature (Part I): The use of modern telemetry systems to monitor core body temperature variability. *Polish Hyperbaric Research*, 55(2), 79–83. <https://doi.org/10.1515/phr-2016-0014>
- Soldan, A., Pettigrew, C., Cai, Q., Wang, J., Wang, M.-C., Moghekar, A., Miller, M. I., Albert, M., & BIOCARD Research Team. (2017). Cognitive reserve and long-term change in cognition in aging and

- preclinical Alzheimer's disease. *Neurobiology of Aging*, 60, 164–172. <https://doi.org/10.1016/j.neurobiolaging.2017.09.002>
- Soldan, A., Pettigrew, C., Zhu, Y., Wang, M.-C., Gottesman, R. F., DeCarli, C., Albert, M., & BIOCARD Research Team. (2020). Cognitive reserve and midlife vascular risk: Cognitive and clinical outcomes. *Annals of Clinical and Translational Neurology*, 7(8), 1307–1317. <https://doi.org/10.1002/acn3.51120>
- Solé-Padullés, C., Bartrés-Faz, D., Junqué, C., Vendrell, P., Rami, L., Clemente, I. C., Bosch, B., Villar, A., Bargalló, N., Jurado, M. A., Barrios, M., & Molinuevo, J. L. (2009). Brain structure and function related to cognitive reserve variables in normal aging, mild cognitive impairment and Alzheimer's disease. *Neurobiology of Aging*, 30(7), 1114–1124. <https://doi.org/10.1016/j.neurobiolaging.2007.10.008>
- Soloveva, M. V., Jamadar, S. D., Hughes, M., Velakoulis, D., Poudel, G., & Georgiou-Karistianis, N. (2018). *Compensation Related Utilization of Neural Circuits Hypothesis Model in Response Inhibition in Premanifest Huntington's Disease* (p. 495416). bioRxiv. <https://doi.org/10.1101/495416>
- Song, Y., Blackwell, T., Yaffe, K., Ancoli-Israel, S., Redline, S., Stone, K. L., & Osteoporotic Fractures in Men (MrOS) Study Group. (2015). Relationships between sleep stages and changes in cognitive function in older men: The MrOS Sleep Study. *Sleep*, 38(3), 411–421. <https://doi.org/10.5665/sleep.4500>
- Souabni, M., Souabni, M. J., Hammouda, O., Romdhani, M., Trabelsi, K., Ammar, A., & Driss, T. (2022). Benefits and risks of napping in older adults: A systematic review. *Frontiers in Aging Neuroscience*, 14, 1000707. <https://doi.org/10.3389/fnagi.2022.1000707>
- Sperling, R. A., Rentz, D. M., Johnson, K. A., Karlawish, J., Donohue, M., Salmon, D. P., & Aisen, P. (2014). The A4 study: Stopping AD before symptoms begin? *Science Translational Medicine*, 6(228), 228fs13. <https://doi.org/10.1126/scitranslmed.3007941>
- Spira, A. P., Chen-Edinboro, L. P., Wu, M. N., & Yaffe, K. (2014). Impact of sleep on the risk of cognitive decline and dementia. *Current Opinion in Psychiatry*, 27(6), 478. <https://doi.org/10.1097/YCO.0000000000000106>
- Spira, A. P., Stone, K. L., Redline, S., Ensrud, K. E., Ancoli-Israel, S., Cauley, J. A., & Yaffe, K. (2017). Actigraphic Sleep Duration and Fragmentation in Older Women: Associations With Performance Across Cognitive Domains. *Sleep*, 40(8), zsx073. <https://doi.org/10.1093/sleep/zsx073>
- Squire, L. R. (2004). Memory systems of the brain: A brief history and current perspective. *Neurobiology of Learning and Memory*, 82(3), 171–177. <https://doi.org/10.1016/j.nlm.2004.06.005>

- Stampi, C., Stone, Polly, & Michimori, A. (1995). A new quantitative method for assessing sleepiness: The alpha attenuation test. *Work & Stress*, 9(2-3), 368-376.
<https://doi.org/10.1080/02678379508256574>
- Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, & Computers*, 31(1), 137-149.
- Stark, S. M., Kirwan, C. B., & Stark, C. E. L. (2019). Mnemonic Similarity Task: A Tool for Assessing Hippocampal Integrity. *Trends in Cognitive Sciences*, 23(11), 938-951.
