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The Neuropsychological and Neurophysiological Signatures of Age-Related Differences in Mind-Wandering

Catherine Nora Moran
B.A. (Hons.), M.Psych.Sc. (NUI), Grad.Dip.Stats. (TCD)
School of Psychology
The University of Dublin, Trinity College

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Supervised by Prof. Paul Dockree (TCD) and Prof. Alan Smeaton (DCU)

Declaration

I, Catherine Nora Moran, declare that this thesis has not been submitted as an exercise for a degree at this or any other university and is entirely my own work.

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Signed,

Catherine Moran

Catherine Nora Moran
March 8th, 2021

I’m fixing a hole where the rain gets in
And stops my mind from wandering
Where it will go
I’m filling the cracks that run through the door
And kept my mind from wandering
Where it will go

- The Beatles, *Fixing a Hole, 1967*

Summary

Our inner mental life is subject to a constant, discursive, dynamically evolving stream of thoughts. Mind-wandering is the mind's default state, occupying up to half of all conscious cogitations, during which our thoughts momentarily stray from the here-and-now of perceptual experience to unrelated, self-generated mental content. Such attentional fluctuations may occur with and without deliberate intention. As a central facet of the human experience, mind-wandering has attracted incremental interdisciplinary research interest over the last decade or so. Despite the quotidian ubiquity of this mental phenomenon, mind-wandering research, particularly as it pertains to healthy ageing, remains exiguous. Although many cognitive abilities decline with advancing age, recent studies have demonstrated a consistent and perhaps, paradoxical finding of reduced mind-wandering propensity with age.

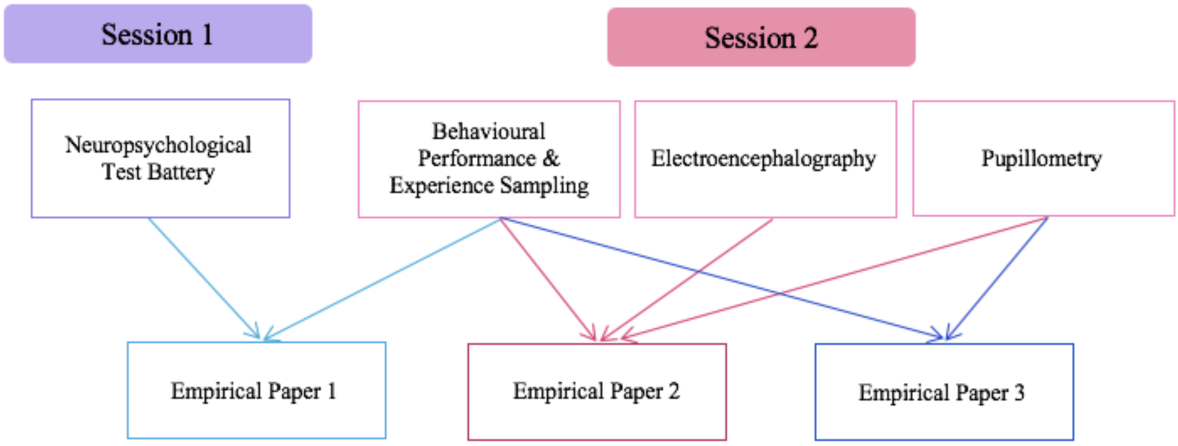
Considering age-related cognitive decline in later life represents a leading cause of disease burden, loss of functional independence, and reduced quality of life, there is a research imperative to explore the impact of age on a broad spectrum of cognitive phenomena. Moreover, considering the possible adaptive and maladaptive corollaries of mind-wandering, the extent to which mind-wandering is disrupted, or influenced, by the natural ageing process is a timely issue. Therefore, the overarching purposes of the present work were two-fold: 1) To examine whether the natural ageing process influences mind-wandering frequency and phenomenology (in an age-comparative design); and 2) To investigate the shared and distinct neuropsychological and neurophysiological signatures of fluctuating attentional states as they unfold over time in younger and older adults.

We employed a multi-faceted methodological approach involving healthy younger (18-35 years of age) and older (65-80 years of age) adult participants. In the first session, participants completed a battery of standardised cognitive and neuropsychological measures. In a second session, participants performed a non-demanding, computerised sustained attention task with built-in experience sampling probes and concurrent electroencephalography and pupillometry recording. Extending traditional research paradigms that utilised tasks with salient, sudden-onset, and predictably occurring targets, our task approach featured elements that circumvented exogenous attention capture and placed greater reliance on endogenous attentional control. The current task, as modified, was therefore well-suited for examining

fluctuating attentional states. Moreover, to overcome methodological challenges for measuring mind-wandering owing to its ephemeral and covert phenomenology, we analysed convergent evidence from subjective, behavioural, electrophysiological, and pupillometric sources. Triangulation was employed to elucidate the neuropsychological and neurophysiological mechanisms underlying mind-wandering, with the capacity to differentiate younger and older adults. The high temporal resolution of these physiological recordings facilitated measurement of the discrete and dissociable neural signals that reflect the transitory shifts that occur between goal-directed thinking and mind-wandering as they unfold in real-time. The manner in which these data were allocated to the three empirical studies presented in the current thesis is summarised in Figure **0.1**.

Figure 0.1

Summary of Data Allocation for the Empirical Papers



Chapter 1 (*Introduction*) presents a comprehensive synthesis of the mind-wandering and ageing literature. It presents a critical review of the fundamental conceptual and methodological issues concerning the definition and measurement of mind-wandering and delineates the advantages and limitations of current methodological approaches. We discuss evolving theoretical frameworks and suggested phenomenological properties and neurocognitive underpinnings of age-related mind-wandering. We identify remaining gaps in the literature and propose the research objectives to be addressed in the current thesis.

Chapter 2 (*Empirical Paper 1*) explored the frequency and phenomenology of mind-wandering as a function of age and examined the neuropsychological variables mediating age-related differences in unintentional and intentional mind-wandering. Our results replicated the finding of an age-related reduction in mind-wandering frequency and demonstrated that unintentional, but not intentional, mind-wandering was predicted by affective and motivational models. Despite evidence of declining executive resources with age, neither cognitive nor task demand variables further contributed to the relationship between age group and mind-wandering propensity.

Further, an age-related behavioural difference in reaction time variability (RTV), a known index of oscillatory attention cycles, was observed and mediated the relationship between intentional mind-wandering and false alarms. Additionally, the large effect size for the age-related reduction in intentional mind-wandering suggests a particular tendency by younger adults to wilfully disengage from the task. Considering the trade-off in competing resources for mind-wandering and task performance, the relative group parity in performance suggests strategic differences in how younger and older adults approached the task.

Together, this study showed that older adults tended to be more focused, less impeded by anxiety, and less mentally restless than younger adults. Notably, older adults appeared to mitigate the negative aspects of cognitive decline and potential performance decrements by increasing motivation and adopting a more efficient exploitative oscillation strategy to suspend the wandering mind when task focus was required. By contrast, younger adults utilised their greater resources to implement a more balanced oscillation strategy. They showed greater explorative tendencies indexed by more frequent mind-wandering (especially intentionally) and more variable performance. Intentional mind-wandering may therefore reflect an adaptive exploratory state that younger adults engage in more frequently without cost. This study showed that distinguishing between the presence, or absence, of intentionality has generated unique insights into age-related mind-wandering that can provide a basis for future research.

Chapter 3 (*Empirical Paper 2*) explored the impact of ageing on the strategic trade-off between competing demands of task focus and mind-wandering, as expressed by the "exploitation/exploration" framework. Neurophysiological measures of endogenous attention revealed age-related reductions in pre-target alpha variability coupled with reduced pre-target mean pupil diameter (PD) and higher post-target PD amplitudes, suggesting steadier attentional engagement with age.

Signal analysis in the pre-probe interval provided support for perceptual decoupling, the process whereby attention is disengaged from sensory input and redirected inward toward self-generated mental content. Specifically, older adults exhibited greater sensory evidence representation (higher mean amplitude for the steady-state visually evoked potential, SSVEP) during focused compared to mind-wandering states. Younger adults displayed greater variability in the SSVEP sensory and alpha attentional signals, as well as higher mean PD amplitudes preceding mind-wandering relative to focused states. As such, younger adults pursued more intermittent sensory encoding and fluctuating attention during mind-wandering. An age-related reduction in alpha variability prior to mind-wandering further supported a less pronounced transition from exploitative to exploratory states by older adults, even when mind-wandering was reported.

Neural indices of perceptual decision formation (centro-parietal positivity (CPP)), sensory evidence encoding (SSVEP), and motor preparation (mu/beta) showed that younger and older participants similarly tracked the exogenously driven feature changes of target evolution over time. Older adults, however, more faithfully tracked the downward trajectory of the visual stimulus (indexed by reduced mean pre-target SSVEP amplitude) and further, demonstrated earlier initiation of sensory evidence accumulation (earlier onset CPP). Against the backdrop of reduced executive resources with age, these findings suggest that older adults employ a more exploitative strategy, attending more consistently to the task. Conversely, younger adults transitioned in and out of an exploratory state more frequently, as corroborated by their increased mind-wandering frequency, and greater variability in evidence encoding and attention. Given that they did not incur relative performance costs, younger adults may have more resources to oscillate between focused and mind-wandering states more optimally.

Chapter 4 (*Empirical Paper 3*) investigated time-on-task changes in momentary attentional fluctuations and deteriorations by examining the temporal evolution of mind-wandering, behavioural performance, and pupil dynamics serially over time for younger and older adults. The task's simplified perceptual requirements meant that performance was relatively non-demanding over shorter timescales but became increasingly challenging over a prolonged duration. Indeed, our task was sensitive to time-on-task performance decrements and showed increased unintentional and intentional mind-wandering frequencies over shorter (within-block) and longer (across-blocks) timescales. Older adults exhibited a linear decrease in self-reported focus across the 8 task blocks, indicating a slow decline in their exploit mode over time. In contrast, younger adults demonstrated a sudden drop after block one, but an absence of subsequent change, signaling that younger adults regulated their exploit/explore ratio more efficiently according to task demands. Further, both groups received a boost in performance and better focus after brief between-block breaks. Following breaks, younger adults exhibited a lower propensity to intentionally mind-wander suggesting that they deliberately explored the mind-wandering space when their task motivation waned by the end of each block. By contrast, older adults remained as focused before and after the break.