<https://doi.org/10.1016/j.tics.2019.08.003>
- Stark, S. M., Yassa, M. A., Lacy, J. W., & Stark, C. E. L. (2013). A task to assess behavioral pattern separation (BPS) in humans: Data from healthy aging and mild cognitive impairment. *Neuropsychologia*, 51(12), 2442-2449. <https://doi.org/10.1016/j.neuropsychologia.2012.12.014>
- Staub, B., Doignon-Camus, N., Després, O., & Bonnefond, A. (2013). Sustained attention in the elderly: What do we know and what does it tell us about cognitive aging? *Ageing Research Reviews*, 12(2), 459-468. <https://doi.org/10.1016/j.arr.2012.12.001>
- Stern, Y. (2002). What is cognitive reserve? Theory and research application of the reserve concept. *Journal of the International Neuropsychological Society: JINS*, 8(3), 448-460.
- Stern, Y. (2009). Cognitive Reserve. *Neuropsychologia*, 47(10), 2015-2028.
<https://doi.org/10.1016/j.neuropsychologia.2009.03.004>
- Stern, Y., Albert, M., Barnes, C. A., Cabeza, R., Pascual-Leone, A., & Rapp, P. R. (2023). A framework for concepts of reserve and resilience in aging. *Neurobiology of Aging*, 124, 100-103.
<https://doi.org/10.1016/j.neurobiolaging.2022.10.015>
- Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., Ewers, M., Franzmeier, N., Kempermann, G., Kremen, W. S., Okonkwo, O., Scarmeas, N., Soldan, A., Udeh-Momoh, C., Valenzuela, M., Vemuri, P., Vuoksima, E., & the Reserve, Resilience and Protective Factors PIA Empirical Definitions and Conceptual Frameworks Workgroup. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's & Dementia: The Journal of the Alzheimer's Association*, 16(9), 1305-1311.
<https://doi.org/10.1016/j.jalz.2018.07.219>

- Stern, Y., Barnes, C. A., Grady, C., Jones, R. N., & Raz, N. (2019). Brain reserve, cognitive reserve, compensation, and maintenance: Operationalization, validity, and mechanisms of cognitive resilience. *Neurobiology of Aging*, 83, 124–129. <https://doi.org/10.1016/j.neurobiolaging.2019.03.022>
- Sternberg, S. (1966). High-speed scanning in human memory. *Science*, 153(3736), 652–654. <https://doi.org/10.1126/science.153.3736.652>
- Stoykova, R., Matharan, F., Raoux, N., & Amieva, H. (2013). An alternative word-list for the Free and cued selective reminding test (FCSRT): List presentation and reliability study. *Geriatric et Psychologie Neuropsychiatrie Du Vieillissement*, 11, 317–322. <https://doi.org/10.1684/pnv.2013.0416>
- Stoynev, A. G., Ikonov, Ognian C., & Stoynev, N. A. (2022). Suprachiasmatic hypothalamic nuclei (SCN) in regulation of homeostasis: A role beyond circadian control? *Biological Rhythm Research*, 53(8), 1226–1243. <https://doi.org/10.1080/09291016.2021.1920125>
- Strawbridge, W. J., Cohen, R. D., Shema, S. J., & Kaplan, G. A. (1996). Successful Aging: Predictors and Associated Activities. *American Journal of Epidemiology*, 144(2), 135–141. <https://doi.org/10.1093/oxfordjournals.aje.a008900>
- Strogatz, S. H., Beersma, D. G., Enright, J. T., & Gander, P. H. (1987). The mathematical structure of the human sleep-wake cycle. *Journal of Biological Rhythms*, 2(4), 317–329. <https://doi.org/10.1177/074873048700200405>
- Sun, J., Ma, C., Zhao, M., Magnussen, C. G., & Xi, B. (2022). Daytime napping and cardiovascular risk factors, cardiovascular disease, and mortality: A systematic review. *Sleep Medicine Reviews*, 65, 101682. <https://doi.org/10.1016/j.smr.2022.101682>
- Suzuki, L. Y., & Meehan, S. K. (2018). Verbal working memory modulates afferent circuits in motor cortex. *European Journal of Neuroscience*, 48(10), 3117–3125. <https://doi.org/10.1111/ejn.14154>
- Swirsky, L. T., & Spaniol, J. (2020). The effect of motivational incentives on face-name hyper-binding in older adults. *Psychology and Aging*, 35(5), 773–779. <https://doi.org/10.1037/pag0000393>
- Swirsky, L. T., Sparrow, E. P., Sullivan, M. D., Valenzano, S. L., Chowdhury, S., & Spaniol, J. (2023). Age Differences in Motivated Cognition: A Meta-Analysis. *The Journals of Gerontology: Series B*, 78(7), 1169–1181. <https://doi.org/10.1093/geronb/gbad049>
- Taillard, J., Gronfier, C., Bioulac, S., Philip, P., & Sagaspe, P. (2021). Sleep in Normal Aging, Homeostatic and Circadian Regulation and Vulnerability to Sleep Deprivation. *Brain Sciences*, 11(8), 1003. <https://doi.org/10.3390/brainsci11081003>

- Terry, R. D., & Katzman, R. (2001). Life span and synapses: Will there be a primary senile dementia? *Neurobiology of Aging*, 22(3), 347–348; discussion 353–354. [https://doi.org/10.1016/s0197-4580\(00\)00250-5](https://doi.org/10.1016/s0197-4580(00)00250-5)
- Tietzel, A. J., & Lack, L. C. (2002). The recuperative value of brief and ultra-brief naps on alertness and cognitive performance. *Journal of Sleep Research*, 11(3), 213–218. <https://doi.org/10.1046/j.1365-2869.2002.00299.x>
- Timofeev, I., Bazhenov, M., Seigneur, J., & Sejnowski, T. (2012). Neuronal Synchronization and Thalamocortical Rhythms in Sleep, Wake and Epilepsy. In J. L. Noebels, M. Avoli, M. A. Rogawski, R. W. Olsen, & A. V. Delgado-Escueta (Eds), *Jasper's Basic Mechanisms of the Epilepsies* (4th edn). National Center for Biotechnology Information (US). <http://www.ncbi.nlm.nih.gov/books/NBK98144/>
- Toepper, M., Gebhardt, H., Bauer, E., Haberkamp, A., Beblo, T., Gallhofer, B., Driessen, M., & Sammer, G. (2014). The impact of age on load-related dorsolateral prefrontal cortex activation. *Frontiers in Aging Neuroscience*, 6, 9. <https://doi.org/10.3389/fnagi.2014.00009>
- Tromp, D., Dufour, A., Lithfous, S., Pebayle, T., & Després, O. (2015). Episodic memory in normal aging and Alzheimer disease: Insights from imaging and behavioral studies. *Ageing Research Reviews*, 24(Pt B), 232–262. <https://doi.org/10.1016/j.arr.2015.08.006>
- Tsapanou, A., Lee, S., Chapman, S., Mourtzi, N., Habeck, C., & Stern, Y. (2025). Sleep Genetics and Cognitive Changes over Time: The Moderating Effect of Age and the Role of Brain. *Genes*, 16(1), Article 1. <https://doi.org/10.3390/genes16010021>
- Tucker-Drob, E. M. (2011). Neurocognitive functions and everyday functions change together in old age. *Neuropsychology*, 25(3), 368–377. <https://doi.org/10.1037/a0022348>
- Tulving, E. (1972). *Episodic and semantic memory*. <https://awspntest.apa.org/record/1973-08477-007>
- Uttara, B., Singh, A. V., Zamboni, P., & Mahajan, R. T. (2019). Oxidative Stress and Neurodegenerative Diseases: A Review of Upstream and Downstream Antioxidant Therapeutic Options. *Current Neuropharmacology*, 7(1), 65–74. <https://doi.org/10.2174/157015909787602823>
- Vallesi, A., Tronelli, V., Lomi, F., & Pezzetta, R. (2021). Age differences in sustained attention tasks: A meta-analysis. *Psychonomic Bulletin & Review*, 28(6), 1755–1775. <https://doi.org/10.3758/s13423-021-01908-x>

- Vallet, F., Mella, N., Ihle, A., Beaudoin, M., Fagot, D., Ballhausen, N., Baeriswyl, M., Schlemmer, M., Oris, M., Kliegel, M., & Desrichard, O. (2018). Motivation as a Mediator of the Relation Between Cognitive Reserve and Cognitive Performance. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, 75. <https://doi.org/10.1093/geronb/gby144>