Endogenous baseline PD was analysed as a proxy psychophysiological measure of locus coeruleus noradrenaline (LC-NA) neuromodulatory activity, representing one potential mechanism through which brain states may flexibly shift between different serial exploit/explore modes. Pre-target PD was analysed according to the different inter-trial-intervals (ITI), namely 3-, 5-, and 7-seconds. Younger adults gradually reduced their PD as time unfolded before the target (especially at 5 and 7 seconds), dropping out of a relatively exploratory state and returning to an exploitative state just in time. Conversely, older adults demonstrated steadier PD before targets, consistent with their more exploitative approach. Together these behavioural and pupillary findings propound a more explorative oscillation strategy in younger adults, adaptively shifting back-and-forth from the task to competing thoughts more frequently than older adults over distinct timescales. By contrast, older adults marshalled their more limited cognitive resources more predominately toward the task, fixed in an exploit mode and prioritising task-relevant information, to mitigate performance costs.

Chapter 5 (*General Discussion*) concludes this thesis with a critical discussion of the principal findings and contributions, and the theoretical and practical implications, of the present work. We outline outstanding challenges in the field and identify future research directions. Our study is the first, to our knowledge, to concurrently contrast competing theories of age-related mind-wandering to directly compare the relative contributions of dominant models in the field. The research provides new insight into the influence of the natural ageing process on mind-wandering, highlighting the adaptive strategies and positive qualities adopted by older adults leading to a beneficial reduction in mind-wandering and equivalent performance with younger adults, despite evidence of age-related cognitive decline. We suggest that this represents an adaptive quality of successful ageing; namely, older adults suspend

the wandering mind to allay potential costs when the context demands it. Younger adults, on the other hand, explore the mind-wandering space and adaptively oscillate between competing strategies. Together, our research highlights the nature, neuropsychological and neurophysiological correlates, and subcortical contributions to fluctuating and deteriorating attentional states. Our findings provide new insight into how unintentional and intentional mind-wandering processes change with age and over time. Dissecting the mechanisms underlying different attentional processes may provide important indications of successful ageing that inform future interventions.

Dedication

In memory of my uncle and godfather, Prof. Aidan Moran, who inspired me to study psychology.

I ndílchuimhne m’uncail Aidán
Ar dheis Dé go raibh a anam dílis.
1956 – 2020

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Giorraíonn beirt bóthar –

[Two people shorten a road]

Writing this thesis was more challenging and yet more rewarding than I could ever have imagined. My work would be a shadow of itself without the support of so many. First and foremost, I would like to express my profound appreciation to my supervisor, Dr. Paul Dockree, Associate Professor in the School of Psychology, Trinity College Dublin (TCD), whose constant guidance and assistance made this research possible. I benefited inordinately from his mentoring, considered and astute insights, unfaltering sense of direction, and breadth of knowledge and theory. His patience for my lengthy meandering monologues (a trait that undoubtedly inspired my interest in mind-wandering), his kind encouragement, and his supportive and calming manner during times of stress (not least during a global pandemic) made this process feel manageable and enjoyable!

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I must offer a special thanks to our collaborators from the School of Computing, DCU; in particular, Prof. Tomas Ward, Prof. Cathal Gurrin, Brendan O'Neill, and their teams for assisting with the planning of the proposed second phase of this research. Unfortunately, due to COVID-19 and accompanying restrictions, we could not launch the proposed naturalistic field study using wearable sensor technology within the

timeframe of this doctoral research. Nonetheless, the cross-disciplinary collaboration in the development phase was endlessly valuable. I benefited from their shared expertise and multi-perspective discussions of theoretical and methodological issues, experiences that I will take forward.

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An enormous debt of gratitude must go to my family, Dermot, Loretta, Eoin, Hannah, and our dog, Charlie. I am privileged to have grown up in a family of academics who immersed me in a world of curiosity, culture, and learning from an early age. I'd particularly like to thank my dad, Dermot, and late uncle, Aidan, for being model examples of hard work, diligence, and perseverance. Their academic and personal support, unfailing direction, and steadfast reassurance have helped me get to this point. In one of dad's books I was mentioned in his Acknowledgements as being a source of "necessary interruptions and distraction". I think it is fitting, therefore, that I take this opportunity now to thank dad for being *his own* source of necessary interruptions and distraction. I especially thank my sister, Hannah, for being a true friend and lifeline over the years, and for providing many baked goods during the last phase! Finally, I'd also like to mention my younger cousin Kevin – our weekend walks and hot chocolates were such joyous breaks!

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Finally, to my mom, Loretta, my greatest inspiration and favourite person – thank you for everything. I know you are so proud of me.

Katie Moran, TCD, March 2021

List of Publications

Publications Arising from this Thesis

Empirical Paper 1

Moran, C. N., McGovern, D. P., Warren, G., Ó Grálaigh, R., Kenney, J., Smeaton, A., & Dockree, P. M. (2021). Young and restless, old and focused: Age-differences in mind-wandering frequency and phenomenology. *Psychology and Aging.* Advance online publication. DOI: 10.1037/pag0000526.

Empirical Paper 2

Moran, C. N., McGovern, D. P., Melnychuk, M. C., Smeaton, A., & Dockree, P. M. (2021). Characterising the electroencephalographic and pupillometric signatures of mind-wandering in healthy ageing. (In prep.).

Empirical Paper 3

Moran, C. N., Melnychuk, M. C., McGovern, D. P., Smeaton, A., & Dockree, P. M. (2021). Tracking the temporal dynamics of mind-wandering in healthy ageing: converging evidence from experience sampling, behavioural, and pupillometric data. (In prep.).

Published Abstracts Arising from this Thesis

Moran, C., McGovern, D., Warren, G., Ó Grálaigh, R., Kenney, J., Smeaton, A., & Dockree, P. (2019). Age-related differences in the frequency and phenomenology of mind-wandering. Psychological Society of Ireland (PSI) Division of Neuropsychology Symposium, December 2019.

Moran, C., McGovern, D., Warren, G., Ó Grálaigh, R., Kenney, J., Smeaton, A., & Dockree, P. (2019). Age-related differences in the frequency and phenomenology of mind-wandering. British Neuropsychological Society Autumn Meeting, London, UK, November 2019.

Moran, C., McGovern, D., Warren, G., Ó Grálaigh, R., Kenney, J., Smeaton, A., & Dockree, P. (2019). Age-related differences in mind-wandering using triangulation of subjective, behavioural and electrophysiological measures. PSI Annual Conference, Kilkenny, November 2019.

Moran, C., Warren, G., Ó Grálaigh, R., Kenney, J., McGovern, D., Smeaton, A., & Dockree, P. (2019). An empirical investigation of age-related differences in mind-wandering using triangulation of subjective, behavioural and electrophysiological measures. *Brain and Neurosciences Advances, 3,* PS011 (SP). *British Neuroscience Association Festival of Neuroscience,* Dublin, April 2019.

Moran, C., Warren, G., Ó Grálaigh, R., Kenney, J., McGovern, D., Smeaton, A., & Dockree, P. (2019). An empirical investigation of age-related differences in mind-wandering using triangulation of subjective, behavioural and electrophysiological measures. *Journal of Cognitive Neuroscience,* (suppl)*,* C2. *Cognitive Neuroscience Society,* San Francisco, March 2019.

Research in the Media

2021: Featured in TCD News and Events: "Young and restless, old and focused: Age-differences in mind-wandering" [10 Feb 2021].

Related Academic Awards and Grants

2021: Winner of Postgraduate Oral Presentations at the All-Ireland Psychology Student Congress

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2019: Shortlisted for the Psychological Society of Ireland Division of Neuropsychology Early Career Award

2016: Irish Research Council Government of Ireland Postgraduate Research Scholarship [€96,000]

Table of Contents

List of Figures

List of Tables

Abbreviations

ADHD	Attention-Deficit /Hyperactivity Disorder
ANOVA	Analysis of Variance
BF	Bayes Factor
BOLD	Blood-Oxygen-Level-Dependent
CAARS	Connor's Adult ADHD Rating Scale
CI	Confidence Interval
CoV	Coefficient of Variance
COWAT	Controlled Oral Word Association Test
CPP	Centro-Parietal Positivity
CRT	Cathode-Ray Tube
CSD	Current Source Density
DCU	Dublin City University
DMN	Default Mode Network
DSSQ	Dundee Stress State Questionnaire
EEG	Electroencephalography
EOG	Electrooculogram
ERP	Event-Related Potential
ES	Experience Sampling
FFT	Fast Fourier Transformation
FIR	Finite Impulse Response
fMRI	Functional Magnetic Resonance Imaging
GradCCD	Gradual Contrast Change Detection
HADS	Hospital Anxiety and Depression Scale
IQR	Interquartile Range
IRC	Irish Research Council
ITI	Inter-Trial-Intervals
LC	Locus Coeruleus
LHB	Left Hemisphere Beta
M	Mean
MCI	Mild Cognitive Impairment
MoCA	Montreal Cognitive Assessment
MPH	Methylphenidate
MW	Mind-Wandering
N	Number of observations
NA	Noradrenaline
NART	National Adult Reading Test
OA	Older Adults
OCD	Obsessive-Compulsive Disorder
PD	Pupil Diameter
RT	Reaction Time
RTV	Reaction Time Variability
SART	Sustained Attention to Response Task
SD	Standard Deviation
SEM	Standard Error of the Mean

SNR	Signal-to-Noise
SSS	Stanford Sleepiness Scale
SSVEP	Steady-State Visually Evoked Potential
STFT	Short-Time Fourier Transformation
TCD	Trinity College Dublin
TCIN	Trinity College Institute of Neuroscience
tDCS	Transcranial Direct Current Stimulation
TEA	Tests of Everyday Attention
YA	Younger Adult

Chapter 1: Introduction

1.1 Thesis Overview

The workings of human consciousness, in the broadest sense have been an object of considerable study by modern philosophers[*] and psychologists, such as Franz Brentano (himself inspired by Aristotle and Hume), Wilhelm Wundt and his student Edward B. Titchener, William James, Edmund Husserl, and the phenomenological tradition (see Gallagher & Zahavi, 2008), as well as by recent philosophers of mind, such as Daniel C. Dennett (Dennett, 1991) and Thomas Metzinger (Metzinger, 1996). Consciousness has many peculiarities, including the way it presents itself as a transparent, seamless, temporal flow to the first-person experiencing it ("first-personal access"). Nevertheless, it has many complicated parts whose work goes largely unnoticed. Perceptions and imaginings are shaded by memories; fantasies interweave with memories and perceptions; judgments are clouded by emotions, and so on. Feelings, emotions and moods wrap around sensuous or cognitive conscious experience at all times and meld with them. The long tradition of descriptive psychology (e.g. Brentano) and phenomenology (e.g. Husserl) has tried to disentangle this complex stream into its constituent parts, disambiguating currents of experience that sometimes appear seamlessly and fluidly together. Contemporary empirical psychology and cognitive neuroscience continues this work of excavating the contents of conscious processes (what Husserl called the "ABC of consciousness"). In this thesis, I focus on a familiar, ubiquitous, foundational, yet largely under-appreciated phenomenon within our conscious self-experience; namely, mind-wandering.