- Van Cauter, E., Leproult, R., & Kupfer, D. J. (1996). Effects of gender and age on the levels and circadian rhythmicity of plasma cortisol. *The Journal of Clinical Endocrinology & Metabolism*, 81(7), 2468–2473. <https://doi.org/10.1210/jcem.81.7.8675562>
- Van Cauter, E., Leproult, R., & Plat, L. (2000). Age-Related Changes in Slow Wave Sleep and REM Sleep and Relationship With Growth Hormone and Cortisol Levels in Healthy Men. *JAMA : The Journal of the American Medical Association*, 284, 861–868. <https://doi.org/10.1001/jama.284.7.861>
- Van der Linden, M. (2014). Chapitre 15. L'évaluation de la mémoire épisodique, autobiographique et prospective. In *Traité de neuropsychologie clinique de l'adulte* (Vol. 2, pp. 211–248). De Boeck Supérieur. <https://doi.org/10.3917/dbu.seron.2014.01.0211>
- Van der Linden, M., Seron, X., & Meulemans, T. (2014). Chapitre 28. L'évaluation des fonctions exécutives. In *Traité de neuropsychologie clinique de l'adulte* (Vol. 2, pp. 461–497). De Boeck Supérieur. <https://doi.org/10.3917/dbu.seron.2014.01.0461>
- Van Dongen, H. P. A., Baynard, M. D., Maislin, G., & Dinges, D. F. (2004). Systematic interindividual differences in neurobehavioral impairment from sleep loss: Evidence of trait-like differential vulnerability. *Sleep*, 27(3), 423–433.
- van Marken Lichtenbelt, W. D., Daanen, H. A. M., Wouters, L., Fronczek, R., Raymann, R. J. E. M., Severens, N. M. W., & Van Someren, E. J. W. (2006). Evaluation of wireless determination of skin temperature using iButtons. *Physiology & Behavior*, 88(4–5), 489–497. <https://doi.org/10.1016/j.physbeh.2006.04.026>
- Van Someren, E. J. (2000). MORE THAN A MARKER: INTERACTION BETWEEN THE CIRCADIAN REGULATION OF TEMPERATURE AND SLEEP, AGE-RELATED CHANGES, AND TREATMENT POSSIBILITIES. *Chronobiology International*, 17(3), 313–354. <https://doi.org/10.1081/CBI-100101050>
- Van Someren, E. J. (2002). Circadian and age-related modulation of thermoreception and temperature regulation: Mechanisms and functional implications. *Ageing Research Reviews*, 1(4), 721–778. [https://doi.org/10.1016/S1568-1637\(02\)00030-2](https://doi.org/10.1016/S1568-1637(02)00030-2)

- Van Someren, E. J. (2007). Thermoregulation and aging. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 292(1), R99–R102.
<https://doi.org/10.1152/ajpregu.00557.2006>
- Van Someren, E. J., Swaab, D. F., Colenda, C. C., Cohen, W., McCall, W. V., & Rosenquist, P. B. (1999). Bright light therapy: Improved sensitivity to its effects on rest-activity rhythms in Alzheimer patients by application of nonparametric methods. *Chronobiology International*, 16(4), 505–518.
<https://doi.org/10.3109/07420529908998724>
- Van Someren EJ, null. (2000). Circadian and sleep disturbances in the elderly. *Experimental Gerontology*, 35(9–10), 1229–1237. [https://doi.org/10.1016/s0531-5565\(00\)00191-1](https://doi.org/10.1016/s0531-5565(00)00191-1)
- Vaportzis, E., Niechcial, M. A., & Gow, A. J. (2019). A systematic literature review and meta-analysis of real-world interventions for cognitive ageing in healthy older adults. *Ageing Research Reviews*, 50, 110–130. <https://doi.org/10.1016/j.arr.2019.01.006>
- Varangis, E., Habeck, C. G., Razlighi, Q. R., & Stern, Y. (2019). The Effect of Aging on Resting State Connectivity of Predefined Networks in the Brain. *Frontiers in Aging Neuroscience*, 11, 234.
<https://doi.org/10.3389/fnagi.2019.00234>
- Vitiello, M. V. (2009). Recent Advances in Understanding Sleep and Sleep Disturbances in Older Adults: Growing Older Does Not Mean Sleeping Poorly. *Current Directions in Psychological Science*, 18(6), 316–320. <https://doi.org/10.1111/j.1467-8721.2009.01659.x>
- von Elm, E., Altman, D. G., Egger, M., Pocock, S. J., Gøtzsche, P. C., Vandenbroucke, J. P., & STROBE Initiative. (2008). The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: Guidelines for reporting observational studies. *Journal of Clinical Epidemiology*, 61(4), 344–349. <https://doi.org/10.1016/j.jclinepi.2007.11.008>
- Von Faber, M., Bootsma–van Der Wiel, A., Van Exel, E., Gussekloo, J., Lagaay, A. M., Van Dongen, E., Knook, D. L., Van Der Geest, S., & Westendorp, R. G. J. (2001). Successful Aging in the Oldest Old: Who Can Be Characterized as Successfully Aged? *Archives of Internal Medicine*, 161(22), 2694.
<https://doi.org/10.1001/archinte.161.22.2694>
- Vyazovskiy, V. V., & Faraguna, U. (2015). Sleep and synaptic homeostasis. *Current Topics in Behavioral Neurosciences*, 25, 91–121. https://doi.org/10.1007/7854_2014_301
- Vyazovskiy, V. V., Olcese, U., Hanlon, E. C., Nir, Y., Cirelli, C., & Tononi, G. (2011). Local sleep in awake rats. *Nature*, 472(7344), 443–447. <https://doi.org/10.1038/nature10009>

- Wahlin, Å., Maitland, S. B., Bäckman, L., & Dixon, R. A. (2003). Interrelations between Subjective Health and Episodic Memory Change in Swedish and Canadian Samples of Older Adults. *The International Journal of Aging and Human Development*, 57(1), 21–35. <https://doi.org/10.2190/9VAA-KMYV-U2HU-PVAW>
- Walker, W. H., Walton, J. C., DeVries, A. C., & Nelson, R. J. (2020). Circadian rhythm disruption and mental health. *Translational Psychiatry*, 10(1), 1–13. <https://doi.org/10.1038/s41398-020-0694-0>
- Walsh, C. M., Blackwell, T., Tranah, G. J., Stone, K. L., Ancoli-Israel, S., Redline, S., Paudel, M., Kramer, J. H., & Yaffe, K. (2014). Weaker Circadian Activity Rhythms are Associated with Poorer Executive Function in Older Women. *Sleep*, 37(12), 2009–2016. <https://doi.org/10.5665/sleep.4260>
- Wang, S. Y., Baker, K. C., Culbreth, J. L., Tracy, O., Arora, M., Liu, T., Morris, S., Collins, M. B., & Wamsley, E. J. (2021). ‘Sleep-dependent’ memory consolidation? Brief periods of post-training rest and sleep provide an equivalent benefit for both declarative and procedural memory. *Learning & Memory*, 28(6), 195–203. <https://doi.org/10.1101/lm.053330.120>
- Waterhouse, J., Fukuda, Y., & Morita, T. (2012). Daily rhythms of the sleep-wake cycle. *Journal of Physiological Anthropology*, 31(1), 5. <https://doi.org/10.1186/1880-6805-31-5>
- Wechsler, D. (1940). THE MEASUREMENT OF ADULT INTELLIGENCE. *The Journal of Nervous and Mental Disease*, 91(4), 548.
- Wechsler, D. (2009). *WISC-V: Technical and interpretive manual*.
- Weinert, D., & Waterhouse, J. (2007). The circadian rhythm of core temperature: Effects of physical activity and aging. *Physiology & Behavior*, 90(2–3), 246–256. <https://doi.org/10.1016/j.physbeh.2006.09.003>
- Weisberg, S., & Fox, J. (2011). An R Companion to Applied Regression. In *Sage*.