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[*] Strictly speaking, the concept of "consciousness" is not present as such in Classical Greek philosophy, though they have a notion of "awareness" (*suneidêsis*) or self-awareness that later got translated in the Latin Middle Ages as the notion of "conscience" (as in moral conscience) (Sorabji, 2014). The idea that one has not just perception, emotions and thoughts but that one is aware of those sensations and thoughts in already found in Aristotle's *De Anima*. Aristotle does allow that when we use our senses in perception, there is an accompanying awareness (i.e. *When I see, I am aware that I am seeing*). The modern English word comes from the Latin "con-scientia" — accompanying knowledge or awareness of one's cognitive states. Even Descartes who often discusses the ego and its mental states very rarely uses the term conscientia. However, after Descartes, consciousness becomes a central feature of the human mind.

Mounting interdisciplinary debate and research efforts have centred on defining the nature, and measuring the occurrence, of mind-wandering. This debate has generated numerous important questions for theoretical and empirical enquiry. For instance, does mind-wandering have a proprietary phenomenological character, or can it be reduced to its attentional, cognitive, perceptual, and affective correlates? Is mind-wandering necessarily intuitive, spontaneous, unrestricted, and out of explicit awareness? Can mind-wandering be deliberate, constrained, and under conscious direction? Under what conditions, and by what mechanisms, does mind-wandering manifest? As we age, does our propensity for mind-wandering change? Is mind-wandering consciously penetrable, or do the very acts of introspection and reflective recovery alter the quality of the experience itself? Against this backdrop of pending research curiosities, the overarching purposes of the present study are two-fold:

- Firstly, we explore whether the *frequency* and *phenomenology* (the "what it is like" character) of mind-wandering are influenced by the natural ageing process.
- Secondly, we examine the shared and distinct *neuropsychological and neurophysiological signatures* of different attentional states in healthy younger and older adults.

To set the current research in context, I will begin by providing an overview of the existing state-of-the-art research on mind-wandering.

- Firstly, I will discuss the evolving frameworks for defining and understanding the nature of mind-wandering (§*1.2*).
- Secondly, I will argue that, despite conceptual developments in the field, existing methodologies remain inadequate for empirical investigations of mind-wandering. I will delineate the advantages and limitations of currently used measures (§§*1.3, 1.4*).
- Thirdly, I will critically analyse the research evidences and theoretical models supporting age-related differences in mind-wandering propensities (§*1.5*).
- Fourthly, I will introduce the specific objectives for each empirical chapter in the present thesis (§§*1.6, 1.7)*.

1.2 Current State-of-the-Art on Mind-Wandering

1.2.1 *The Era of the Wandering Mind: History of the Research Problem*

Despite our deep sense of being in the lived presence, our consciousness is only intermittently tethered to the here and now of perceptual experience. The human mind has a natural proclivity to wander. When unconstrained, our thoughts ebb and flow from topic to topic, from the external to the internal, from task to personal concerns, and from the present to the past or future. "*Mind-wandering"* is a member of spontaneous thought phenomena and is broadly defined as a core mental state wherein attention shifts inward from task-related contents, or thoughts cued from the environment, to unrelated or self-generated mental content (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016; Smallwood & Schooler, 2015). As so defined, mind-wandering is a prevalent feature of human cognition, estimated as occupying between 10% and 50% of all conscious cogitations (Kane et al., 2007; Killingsworth & Gilbert, 2010; McVay, Kane, & Kwapil, 2009). Considering the dynamic, universal, and frequently occurring nature of this mental state, it is no surprise that over the past decade or so, mind-wandering has attracted rapidly evolving conceptual and empirical interest. Indeed, this recent proliferation of research activity has been heralded "the era of the wandering mind" (Callard, Smallwood, Golchert, & Margulies, 2013).

Although there is an established research tradition for exploring attentional shifts between externally oriented sources (Desimone & Duncan, 1995; Posner & Petersen, 1990), comparably less is known about how attention redirects from external events to internally oriented endogenously generated mental content. Following influential work on daydreaming in the late nineteen sixties and seventies (Antrobus, Antrobus, & Singer, 1964; Klinger, 1966), there was a shift in the empirical Zeitgeist towards an appreciation of consciousness and internal thought processes as deserving subjects for scientific enquiry. Mind-wandering is a beneficiary of this development and despite initial skepticism and theoretical relegation, there has been an upsurge in scientific consideration from the cognitive psychology and cognitive neuroscience disciplines (e.g. Andrews-Hanna, Irving, Fox, Spreng, & Christoff, 2017; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Smallwood & Schooler, 2006, 2015).

Converging with this growing interest is the acknowledgement that mind-wandering is a pervasive feature of the human condition (Kane et al., 2007; Killingsworth & Gilbert, 2010; McVay et al., 2009) and moreover, displays complex orthogonal interrelationships with attention (McVay & Kane, 2010; Smallwood & Schooler, 2006) and wellbeing (Giambra & Traynor, 1978; Marchetti, Koster, & De Raedt, 2012; Marchetti, Koster, Klinger, & Alloy, 2016). Specifically, the evidence to date suggests that mind-wandering at critical moments is associated with a number of behavioural and functional costs including disruptions to task performance, reading comprehension, and sustained attention (Bastian & Sackur, 2013; Cheyne, Carriere, & Smilek, 2006; Kahmann, Ozuer, Zedelius, & Bijleveld, 2021; McVay & Kane, 2009; Mooneyham & Schooler, 2013; Smallwood, McSpadden, & Schooler, 2008). Mind-wandering is also associated with potentially more far-reaching consequences in daily life; that is, mind-wandering has been implicated as a leading cause of traffic accidents in real and simulated driving contexts for younger adults (Lohani, Payne, & Strayer, 2019; Schmidt, Decke, Rasshofer, & Bullinger, 2017; Yanko & Spalek, 2013). Suboptimal attention and distraction has been identified as a major contributor to traffic accidents and poor driving performance according to the Traffic Safety Culture Index (AAA Foundation for Traffic Safety, 2018). Further, in simulated driving scenarios increased automatisation of driving behaviours borne from route familiarity or monotony led to more hazardous driving in undergraduate student samples (Yanko et al 2013; 2014). Additionally, increased mind-wandering has also been associated with poorer educational and employment outcomes (e.g. Kalechstein, Newton, & van Gorp, 2003; Pachai, Acai, LoGiudice, & Kim, 2016; Seli, Wammes, Risko, & Smilek, 2016), and increased risk of falls in older adults (Nagamatsu, Kam, Liu-Ambrose, Chan, & Handy, 2013; O'Halloran et al., 2011). However, given the high frequency of mind-wandering, it is intuitive that there may also be a number of associated adaptive functions, and in this regard, mind-wandering at opportune moments may espouse a number of benefits, such as for autobiographical planning, problem solving, creative incubation, relief from boredom, and pattern learning (Baird et al., 2012; Mooneyham & Schooler, 2013). These discoveries of purported costs and benefits further bolstered the growing research interest in the nature of mind-wandering.

In parallel, the refinement of investigative approaches further accelerated interest in mind-wandering research. Notable advances include the advent of experience sampling (ES), an approach for eliciting subjective reports on momentary conscious experiences (Csikszentmihalyi & Larson, 1987; Hulburt, 1997), and the increasingly propounded strategy of triangulation, the synchronised use of convergent measures (Schooler & Schreiber, 2004; Varela & Thompson, 2003). Closely allied with these advances was the development of neuroimaging tools including functional magnetic resonance imaging (fMRI) (Ogawa, Lee, Kay, & Tank, 1990) and the consequent discovery of the brain's Default Mode Network (DMN) (Raichle, 2015; Raichle et al., 2001). The dynamics of the DMN have been widely implicated in internally oriented and self-generated spontaneous cognitions (Buckner, Andrews-Hanna, & Schacter, 2008; Fox et al., 2015; Mason et al., 2007), although its precise functionality remains to be clarified (Christoff et al., 2016). Nonetheless, this development was important for spurring research into the neural substrates of different conscious or self-emergent experiences and internal modes of cognition. This confluence of factors laid the foundations for a burgeoning field of mind-wandering investigations.

1.2.2 *Terminological Clarifications*

Mind-wandering is a natural and prominent feature of human cognition, as so far stated. Indeed, the ubiquity of mind-wandering is demonstrated by the vast array of terminologies used to describe the experience embedded within colloquial parlance. We say that we are "distracted", "unfocused", "lost", "inattentive", "absent-minded", "preoccupied", "spacing out", "daydreaming", "staring into space", or "ag siúl leis na sióga" ("away with the fairies"). Perhaps no other conscious experience is as intimately familiar to us, and as foundational to our being, but remains as poorly scientifically understood as mind-wandering.

The variety of everyday names for the phenomenon of mind-wandering is compounded by the sundry competing esoteric terms interchanged within the scientific literature. Terms such as "task-unrelated thought" (Giambra, 1989), "stimulus-independent thought" (Antrobus, Singer, & Greenberg, 1966), and "lapses of attention" (Cheyne et al., 2006) categorise the content and associational nature of mind-wandering by its attentional disengagement from the external environment. Alternative classifications, including "autobiographical thought" and "mind pops" (Kvavilashvili & Mandler, 2004), and "zone-outs" (Schooler, 2002) reflect the generative character of mind-wandering. While terms such as "self-generated thoughts" (Smallwood, 2013) capture the generative and self-referential qualities of mind-wandering - that the experience is both internally oriented and occurs independently of perceptually-guided cues or ongoing actions. The landscape of naming variation demonstrates the convergence of mind-wandering interest across different traditions; still, "mind-wandering" is most commonly conceived and operationalised as an all-inclusive unified term (Murray, Krasich, Schooler, & Seli, 2020), and will be so utilised in this study.

While the term "mind-wandering" is commonly conceived, the lack of a universal consensus on terminology reflects a field of study that remains exiguous. The range of existing terms denotes the challenge of encompassing qualitatively distinct types of spontaneous thought with different phenomenal properties under one portmanteau term. The challenge of setting definitive boundaries for nomenclature is that overly specific terminologies may be too restrictive and exclusive, whereas forgoing specification and consolidating different experiences under the general rubric of "mind-wandering" may be overly inclusive and simplistic (Seli, Kane, et al., 2018). Therefore, an enduring challenge of the field is how best to define mind-wandering, and we shall turn to discuss that now.