- Weiss, M., Milman, B., Rosen, B., Eisenstein, Z., & Zimlichman, R. (1992). Analysis of the Diminished Skin Perfusion in Elderly People by Laser Doppler Flowmetry. *Age and Ageing*, 21(4), 237–241. <https://doi.org/10.1093/ageing/21.4.237>
- Weissová, K., Bartoš, A., Sládek, M., Nováková, M., & Sumová, A. (2016). Moderate changes in the circadian system of Alzheimer’s disease patients detected in their home environment. *PLoS ONE*, 11(1), 1–19. <https://doi.org/10.1371/journal.pone.0146200>

- Welsh, D. K., Takahashi, J. S., & Kay, S. A. (2010). Suprachiasmatic Nucleus: Cell Autonomy and Network Properties. *Annual Review of Physiology*, 72(Volume 72, 2010), 551–577. <https://doi.org/10.1146/annurev-physiol-021909-135919>
- Wen, X., Li, W., Liu, Y., Liu, Z., Zhao, P., Zhu, Z., & Wu, X. (2021). Exploring communication between the thalamus and cognitive control-related functional networks in the cerebral cortex. *Cognitive, Affective & Behavioral Neuroscience*, 21(3), 656–677. <https://doi.org/10.3758/s13415-021-00892-y>
- Werth, E., Dijk, D.-J., Achermann, P., & Borbély, A. A. (1996). Dynamics of the sleep EEG after an early evening nap: Experimental data and simulations. *The American Journal of Physiology*, 271(3 Pt 2), R501–510. <https://doi.org/10.1152/ajpregu.1996.271.3.R501>
- West, N. A., Johnson, D. A., Lutsey, P. L., Mosley, T. H., & Redline, S. (2021). Cognition and 20-year subsequent sleep disturbances. *Sleep Health: Journal of the National Sleep Foundation*, 7(5), 631–637. <https://doi.org/10.1016/j.sleh.2021.01.008>
- West, R., Murphy, K. J., Armilio, M. L., Craik, F. I. M., & Stuss, D. T. (2002). Effects of Time of Day on Age Differences in Working Memory. *The Journals of Gerontology: Series B*, 57(1), P3–P10. <https://doi.org/10.1093/geronb/57.1.P3>
- Westlye, L. T., Walhovd, K. B., Dale, A. M., Bjørnerud, A., Due-Tønnessen, P., Engvig, A., Grydeland, H., Tamnes, C. K., Ostby, Y., & Fjell, A. M. (2010). Life-span changes of the human brain white matter: Diffusion tensor imaging (DTI) and volumetry. *Cerebral Cortex (New York, N.Y.: 1991)*, 20(9), 2055–2068. <https://doi.org/10.1093/cercor/bhp280>
- Wetter, O. E., Wegge, J., Jonas, K., & Schmidt, K.-H. (2012). Dual Goals for Speed and Accuracy on the Same Performance Task. *Journal of Personnel Psychology*, 11(3), 118–126. <https://doi.org/10.1027/1866-5888/a000063>
- Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. <https://cran.r-project.org/web/packages/ggplot2/citation.html>
- Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). *dplyr: A Grammar of Data Manipulation*. <https://dplyr.tidyverse.org/>
- Wickham, H., Vaughan, D., & Girlich, M. (2024). *tidyr: Tidy Messy Data*. <https://tidyr.tidyverse.org/authors.html>

- Wiegand, I., & Sander, M. C. (2019). Cue-related processing accounts for age differences in phasic alerting. *Neurobiology of Aging*, 79, 93–100. <https://doi.org/10.1016/j.neurobiolaging.2019.03.017>
- Williams, H. L., Hammack, J. T., Daly, R. L., Dement, W. C., & Lubin, A. (1964). Responses to auditory stimulation, sleep loss and the EEG stages of sleep. *Electroencephalography and Clinical Neurophysiology*, 16(3), 269–279. [https://doi.org/10.1016/0013-4694\(64\)90109-9](https://doi.org/10.1016/0013-4694(64)90109-9)
- Willoughby, A. R., Alikhani, I., Karsikas, M., Chua, X. Y., & Chee, M. W. L. (2023). Country differences in nocturnal sleep variability: Observations from a large-scale, long-term sleep wearable study. *Sleep Medicine*, 110, 155–165. <https://doi.org/10.1016/j.sleep.2023.08.010>
- Winer, J. R., Mander, B. A., Kumar, S., Reed, M., Baker, S. L., Jagust, W. J., & Walker, M. P. (2020). Sleep Disturbance Forecasts β -Amyloid Accumulation across Subsequent Years. *Current Biology: CB*, 30(21), 4291–4298.e3. <https://doi.org/10.1016/j.cub.2020.08.017>
- Witting, W., Kwa, I. H., Eikelenboom, P., Mirmiran, M., & Swaab, D. F. (1990). Alterations in the circadian rest-activity rhythm in aging and Alzheimer's disease. *Biological Psychiatry*, 27(6), 563–572. [https://doi.org/10.1016/0006-3223\(90\)90523-5](https://doi.org/10.1016/0006-3223(90)90523-5)
- Wobbrock, J. O., Findlater, L., Gergle, D., & Higgins, J. J. (2011). The aligned rank transform for nonparametric factorial analyses using only anova procedures. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 143–146. <https://doi.org/10.1145/1978942.1978963>
- Wong, C. G., Jeffers, S. L., Bell, S. A., Caldwell, J. Z. K., Banks, S. J., & Miller, J. B. (2022). Story Memory Impairment Rates and Association with Hippocampal Volumes in a Memory Clinic Population. *Journal of the International Neuropsychological Society*, 28(6), 611–619. <https://doi.org/10.1017/S1355617721000850>
- Wood, J. N. (2011). When do spatial and visual working memory interact? *Attention, Perception, & Psychophysics*, 73(2), 420–439. <https://doi.org/10.3758/s13414-010-0048-8>
- Wright, K. P., Hull, J. T., & Czeisler, C. A. (2002). Relationship between alertness, performance, and body temperature in humans. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 283(6), R1370–R1377. <https://doi.org/10.1152/ajpregu.00205.2002>
- Wyatt, J., Dijk, D., Cecco, A., Ronda, J., & Czeisler, C. (2006). Sleep-facilitating effect of exogenous melatonin in healthy young men and women is circadian dependent. *Sleep*, 29, 609–618. <https://doi.org/10.1093/sleep/29.5.609>

- Wyatt, J. K., Ritz-De Cecco, A., Czeisler, C. A., & Dijk, D.-J. (1999). Circadian temperature and melatonin rhythms, sleep, and neurobehavioral function in humans living on a 20-h day. *The American Journal of Physiology*, 277(4 Pt 2), R1152-1163. <https://doi.org/10.1152/ajpregu.1999.277.4.r1152>
- Xin, C., Zhang, B., Fang, S., & Zhou, J. (2020). Daytime napping and successful aging among older adults in China: A cross-sectional study. *BMC Geriatrics*, 20(1), 2. <https://doi.org/10.1186/s12877-019-1408-4>
- Xu, K., Liu, Y., Zhan, Y., Ren, J., & Jiang, T. (2018). BRANT: A Versatile and Extendable Resting-State fMRI Toolkit. *Frontiers in Neuroinformatics*, 12(September), 1–13. <https://doi.org/10.3389/fninf.2018.00052>
- Xu, X., Lin, L., Wu, S., & Sun, S. (2023). Exploring Successful Cognitive Aging: Insights Regarding Brain Structure, Function, and Demographics. *Brain Sciences*, 13(12), Article 12. <https://doi.org/10.3390/brainsci13121651>
- Yetish, G., Kaplan, H., Gurven, M., Wood, B., Pontzer, H., Manger, P. R., Wilson, C., McGregor, R., & Siegel, J. M. (2015). Natural sleep and its seasonal variations in three pre-industrial societies. *Current Biology: CB*, 25(21), 2862–2868. <https://doi.org/10.1016/j.cub.2015.09.046>
- Yoon, I.-Y., Kripke, D. F., Youngstedt, S. D., & Elliott, J. A. (2003). Actigraphy suggests age-related differences in napping and nocturnal sleep. *Journal of Sleep Research*, 12(2), 87–93. <https://doi.org/10.1046/j.1365-2869.2003.00345.x>
- Yousefzadehfard, Y., Wechsler, B., & DeLorenzo, C. (2022). Human circadian rhythm studies: Practical guidelines for inclusion/exclusion criteria and protocol. *Neurobiology of Sleep and Circadian Rhythms*, 13, 100080. <https://doi.org/10.1016/j.nbscr.2022.100080>
- Yushkevich, P., Amaral, R., Augustinack, J., Bender, A., Bernstein, J., Boccardi, M., Bocchetta, M., Burggren, A., Carr, V., Chakravarty, M., Chételat, G., Daugherty, A., Davachi, L., Ding, S.-L., Ekstrom, A., Geerlings, M., Hassan, A., Iglesias, J., La Joie, R., & (HSG, for. (2015). Quantitative Comparison of 21 Protocols for Labeling Hippocampal Subfields and Parahippocampal Subregions in In Vivo MRI: Towards a Harmonized Segmentation Protocol. *NeuroImage*, 111. <https://doi.org/10.1016/j.neuroimage.2015.01.004>
- Zaregarizi, M., Edwards, B., George, K., Harrison, Y., Jones, H., & Atkinson, G. (2007). Acute changes in cardiovascular function during the onset period of daytime sleep: Comparison to lying awake and

- standing. *Journal of Applied Physiology*, 103(4), 1332–1338.