1.2.3 *Current Frameworks for Defining Mind-Wandering*

What does it mean to mind-wander? Different frameworks have been proffered to answer this question; most notably, (1) Task Centric and Content-Based (Smallwood & Schooler, 2006, 2015), (2) Dynamic Process (Christoff et al., 2016), and (3) Family-Resemblances (Seli, Kane, et al., 2018) perspectives. Let us critically discuss how mind-wandering is treated by these prominent frameworks.

1.2.3.1 Task-Centric and Content-Based Approaches. Until recently, empirical investigations of mind-wandering have predominantly operated from a *task-centric* or *Content-Based* perspective (Smallwood & Schooler, 2006, 2015). In this approach, mind-wandering is characterised by the content of thoughts in relation to an ongoing activity or environmental referent. Thus, thoughts are typified as being either "perceptually-guided" (i.e. thought contents are derived from extrinsic sources) or "self-generated" (i.e. thought contents arise from intrinsic sources), and as either "task-related" or "task-unrelated". Using this taxonomy, mind-wandering is qualified as task-unrelated self-generated thought. This is the most commonly endorsed approach in the extant literature and has had a salutary impact in facilitating developments in empirical research (Smallwood & Schooler, 2015).

Nonetheless, the relatively narrow scope confining mind-wandering by its task-relatedness fails to account for the processes by which the thoughts are generated or how they unfold over time (Irving, 2016). Additionally, the lack of distinction between task-imposed goals versus self-imposed goals means that self-generated thoughts regarding personal goals during task performance may be misclassified (Christoff et al., 2016). Moreover, from intuition and neuroimaging evidence (e.g. DMN activation during wakeful rest, Mason et al., 2007), we know that mind-wandering may also occur in the absence of any focal task or external stimulation at all (Murray et al., 2020). Therefore, task-centric approaches do not fully exemplify the mind-wandering experience.

1.2.3.2 Dynamic Process Model. A contending *Dynamic Process* model postulated by Christoff and colleagues (2016) attempts to address the dynamics by which thoughts arise, persist, or transition in their understanding of mind-wandering. According to the Dynamic Process perspective, mind-wandering is a core mental state within the species of spontaneous thought phenomena, alongside dreaming, fantasy, and creative imagining. The integral tenet of this framework is that mind-wandering occurs and unfolds relatively freely due to an absence of constraints - deliberate (e.g. cognitive control) or automatic (e.g. affective or sensory salience) - on cognition. In other words, mind-wandering is qualified as unguided, freely moving, and meandering thought (Christoff et al., 2016; see also Irving, 2016). By this framework, the influence of different constraints and resulting dynamics can distinguish mind-wandering from creative thought and from experiences that characterise clinical conditions such as rumination (e.g. in depression, anxiety, and obsessive-compulsive disorder (OCD)) and excessive attentional shifting (e.g. in attention-deficit/hyperactivity disorder (ADHD) or psychosis) (Christoff et al., 2016).

However, this framework is insufficient as the endorsed condition of “absence of constraint” excludes some thoughts that might otherwise be considered mind-wandering. For example, volitional thoughts (e.g. wilfully planning an upcoming holiday while on the bus) are not freely moving and would, hence, be excluded from consideration as mind-wandering. Moreover, there is an inherent contradiction built into the framework itself, that the assumptive condition that mind-wandering must be unconstrained is itself a constraining classification that does not allow for the heterogeneity of mind-wandering experiences (for a similar criticism see Seli, Kane, et al., 2018).

1.2.3.3 Family-Resemblances Framework. Extending previous work, the *Family-Resemblances* framework (Seli, Kane, et al., 2018) aims to synthesise different terminologies and previously espoused definitional frameworks under a multi-dimensional natural-kind conceptual structure. Seli and colleagues argue against a single circumscribed definition of mind-wandering and suggest that different varieties of mind-wandering need not be treated as theoretical competitors. Instead, they propose a parsimonious account of mind-wandering as encompassing heterogenous mind-wandering experiences with unique and overlapping characteristics, or “family-resemblances” (Seli, Kane, et al., 2018). This framework is an adaptation of an idea originally propounded by the philosopher Ludwig Wittgenstein (Wittgenstein, 1953) who claimed that there was no “essence” of what a game is but that games bear family resemblances to each other. This concept was also later developed by psychologist Eleanor Rosch who applied exemplars and prototypes to how we represent knowledge structures (Rosch & Mervis, 1975).

Here, the Family Resemblances framework suggests a graded membership to the “mind-wandering family” with a variety of exemplars or instances of mind-wandering defined by how prototypical they are along three central dimensions. These dimensions include: 1) *task-relatedness*: how the thought relates to the focal task, goal, or context; (2) *intentionality*: whether the thought was engaged in with or without volition; (3) *thought constraint:* how freely evolving or constrained the thought was. Indeed, the utility and separability of these different dimensions has been recently demonstrated (O'Neill, Smith, Smilek, & Seli, 2020). The most prototypical aspects of mind-wandering pertain to task-unrelated (e.g. Smallwood & Schooler, 2015), unintentional (e.g. Seli, Risko, Smilek, & Schacter, 2016), and unconstrained thoughts (e.g. Christoff et al., 2016), but importantly, this framework does not exclude atypical or peripheral cases from consideration as mind-wandering (Seli, Kane, et al., 2018).

Moving beyond previous conceptualisations, this framework facilitates two specific developments. Firstly, it enables consideration of different types of mind-wandering experience, bringing together dimensions from task-centric (i.e. task-relatedness) and Dynamic Process models (i.e. thought constraint). Secondly, it captures the important mind-wandering dimension of intentionality, a facet largely overlooked in the extant literature. Notwithstanding, it should be noted that disputation remains regarding the utility of this approach; for instance, Christoff and colleagues reject this framework as being overly inclusive and therefore, not helpful in delineating mind-wandering from other cognitive phenomena (Christoff et al., 2018).

1.2.3.3.1 *Mind-Wandering Intentionality Dimension.* In support of the aforementioned intentionality dimension, recent research has embraced an operational definition of mind-wandering distinguished by its intentionality. Attentional fluctuations that occur spontaneously (i.e. unintentional mind-wandering) have been dissociated from those that occur more purposefully (i.e. intentional mind-wandering) (Seli, Risko, & Smilek, 2016; Seli, Risko, Smilek, et al., 2016). Unintentional mind-wandering represents an involuntary decoupling of attention and is the most prototypical, but not exhaustive, form of mind-wandering (Seli, Kane, et al., 2018). The experience of unintentional mind-wandering occurs without a consciously aware moment of initiation and is thus a more unguided and nescient form of mind-wandering. For example, this may include the common experience of reading a page and then realising, despite your best efforts, that you didn’t take in anything that you have just read. Intentional mind-wandering, on the other hand, represents the deliberate deployment of attention away from an ongoing task or environmental referent towards task-unrelated self-referential thought (Seli, Risko, & Smilek, 2016; Seli, Risko, Smilek, et al., 2016). For example, you may think about an upcoming party during a boring lecture. Mind-wandering episodes that are initiated or maintained with intention are thus more deliberately guided and strategically adjusted. This intentionality dichotomy, however, has been largely relegated from consideration in the extant mind-wandering literature despite an earlier similarly proposed distinction (Giambra, 1989).

The practical and theoretical utility of this intentionality division derives from the reported dissociable trait-level associations, temporal foci, neural correlates, and functional consequences of unintentional and intentional mind-wandering across a range of behavioural paradigms, experimental manipulations, and clinical contexts (Corbetta & Shulman, 2002; Golchert et al., 2017; Seli, Ralph, Konishi, Smilek, & Schacter, 2017; Seli, Risko, Purdon, & Smilek, 2017; Seli, Risko, Smilek, et al., 2016; Seli, Smallwood, Cheyne, & Smilek, 2016). Indeed, a key factor dissociating the adaptive or maladaptive functionality of mind-wandering may lie in its intentionality. For instance, unintentional mind-wandering is uniquely associated with ADHD symptomatology at both clinical and non-clinical levels (Seli, Smallwood, et al., 2016) and with higher ratings of OCD-like symptoms in a non-clinical sample (Seli, Risko, et al., 2017). Further, unintentional mind-wandering is negatively associated with a facet of mindfulness, namely non-reactivity to inner experience, whereas intentional mind-wandering is positively associated with this trait (Seli, Carriere, & Smilek, 2015). The intentionality distinction is further supported by a recent neuroimaging study that observed differential neural activations for trait variation in unintentional and intentional mind-wandering (Golchert et al., 2017). This indicates that the involvement of executive control for co-ordinating these distinct mind-wandering types may vary depending on intentionality. Specifically, intentional mind-wandering involves greater integration between fronto-parietal control networks and the DMN. By contrast, unintentional mind-wandering is associated with cortical thinning in these regions (Golchert et al., 2017).

1.2.4 *Interim Summary of the Discussion Concerning the Definition of Mind-Wandering*

Theoretical unanimity has yet to be achieved regarding the characterization of mind-wandering as seen by the broad range of contending approaches and partial definitions. The continued theoretical disputation reflects a young field and a complex phenomenon. Defining the boundaries of mind-wandering in abstraction is an ongoing challenge, but operational definitions may be useful in the interim to elucidate the nature of different mind-wandering experiences. To avoid conceptual confusion, researchers should aim to articulate the operational definition of mind-wandering implemented and identify the specific type of mind-wandering investigated in their research (Murray et al., 2020; Seli, Kane, et al., 2018). Following this lead, and in line with existing frameworks, the present thesis conceptualizes mind-wandering in its broadest sense as a dynamic, discursive, and ubiquitous mental state under the broad umbrella of spontaneous thought phenomena. More specifically, we consider the intentionality of mind-wandering, and operationalise mind-wandering as the unintentional or intentional momentary redirection of attentional resources away from an ongoing action or environmental referent towards self-generated mental content.

1.3 Conceptual Challenges for the Assessment of Mind-Wandering

Despite the explosion of different theoretical frameworks and the emergence of various research tendencies within the field, associated advances in experimental techniques have not kept pace. One major methodological challenge affecting the measurement of mind-wandering is that mind-wandering is a largely internally directed and ephemeral phenomenon that may sometimes occur in the absence of deliberate intention. Its largely unpredictable and covert nature precludes it from direct experimental manipulation or measurement in the traditional manner (i.e. through presentation and variation of task stimuli and recording the elicited response (Donders, 1969)). Instead there is a reliance on subjective and indirect proxy measures to index changing mind-wandering states. Another major drawback is that the experimenter cannot predict or directly induce an experience of mind-wandering (Smallwood, 2013), and therefore, it is difficult to establish a causal link between the experience and precipitating processes or consequent outcomes. Indeed, if one could induce an episode of mind-wandering, the spontaneous phenomenology inherent to mind-wandering may itself be altered (Schooler, 2002).

Although mind-wandering is impervious to direct experimental investigation, as so far stated, certain conditions may influence the likelihood of its occurrence. In this regard, stimulating negative affect (e.g. Smallwood, Fitzgerald, Miles, & Phillips, 2009) or provoking states of craving or intoxication (e.g. Sayette, Reichle, & Schooler, 2009; Sayette, Schooler, & Reichle, 2010) have been shown to increase the probability of mind-wandering events, and with the latter, to reduce explicit awareness of such states. Moreover, manipulation of the complexity of task demands and performance motivation may also influence the nature of the cognitive state. For instance, mind-wandering decreases with more difficult tasks where demands placed on attention are greater, and increases during well-practiced, low demand, or non-stimulating tasks (Cohen & Maunsell, 2011; Robertson & Garavan, 2004; Seli, Konishi, Risko, & Smilek, 2018; Smallwood & Schooler, 2006; Thomson, Besner, & Smilek, 2015; Turnbull et al., 2019). Conversely, mindfulness meditation practices may reduce mind-wandering tendencies (e.g. Mrazek, Franklin, Phillips, Baird, & Schooler, 2013). The influence of such methodological factors shows that some degree of experimental control is possible.

The internally directed nature of mind-wandering means that it has few proprietary external manifestations that can be directly measured or outwardly observed, aside, perhaps, from a "faraway look" in the individual. The individual can appear lost in thought, preoccupied, absorbed in other matters, etc.; but these phenomena are difficult to track in a controlled manner. Indeed, the philosopher, Thomas Metzinger, conceptualized the challenge of assessing internally oriented cognition through the metaphor of "the dolphin model of cognition" (Pliushch & Metzinger, 2015). This model compares the flow of conscious experience to dolphins swimming under water. Just as dolphins emerge from the water, so too can our thoughts breach consciousness and awareness. By introspection, reflective recovery, or selective attentional control, we can sometimes access the contents of our thoughts; but these are just momentary insights into the automatic cognitive processing happening beneath the waves of our awareness most of the time.

Overall, the unique challenge posed to researchers is to *track the dolphin under water*, that is, to isolate and make visible mind-wandering experiences, given that they may occur at unpredictable times, independent of the external perceptual environment and experimental stimuli, and even, oftentimes, eluding the awareness of the person experiencing the thoughts.

1.4 Evolving Methodologies for Measuring Mind-Wandering

1.4.1 The Introspective Approach

The traditional approach for measuring mind-wandering depends on subjective "first-personal" reporting (Kahneman, Krueger, Schkade, Schwarz, & Stone, 2004). Specific challenges have been raised regarding introspective approaches including whether only content, rather than process, is consciously penetrable (Nisbett & Wilson, 1977), or whether the act of introspection alters the original phenomenal quality of the experience being reported on (Schooler, 2002). This objection against introspection has a long history in psychology dating back to Wundt and Brentano (Lyons, 1988).

A further assumption underlying verbal reporting is that the experience be accessible by meta-awareness, namely, the capacity to take heed, or become aware, of the current mental experience (Smallwood & Schooler, 2006). Indeed, Schooler makes the distinction between consciousness and meta-consciousness[†]; namely, meta-consciousness is what we report on (the conscious awareness brought to self-consciousness). That is, meta-consciousness is the secondary re-representation or translation of our experience that occurs in the act of verbalization or self-reporting (Schooler, 2002). In verbalizing our mental experiences, furthermore, certain interpretive biases may intrude on the accuracy of these reports; for example, memory or metacognitive efficiency, social desirability biases, misrepresentation of ambiguous or complicated non-verbal experiences, priming, and so on (Schooler & Schreiber,

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[†] Psychologists tend to speak of meta-cognition as the awareness of one's own cognitive states, especially involving one's ability to plan or correct or alter those cognitive states, e.g. in awareness of one's own competence. The phenomenological tradition recognizes levels of self-awareness below the level of cognition, in one's embodied consciousness, emotional states, and so on.

2004; Smallwood & Schooler, 2006, 2015). Additionally, the capacity for introspection and metacognition may be affected in different populations (e.g. with advancing age, Palmer, David, & Fleming, 2014).

Despite these potential challenges, the validity of carefully controlled introspective evidence has been established against a number of behavioural and physiological concomitants in both younger and older adults (Cheyne, Solman, Carriere, & Smilek, 2009; Frank, Nara, Zavagnin, Touron, & Kane, 2015; Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2013; Golchert et al., 2017; McVay & Kane, 2009; Mooneyham & Schooler, 2013; Smallwood, McSpadden, Luus, & Schooler, 2008). As such, there is inherent value in subjective reports as a means for understanding the nature of different mental experiences, at least until such time that reliable and valid objective measures of mind-wandering become available, if indeed possible. For instance, pain measurement based on a numeric rating scale, interpreted by the individual reporting pain, is an example of a medical assessment technique where introspective first-person reporting retains validity over other supposedly objective criteria (Bendinger & Plunkett, 2016).

1.4.1.1 Experience Sampling. One popular method of accessing introspective reports is ES, a self-report technique, typically employed during a controlled experimental task, whereby ongoing conscious cognitive experiences are assessed for their contents at discrete moments in time (Kahneman et al., 2004). Online ES can be divided into "self-caught" and "probe-caught" methods (Smallwood & Schooler, 2006). The self-caught method relies on participants to self-report as soon as they notice that their thoughts have strayed off-task with either a manual response or vocalization (Jackson & Balota, 2012). Self-caught approaches, however, are restricted by their dependence on thoughts reaching the participant's awareness, even though such meta-awareness may not be necessary for the thoughts to occur in the first place (Schooler, Reichle, & Halpern, 2004). Moreover, the act of self-monitoring places greater demands on cognitive processing and may be considered a task demand in and of itself (Maillet & Schacter, 2016).

The alternate probe-caught method is the most commonly used measure, and, as will later be addressed, is the form of ES implemented in the present methodological paradigm. Here, cognitive experience is sampled periodically in a random or quasi-random fashion by interrupting task performance, or activities of daily living, to ask or "probe" the participant to classify the content of their thoughts at that moment (Kane et al., 2007; McVay et al., 2009; Smallwood & Schooler, 2015). Probes are typically structured with a forced-choice response set of possible dimensions of mind-wandering requiring participants to categorise the content of their thoughts[‡]. Most commonly, experimental studies offer a bilateral choice between on- and off-task thoughts (Baird et al., 2012); while other studies provide a broader array of more nuanced categories; for example, the extent of stimulus dependence (Stawarczyk, Majerus, Maquet, & D'Argembeau, 2011), temporal orientation (Plimpton, Patel, & Kvavilashvili, 2015), and, relevant to the current paradigm, intentionality (Seli, Cheyne, Xu, Purdon, & Smilek, 2015). A significant advantage of the probe-caught method is that the probes can capture mind-wandering episodes that may be otherwise missed if metacognitive judgments were to be solely relied upon.

Although the Family Resemblances framework argues that multiple dimensions of mind-wandering are worthy of consideration (Seli, Kane, et al., 2018), the efficacy of probes for sampling multiple dimensions of thought at one time is unclear. This relates to practical concerns, such as acquiring sufficient trial counts for analyses, but also to more conceptual concerns regarding an individual's ability to report on multiple features of an experience at once (Seli, Kane, et al., 2018). This becomes especially challenging as memory for such transient experiences begins to degrade with passing time. Timing of probes is another important consideration for experimental manipulation, with changes in mind-wandering apparent with different lead in times and probe frequencies (Seli, Carriere, Levene, & Smilek, 2013; Seli, Carriere, et al., 2018; Smallwood, McSpadden, & Schooler, 2007). Probe-caught sampling is also

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[‡] The probe caught method discussed in the main text is referred to as "self-classification" probing (Smallwood & Schooler, 2006) – namely, participants are trained on different probe categories and report on their experiences, according to pre-set categories at distinct moments in time. Another potentially useful open-ended method is "experimenter-classified" probe-caught sampling, which prompts individuals at set times to verbally report on their inner mentations in the moments prior. These reports are subsequently classified by an experimenter-devised coding system. This bottom-up qualitative classification (albeit, usually theoretically-driven) may therefore be useful in studies that are particularly interested in the content, multidimensionality, and richness of spontaneous cognitive experiences (e.g. see Baird, Smallwood, & Schooler, 2011; Irish, Goldberg, Alaeddin, O'Callaghan, & Andrews-Hanna, 2019; Smallwood, Baracaia, Lowe, & Obonsawin, 2003). Although, as with all subjective methods, experimenter-classification may be susceptible to interpretive or social acquiescence biases (Smallwood & Schooler, 2006; Weinstein, 2018).

restricted to recording mind-wandering events that occur at set probe times, whether the participant was aware of thoughts at other intervals or not. ES is unable to collect rich temporal data on mind-wandering events as they unfold in real-time. Therefore, the potential influence of probe framing, timing intervals, and frequency, pose a challenge for the reliable measurement of the mind-wandering experience (Weinstein, 2018). However, the validity of mind-wandering ES self-reports has been established against behavioural concomitants (McVay, Meier, Touron, & Kane, 2013), eye-movements (Frank et al., 2015), and neural correlates (Golchert et al., 2017). Considering the aforementioned, combining ES with external behavioural and objective indices may provide a more comprehensive understanding of the mind-wandering experience as it unfolds over time (Schooler & Schreiber, 2004). This strategy of triangulation will be adopted in the present study.

1.4.2 *Alternative Approaches for Parsing the Mechanisms Underlying Attentional Disengagement in Mind-Wandering*

1.4.2.1 Behavioural Performance. As so far stated, mind-wandering is a pervasive phenomenon that may disrupt task-related processing and perturbate concurrent task performance (Bastian & Sackur, 2013; Cheyne et al., 2006; Kahmann et al., 2021; McVay & Kane, 2009; Mooneyham & Schooler, 2013; Smallwood, McSpadden, & Schooler, 2008). The experience of self-reported mind-wandering is a common correlate of lapses in sustained attention (Smallwood & Schooler, 2006) and has been shown to contribute to more erroneous performance (McVay & Kane, 2012) and increased response time variability (Bastian & Sackur, 2013; Cheyne et al., 2009; Esterman, Noonan, Rosenberg, & Degutis, 2013; Seli, Cheyne, & Smilek, 2013). Mind-wandering at critical moments is thus associated with a number of performance decrements and, as such, behavioural measures may provide useful indirect indicators of the occurrence (and impact) of mind-wandering.