<https://doi.org/10.1152/japplphysiol.00474.2007>
- Zeitzer, J., Lopez-Rodriguez, F., Behnke, E., Ackerson, L., Fried, I., Engel, J., & Wilson, C. (2001). Serotonin and dopamine in the human cortex and limbic system during a 40h sleep deprivation challenge. *Sleep*, 24, A76–A76.
- Zeitzer, J. M., Blackwell, T., Hoffman, A. R., Cummings, S., Ancoli-Israel, S., Stone, K., & Osteoporotic Fractures in Men (MrOS) Study Research Group. (2018). Daily Patterns of Accelerometer Activity Predict Changes in Sleep, Cognition, and Mortality in Older Men. *The Journals of Gerontology: Series A*, 73(5), 682–687. <https://doi.org/10.1093/gerona/glw250>
- Zhang, L., Chen, C., Zhang, H., & Peng, B. (2023). Longitudinal associations between daytime napping and cognitive function in Chinese older adults. *Archives of Gerontology and Geriatrics*, 107, 104909. <https://doi.org/10.1016/j.archger.2022.104909>
- Zhang, Z., Xiao, X., Ma, W., & Li, J. (2020). Napping in Older Adults: A Review of Current Literature. *Current Sleep Medicine Reports*, 6(3), 129–135. <https://doi.org/10.1007/s40675-020-00183-x>
- Zhao, Z.-Y., Xie, Y., Fu, Y., Yue-Rong, Bogdan, André, & and Touitou, Y. (2002). Aging and the Circadian Rhythm of Melatonin: A Cross-Sectional Study of Chinese Subjects 30–110 Yr of Age. *Chronobiology International*, 19(6), 1171–1182. <https://doi.org/10.1081/CBI-120015958>
- Zhong, G., Wang, Y., Tao, T., Ying, J., & Zhao, Y. (2015). Daytime napping and mortality from all causes, cardiovascular disease, and cancer: A meta-analysis of prospective cohort studies. *Sleep Medicine*, 16(7), 811–819. <https://doi.org/10.1016/j.sleep.2015.01.025>
- Zhu, D., Al Mahmud, A., & Liu, W. (2023). Social connections and participation among people with mild cognitive impairment: Barriers and recommendations. *Frontiers in Psychiatry*, 14, 1188887. <https://doi.org/10.3389/fpsy.2023.1188887>
- Zisapel, N. (2001). Circadian rhythm sleep disorders: Pathophysiology and potential approaches to management. *CNS Drugs*, 15(4), 311–328. <https://doi.org/10.2165/00023210-200115040-00005>
- Zook, N., Davalos, D., DeLosh, E., & Davis, H. (2005). Working memory, inhibition, and fluid intelligence as predictors of performance on Tower of Hanoi and London tasks. *Brain and Cognition*, 56, 286–292. <https://doi.org/10.1016/j.bandc.2004.07.003>
- Zulley, J., & Campbell, S. S. (1984). *Napping behavior during "spontaneous internal desynchronization": Sleep remains in synchrony with body temperature.*

Zuurbier, L. A., Luik, A. I., Hofman, A., Franco, O. H., Van Someren, E. J. W., & Tiemeier, H. (2015). Fragmentation and Stability of Circadian Activity Rhythms Predict Mortality. *American Journal of Epidemiology*, 181(1), 54–63. <https://doi.org/10.1093/aje/kwu245>