1.4.2.2 Electrophysiology. In addition to behavioural measures, more temporally precise physiological methods have begun to elaborate on the mechanisms involved in mind-wandering. To this end, mind-wandering is thought to precipitate a shift in the orientation of attentional engagement in a process known as perceptual decoupling (Antrobus, Singer, Goldstein, & Fortgang, 1970; Schooler et al., 2011; Smallwood & Schooler, 2006, 2015). Specifically, attention disengages or “decouples” from sensory processing of the perceptual environment in favour of intrinsic input, to support internal cognition. In support, studies have demonstrated attenuated electrophysiological responses to external stimuli during mind-wandering (Barron, Riby, Greer, & Smallwood, 2011; Braboszcz & Delorme, 2011; Kam & Handy, 2013; Smallwood, 2013). Specifically, electrophysiological evidence has shown reduced sensory-level processing of visual and auditory stimuli (Braboszcz & Delorme, 2011; Kam et al., 2011) and altered cognitive-level target processing (Barron et al., 2011; Macdonald, Mathan, & Yeung, 2011; O'Connell et al., 2009; Smallwood, Beach, Schooler, & Handy, 2008) during off-task states.

Alongside suppressed sensory and cognitive processing, studies have also shown concurrent increases in alpha band oscillations over parietal-occipital regions antecedent to mind-wandering (Compton, Gearinger, & Wild, 2019; Dockree et al., 2017; Macdonald et al., 2011; O'Connell et al., 2009). Together, these findings of reduced sensitivity to external events and synchronised alpha activity suggest that during transient periods of mind-wandering, the integrity of task-related processing and performance is disrupted. Mind-wandering may gate sensory processing to insulate endogenously oriented cognition from external distractions or it may withdraw limited resources from the perceptual processing of the external task (see Franklin, Mrazek, Broadway, & Schooler, 2013; Kam & Handy, 2013; Smallwood, 2013). However, these previous studies have typically investigated perceptual decoupling using tasks that feature discrete, sudden-onset, and abrupt stimulus feature changes. Such punctuated target transitions may capture exogenous attention and evoke spatially and temporally overlapping signals in the physiological recordings that are difficult to disentangle. This renders it difficult to track the evolution of continuously unfolding perceptual information alongside the wandering mind. Therefore, a new experimental paradigm is warranted to isolate the individual dynamics of perceptual decoupling as it unfolds in the absence of such sensory-evoked deflections.

1.4.2.3 Psychophysiology. Recent research suggests that the oscillatory attentional dynamics in mind-wandering are coordinated and modulated by the locus coeruleus noradrenaline (LC-NA) system (Aston-Jones & Cohen, 2005; Mittner, Hawkins, Boekel, & Forstmann, 2016). Specifically, the “exploitation/exploration” framework (Sripada, 2018) suggests an antagonistic alternation between serial modes of thought that are comparatively more exploitative (e.g. constrained goal-directed thinking) or explorative (e.g. open-ended mind-wandering). Optimised behaviour is facilitated by a balance between exploitative and explorative strategies, in line with changing task demands and temporal uncertainties. The “adaptive gain theory” suggests that strategic oscillation between these exploit/explore states is regulated according to LC dynamics (Aston-Jones & Cohen, 2005) which alternate between tonic and phasic levels of NA (O'Callaghan, Walpola, & Shine, 2021; Sripada, 2018). These transitions appear to follow a Yerkes-Dodson inverted u-shape relationship with task performance, whereby relatively high or low tonic NA levels are associated with behavioural deficits, lower alertness, and greater explorative tendencies. Conversely, moderate tonic NA, with corresponding phasic activity, culminate in exploitative task focus and optimised performance (Aston-Jones & Cohen, 2005; O'Callaghan et al., 2021).

Non-luminance mediated changes in pupil diameter have been propounded as an indirect psychophysiological measure of arousal, mental effort, and exploit/explore shifts, tracking changes in the allocation of attentional resources (Alnaes et al., 2014; Beatty, 1982; Kahneman, 1973; Kahneman & Beatty, 1966, 1967) and fluctuating endogenous attentional states (Aston-Jones & Cohen, 2005; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014; Murphy, Robertson, Balsters, & O'Connell, 2011). Until recently, these associations were largely derived from indirect evidence (e.g. Aston-Jones & Cohen, 2015), until substantiated by a direct relationship between single-unit LC firing rates and pupil diameter in non-human primates (Joshi, Kalwani, & Gold, 2016). Joshi et al. (2016) showed that the co-variation of LC activity and pupil dilations (not also seen during pupil constrictions), and the associated release of NA throughout the brain, was indicative of underlying changes in arousal over distinct timescales in macaque monkeys.

Studies have shown decreasing phasic pupil responses during mind-wandering (Smallwood et al., 2011) and relatively large and small baseline pupil sizes preceding attentional lapses (McGinley, David, & McCormick, 2015; Murphy et al., 2011; Smallwood et al., 2012; Unsworth & Robison, 2016; Van Orden, Jung, & Makeig, 2000). PD therefore represents a promising covert and non-invasive measure that may be sensitive to changing attentional states over time.

1.4.3 Interim Summary of the Discussion Concerning the Measurement of Mind-Wandering

The major challenge for the measurement of mind-wandering owes to its inherently complex, internal, and covert phenomenology. The instrumental utility of current methodological approaches has facilitated a number of advancements in the field of mind-wandering; however, each method is afflicted by a number of conceptual challenges and practical limitations. The present study will expand on evolving methodologies for measuring and classifying the frequency and nature of mind-wandering by (1) employing a novel task paradigm using an adapted Gradual Contrast Change Detection task (McGovern, Hayes, Kelly, & O'Connell, 2018; O'Connell, Dockree, & Kelly, 2012) that features smooth and gradually unfolding target transitions and intermittent probe-caught ES; and (2) amalgamating self-report with indirect and real-time behavioural and neurophysiological (EEG and pupillometry) assessments in a triangulated approach. Implementing convergent methods will enable us to track the evolving signatures of mind-wandering and to chart intrinsic attentional fluctuations over time, while obviating over-reliance on one particular approach.

1.5 Ageing and Mind-Wandering

By the year 2050, one in six people globally will be aged 65 years or older, representing 16% of the world’s population (United Nations, 2019). This incremental demographic growth of the ageing population flags the advancements of modern medical science, but also constitutes a challenge for contemporary society. Coincident with growing life expectancies is the increase in health comorbidities and the associated risk of cognitive decline with progressive function losses (Nyberg, Lovden, Riklund, Lindenberger, & Backman, 2012). Age-related cognitive decline poses a considerable threat to the independent living, wellbeing, and quality of life of individuals in later life. Therefore, distinguishing cognitive changes that represent normal ageing from those that precipitate pathological decline is of pressing importance.

Research increasingly espouses the multidimensionality and heterogeneity of cognitive ageing; namely, that there is a variability in cognitive function between-individuals (i.e. different cognitive profiles amongst age matched peers) but also within-individuals (i.e. different developmental trajectories of various cognitive functions) (Brayne, 2007). Cognitive processes do not uniformly or linearly deteriorate over the lifespan (Fortenbaugh et al., 2015); indeed, some cognitive functions show relative preservation and even, improvement with advancing age (e.g. vocabulary, semantic knowledge, and emotional regulation). Such divergence may be somewhat shaped by cognitive reserve and neural plasticity (the adaptive functional and structural reorganisation of neural networks, Burke & Barnes, 2006), or represent compensatory strategies in ageing. Delineation of aberrations from adaptive changes in cognitive function is imperative to identify the processes that underpin successful ageing. Therefore, clarifying the extent to which ageing influences a broad array of cognitive processes is paramount. In this regard, research has recently begun exploring the extent to which self-generated cognition is affected by the natural ageing process.

Considering the trends of global population ageing and the explosion of research interest in mind-wandering, there has been a corresponding proliferation of studies exploring the phenomenon within healthy ageing in age-comparison studies (e.g. Jackson & Balota, 2012; Krawietz, Tamplin, & Radvansky, 2012; Maillet, Seli, & Schacter, 2017; Maillet, Yu, Hasher, & Grady, 2020). Recent research evidence points to a reliable decrease in mind-wandering as a function of age in healthy individuals (see meta-analysis Jordao, Ferreira-Santos, Pinho, & St Jacques, 2019; see review Maillet & Schacter, 2016). This finding has been observed across a range of lab paradigms including those assaying sustained attention, reading comprehension, working memory, and episodic encoding (Frank et al., 2015; Giambra, 1989; Irish et al., 2019; Jackson & Balota, 2012; Krawietz et al., 2012; Maillet et al., 2020; McVay et al., 2013; Shake, Shulley, & Soto-Freita, 2016; Zavagnin, Borella, & De Beni, 2014). Further corroboration for an age-related diminution in the frequency of mind-wandering has also been provided within online (Jackson, Weinstein, & Balota, 2013; Seli et al., 2020) and daily-life (Maillet et al., 2018) settings. Moreover, the emerging literature seems to indicate an attenuation in the frequency of unintentional and intentional mind-wandering for older relative to younger adults (Grodsky & Giambra, 1990; Seli, Maillet, Smilek, Oakman, & Schacter, 2017). However, research on ageing and mind-wandering intentionality has been largely neglected from empirical scrutiny to date.

1.5.1 *Current Theoretical Approaches to Explain Age-Related Mind-Wandering Differences*

What factors influence the propensity to mind-wander in younger but not older adults? Understanding the factors underpinning the age and mind-wandering effect is not simple, and indeed, existing posited theoretical approaches are not widely agreed upon in the field.

The predominant theoretical disputation concerns the putative explanatory power of accounts that emphasise the role of the executive control system (McVay & Kane, 2010; Smallwood & Schooler, 2006), within the context of reduced cognitive resources with age (Braver & West, 2008; Foster, Cornwell, Kisley, & Davis, 2007). The central debate relates to whether mind-wandering requires the involvement of executive resources, or whether it occurs as a result of executive control failure. For instance, the Executive Control Hypothesis (Smallwood & Schooler, 2006) suggests that the executive control system is required to facilitate the shift in resources away from an ongoing task/activity toward self-generated thought. Therefore, with age-related cognitive decline, mind-wandering should be attenuated in older adults as the pool of resources available to deploy to mind-wandering is more limited. Conversely, the Control Failure X Concerns theory (McVay & Kane, 2010) proposes that executive control is needed to inhibit distractions, either external or internal, from eliciting mind-wandering and detracting from goal maintenance. In particular, when personal goals or concerns supersede task-related goals or the draw of external events, momentary inhibition failure may allow mind-wandering to breach consciousness. Hence, with executive control deficits and poorer inhibition capacities with age (Lustig, Hasher, & Zacks, 2007), this theory predicts that older adults should be more susceptible to mind-wandering.

The debate regarding the involvement of executive resources in age-related mind-wandering may be further constrained by task demands and the level of controlled processing required (Smallwood & Schooler, 2015). However, the unresolved role of executive functions in mind-wandering may be better understood if different mind-wandering dynamics were considered. For instance, executive control may support the coordination of intentional mind-wandering, whereas the loss of task-related executive control may yield unintentional mind-wandering (Golchert et al., 2017). The involvement of executive resources in mind-wandering intentionality as it pertains to ageing has not yet been addressed.

Other factors may be important moderators of the age and mind-wandering effect (for a comprehensive overview of the range of potentially influential methodological and sociodemographic factors, see Jordao et al., 2019). Increasingly, research attention has been dedicated to elucidating the role of dispositional factors in age-related mind-wandering. Most notably, affective (e.g. Frank et al., 2015) and motivational (e.g. Jackson & Balota, 2012) accounts suggest that older adults' more positive orientation and affect, and greater conscientiousness and task-related interest, respectively, may reduce their inclination to wander off-task. Indeed, when such dispositional factors are controlled for, age-related differences in mind-wandering become less pronounced (Frank et al., 2015; Krawietz et al., 2012; Seli et al., 2020; Shake et al., 2016). Few studies, however, have investigated the role of such factors underscoring age-related differences in unintentional and intentional mind-wandering specifically (although see Seli, Maillet, et al., 2017).

1.6 Summary and Outstanding Gaps in the Literature

Mind-wandering is a pervasive, dynamic, and complex feature of our inner mental life. Despite its quotidian ubiquity, it remains an under-examined phenomenon owing to various conceptual and methodological barriers imposed on the measurement of an inherently covert, unbound, and ephemeral mental experience. In light of global population ageing, and the potential functional impact of mind-wandering, recent research attention has focused on clarifying the influence of the natural ageing process on mind-wandering. Although normal ageing is characterised by a decline in many cognitive abilities, recent studies have demonstrated a robust and, perhaps, puzzling finding of reduced mind-wandering with age. This finding stands seemingly opposed to conventional wisdom and further challenges theoretical accounts that present mind-wandering as an executive control failure. Despite the instrumental utility of theoretical advances in the field, there remains a lack of unanimity on how best to reconcile this age-related mind-wandering attenuation. Closely allied is the paucity of research exploring the dynamics, factors, and neurocognitive mechanisms underpinning mind-wandering intentionality as it pertains to ageing. As such, the experience and impact of unintentional and intentional mind-wandering for younger and older adults remains poorly understood. Additionally, as mind-wandering is an atelic phenomenon, that is, it evolves over time without a definitive end, the temporal dynamics of momentary changes in mind-wandering have been largely precluded from investigation.

1.7 Aims and Objectives of the Present Research

Against this backdrop of outstanding research issues, the present study aimed to leverage current theoretical developments, evolving methodologies, and triangulated strategies to explore different mind-wandering qualia as they unfold to provide deeper insight into cognitive ageing. Specifically, the present research is concerned with two over-arching research questions: 1) Does the frequency and phenomenology of unintentional and intentional mind-wandering change with age? 2) What are the neuropsychological and neurophysiological signatures of different attentional states in healthy younger and older adults? The three empirical chapters contained in this thesis investigate the following research objectives:

- **Chapter 2 (*Empirical Paper 1*)** investigates age-related differences in the frequency and phenomenology of unintentional and intentional mind-wandering experiences and examines the neuropsychological factors mediating their advent to dissociate between prominent theories in the field of mind-wandering and ageing.
- **Chapter 3 (*Empirical Paper 2*)** traces the neurophysiological signals of oscillatory endogenous attention and task-related processing to ascertain the mechanistic basis of transient strategic shifts in brain states between competing task focus and mind-wandering and explore how they are differentially affected by the ageing process. We examine whether neurophysiological measures preceding subjective probe attentional states provide support for perceptual decoupling.
- **Chapter 4 (*Empirical Paper 3*)** investigates time-on-task changes in moment-to-moment attentional fluctuations by delineating the temporal trajectory of behavioural sustained attention performance and subjective mind-wandering states over longer- and short-term timescales for younger and older adults. Additionally, we investigate pupil dilation changes as a proxy measure of exploit/explore shifts during variable pre-trial intervals to distinguish the different task strategies implemented by younger and older adults to maintain attentional engagement throughout the task.

Chapter 2: Empirical Paper 1

Young and Restless, Old and Focused: Age-Differences in Mind-Wandering Frequency and Phenomenology[§]

2.1 Introduction

2.1.1 What is the Nature of Mind-Wandering in Aging?

Our inner mental life is subject to a constant, discursive stream of thoughts (Christoff et al., 2016). In 'mind-wandering', attention disengages from processing the perceptual environment and shifts inward toward endogenously-generated mental content (Smallwood & Schooler, 2006, 2015). In recent decades, there has been an explosion in mind-wandering research with a proliferation of studies exploring mind-wandering within healthy aging populations. Research has consistently shown mind-wandering to decrease as a function of age in healthy individuals (see meta-analysis Jordao et al., 2019; see review Maillet & Schacter, 2016). This finding has been widely corroborated across lab paradigms (Frank et al., 2015; Giambra, 1989; Irish et al., 2019; Jackson & Balota, 2012; Krawietz et al., 2012; Maillet et al., 2020; McVay et al., 2013; Shake et al., 2016; Zavagnin et al., 2014), as well as in online (Jackson et al., 2013; Seli et al., 2020) and daily-life (Maillet et al., 2018) settings. Considering the global phenomenon of population aging, and in view of the purported adaptive (e.g. creativity, problem solving) and maladaptive (e.g. poorer sustained attention, negative clinical outcomes) corollaries of mind-wandering (see Mooneyham & Schooler, 2013) with implications for the wellbeing, independence, and safety of older adults, the extent to which mind-wandering is disrupted, or influenced, by the natural aging process is a timely issue.

Despite a lacking universal consensus on nomenclature (see Christoff et al., 2016; Christoff et al., 2018; Seli, Kane, et al., 2018; Smallwood & Schooler, 2015), mounting empirical evidence supports an operational distinction of mind-wandering as occurring due to the unintentional or intentional redirection of attentive resources (Forster & Lavie, 2009; Golchert et al., 2017; Grodsky & Giambra, 1990; Seli, Maillet,

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[§] This chapter has been adapted from its published manuscript format (Moran et al., 2021, Psychology & Aging). It conforms to US spelling and grammar, and other journal specific formatting guidelines. DOI: 10.1037/pag0000526 et al., 2017; Seli, Ralph, et al., 2017; see review Seli, Risko, Smilek, et al., 2016). *Unintentional* mind-wandering involves an involuntary and unguided decoupling of attention (e.g. drifting off while reading), whereas *intentional* mind-wandering is the deliberate deployment of attention away from an ongoing task or environmental referent toward unrelated self-generated thought (e.g. planning your to-do list while driving) (Seli, Risko, Smilek, et al., 2016). Recent studies have provided initial findings showing that older adults report fewer incidences of unintentional and intentional mind-wandering using self-caught (Grodsky & Giambra, 1990) and probe-caught (Seli, Maillet, et al., 2017) experience sampling (ES; a self-report technique whereby participants judge their mental state at discrete moments (Kahneman et al., 2004)). The validity of this intentionality distinction is supported by differential associations between unintentional and intentional mind-wandering reports and distinct content, neural, behavioral and clinical correlates (Corbetta & Shulman, 2002; Golchert et al., 2017; Seli, Ralph, et al., 2017; Seli, Risko, et al., 2017; Seli, Risko, Smilek, et al., 2016; Seli, Smallwood, et al., 2016). Research on aging and mind-wandering intentionality, however, remains underdeveloped, and further research is needed to clarify to what extent, if any, aging has on dissociable mind-wandering experiences.

2.1.2 What Theoretical Approaches Have Evolved to explain Mind-Wandering in Aging?

The preceding findings have prompted numerous research questions. Does age-related mind-wandering have its own proprietary phenomenology? What mechanisms contribute to the age-related effect? Do existing models enable consideration of different mind-wandering dynamics? In response, several competing theoretical frameworks have evolved to account for mind-wandering in aging. One framework considers the role of executive function; most notably, 1) the “Executive Control Hypothesis” (Smallwood & Schooler, 2006) and 2) the “Control Failure X Concerns theory” (McVay & Kane, 2010). Alternatively, 3) the “Exploitation/Exploration” framework (Sripada, 2018) postulates the underlying oscillatory dynamics of mind-wandering. A final framework underscores the roles of non-cognitive, dispositional factors, namely 4) affective (e.g. Frank et al., 2015), and 5) motivational (e.g. Jackson & Balota, 2012) accounts.

2.1.2.1 Role of Executive Function. Firstly, the *Executive Control Hypothesis* (Smallwood & Schooler, 2006) suggests that mind-wandering requires controlled processing to facilitate the shift of resources away from an ongoing task/activity toward personally relevant goals. Given that older adults have fewer cognitive resources than younger adults (Braver & West, 2008; Foster et al., 2007), and hence, fewer resources available during a task to deploy to off-task thought, this model predicts a reduction in mind-wandering frequency with age. The role of executive function, and how efficient an individual is at consigning mind-wandering, is further constrained and modulated according to the ongoing context and primary task demands. According to the "context-regulation hypothesis" (Smallwood & Schooler, 2015), difficult tasks that require considerable controlled processing should see a corresponding attenuation in mind-wandering as more executive resources are required for successful task performance (Giambra, 1989; Jackson & Balota, 2012). By this view, a trade-off in competing resources for mind-wandering and task will incur performance impairments. It follows that the involvement of executive functions in age-related mind-wandering varies depending on task demands. In particular, age-related differences in mind-wandering should be more pronounced in non-demanding tasks (Jordao et al., 2019). Age-accompanied reductions in mind-wandering, however, have been observed across conditions that were more or less demanding (Jackson & Balota, 2012).

Secondly, the *Control Failure X Concerns theory* (McVay & Kane, 2010) proposes that "*concerns*" cued from the environment or personal goals prompt the automatic initiation of mind-wandering as a consequence of momentary inhibition failure. This model suggests that executive control is required to impede thoughts triggered by current concerns from breaching consciousness and detracting from goal maintenance. Hence, with declining executive functions in advanced age, or "*control failure"*, older adults should be more susceptible to mind-wandering. Given the converse finding has been generally observed, it has been suggested that older adults' self-reports may be unreliable due to their orientation toward social desirability (Soubelet & Salthouse, 2011) and/or poorer metacognition (Maillet & Schacter, 2016). However, there is established validity for older adults' self-reports (Frank et al., 2015). Klinger's (1971) original "*current concerns"* hypothesis, however, proffers that despite older adults having poorer inhibition capacities (Lustig et al., 2007), they may have fewer concerns to inhibit (Parks, Klinger, & Perlmutter, 1989), thereby leading to reduced mind-wandering. Although, the over-arching Control Failure X Concerns perspective does not sufficiently explain the consistent finding of age-accompanied decreases in mind-wandering, the "current concerns" component offers a promising avenue for future enquiry (McVay & Kane, 2010).

These accounts highlight the complex, and often confusing, relationship between mind-wandering and executive control. There is a more nuanced view that if we take account of different mind-wandering types: executive control aids the regulation of cognition and supports coordination of intentional mind-wandering, whereas it is the loss of task-related executive control that yields unintentional mind-wandering. In support of this view, intentional mind-wandering involves greater integration between fronto-parietal control networks and the default mode network (DMN) than unintentional mind-wandering (Golchert et al., 2017).

2.1.2.2 Role of Oscillatory Dynamics. Thirdly, and more broadly, are there different oscillatory dynamics of mind-wandering in younger and older adults? The *Exploitation/Exploration* framework (Sripada, 2018), typically applied to learning models (e.g. Sutton & Barto, 1998) and attention (Aston-Jones & Cohen, 2005), frames goal-directed thinking as an exploitative process that capitalizes on current cognitive resources in the service of a specific goal. Mind-wandering is more explorative; entailing an open-ended search strategy for possible opportunities and information, that can enable pattern learning and enhance creativity. Although this framework has provided a relatively new viewpoint on mind-wandering functionality, neuroimaging evidence has supported this and shown differential activation of distinct neural regions supporting an antagonistic alternation between goal-directed thinking and mind-wandering (see Sripada, 2018). Optimal performance is enhanced by a balance of strategies relative to the context and is modulated by an inner drive that exhibits temporal oscillations. Indeed, performance variability, most notably reaction time variability (RTV), has been suggested as a quantitative index measuring oscillatory attention cycles. In support, lower RTV has been observed during periods of goal-directed thought, with higher variability during mind-wandering (Cheyne et al., 2009; see Mooneyham & Schooler, 2013). Given evidence for an exploration bias in younger adults (Mata, Wilke, & Czienskowski, 2013), a further proposition for how mind-wandering changes with age is that reduced executive resources may limit older adults' capacity to optimize and adaptively oscillate between competing strategies, especially within the context of intentional mind-wandering.

2.1.2.3 Role of Dispositional Factors. Fourthly, *affective accounts* (e.g. Frank et al., 2015) have been proposed to explain age-related reductions in mind-wandering, drawing from two observations:

- Mind-wandering has been associated with negative affect in younger adults (Kane et al., 2007; Killingsworth & Gilbert, 2010; McVay et al., 2009; Smallwood, O'Connor, Sudbery, & Obonsawin, 2007).
- Older adults report less negative affect, greater positive orientation and life satisfaction, and better emotional regulation than younger adults (Carstensen, Isaacowitz, & Charles, 1999; Grühn, Kotter-Grühn, & Röcke, 2010; Zavagnin et al., 2014). Indeed, during a reading comprehension task, the effect of age on mind-wandering was partially mediated by older adults' greater positive affect (Frank et al., 2015).

Fifthly, *motivational accounts* (e.g. Jackson & Balota, 2012) have gained momentum, attributing age-differences in mind-wandering to task-related engagement and interest. An increasingly documented finding is that older adults tend to be more conscientious and motivated while completing traditional lab-based tasks than younger adults (Jackson & Balota, 2012; Krawietz et al., 2012; Maillet & Rajah, 2013; Shake et al., 2016). In studies with younger adults, higher levels of interest were correlated with reduced overall mind-wandering (Unsworth & McMillan, 2013), with less unintentional and intentional mind-wandering (Seli, Wammes, et al., 2016), and with reduced proportional intentional mind-wandering (Seli, Cheyne, et al., 2015). It follows that older adults, through their greater task interest, should mind-wander less. Indeed, the age-related reduction in mind-wandering was attenuated in two reading task studies that covaried for text interest (Krawietz et al., 2012), or interest and age (Shake et al., 2016), with no additional contribution from cognitive variables. Recent mediation analyses have also supported an indirect effect of motivation/interest, showing that older adults mind-wander less frequently due, in part, to their higher engagement (Frank et al., 2015; Seli et al., 2020). This effect was consistent when motivation ratings were taken post-lab task allowing the possibility of performance bias (Frank et al., 2015) but also when recorded prior to an online task (Seli et al., 2020). Additionally, experimentally increasing motivation minimised the degree of mind-wandering in younger adults (Seli, Schacter, Risko, & Smilek, 2019) and further decreased age-related differences in mind-wandering (Seli et al., 2020). Few studies have investigated the impact of age-related differences in motivation on unintentional and intentional mind-wandering separately. However, initial research demonstrated a negative correlation between motivation and unintentional, but not intentional, mind-wandering for both age groups (Seli, Maillet, et al., 2017).

2.1.3 What Mechanisms Contribute to the Age and Mind-Wandering Effect?

The phenomenon of age-accompanied diminution in mind-wandering contradicts perceived wisdom and stands seemingly opposed to accounts that present mind-wandering as executive control failure. Although dispositional accounts hold promise, there is no unanimity on how best to reconcile the paradoxical decrease in mind-wandering with age. The best explanation may derive from some amalgamation of these frameworks or they may, perhaps, partially explain different aspects of mind-wandering generation or continuity (Smallwood, 2013). Regardless, the presupposed broad definition of mind-wandering neglects the established role of intentionality. Closely allied is the paucity in conclusive research elucidating the distinct neuropsychological mechanisms underlying unintentional and intentional mind-wandering. Given the potential far-reaching consequences of mind-wandering for the wellbeing and safety of older adults, future studies must investigate the forgoing to decompose the impact of intentionality and to clarify the impact of the natural aging process on mind-wandering.

2.1.4 The Present Study

The present study aimed to investigate whether the frequency and phenomenology of mind-wandering changed as a function of age and examine the distinct neuropsychological mechanisms mediating age-related differences in unintentional and intentional mind-wandering. We capitalized on evolving methodologies for measuring and classifying the frequency and nature of mind-wandering by employing a multi-faceted approach comprising a comprehensive neuropsychological test battery and Gradual Contrast Change Detection task (McGovern et al., 2018; O'Connell et al., 2012) with built-in experience sampling (GradCCD-ES) mind-wandering probes. Our methodological approach captured self-reported mind-wandering episodes during a continuous task featuring smooth and gradually evolving target transitions extending typical tasks that employ discrete, sudden-onset and predictably occurring target and non-target stimuli (e.g. the Sustained Attention to Response Task, SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). The gradually unfolding stimulus features minimized the need for rapid information processing and response demands and hence, required greater reliance on endogenous control. The GradCCD-ES was therefore well suited to induce and measure off-task thought.

In the GradCCD-ES, healthy younger and older adults monitored a continuously presented flickering annulus to identify intermittent contrast reductions and pseudo-randomly responded to probes asking participants to classify their current cognitive experience as “Focused on the task”, or “Unintentionally” or “Intentionally” mind-wandering (Seli, Cheyne, et al., 2015). Given the low task demands, we did not anticipate appreciable age-related decrements in performance (*Hypothesis One*). Indeed, a study using an earlier version of this task (McGovern et al., 2018) found similar between-group RTs and false alarm rates but increased correct target detections and reduced RTV by older adults. In response to the ES probes, we predicted that older adults would report fewer incidences of unintentional and intentional mind-wandering throughout the task (*Hypothesis Two*). The finding that mind-wandering has a pernicious effect on concurrent performance on sustained attention tasks led to our next prediction that unintentional and intentional mind-wandering would negatively impact behavioral performance (*Hypothesis Three*). Additionally, based on research showing dissociable correlates of unintentional and intentional mind-wandering, we postulated differential associations with key neuropsychological outcomes (*Hypothesis Four*). Finally, to dissociate between prominent mind-wandering theories, we examined the indirect effects of cognitive function, task demand, affective, and motivation variables. We hypothesized that distinct theoretically derived neuropsychological factors would mediate the age effect for unintentional and intentional mind-wandering (*Hypothesis Five*).

2.2 Methodology

2.2.1 Participants

Eighty-one community-dwelling older adults (65-80 years old) were contacted from a university research participant panel. Of those contacted, 47 older adults expressed interest and were assessed for eligibility. Initial inclusion criteria were normal or corrected-to-normal vision, no personal or family history of neurological or psychiatric illness, no personal or family history of brain injury or unexplained fainting, no sensitivity to flickering light, and no recent history of drug, alcohol, or pharmaceutical abuse. From this pool, 40 older adults were selected and participated. Six participants were later excluded from the analyses: five were excluded based on a Montreal Cognitive Assessment (MOCA; Nasreddine et al., 2005) score of less than 24, indicating possible cognitive impairment (O'Caoimh, Timmons, & Molloy, 2016), and one participant was excluded due to illness. This resulted in a sample of 34 cognitively normal healthy older adult participants (age: mean (*M*) = 71 years, standard deviation (*SD*) = 3.54, 20 female).

Younger participants, aged between 18 and 35 years, were recruited from the Trinity College Dublin (TCD) student population. Forty-three younger adults expressed interest, 35 of whom were selected after pre-screening. One participant was excluded prior to analysis due to technical issues. Consequently, data from 34 younger adult participants (age: *M*= 22 years, *SD* = 4.59, 16 female) were included in the per-protocol analyses (see Figure **S.2.1** consort flow diagram, §2.5 *Supplemental Material*).

Participants took part in the study across two sessions (median days apart= 2, inter-quartile range (IQR)= 5) in the lab in TCD Institute of Neuroscience and received partial course credit or a €20 gratuity to cover travel costs. Participation was entirely voluntary, and all participants provided willful and explicit written informed consent to the procedures that were approved by the School of Psychology Research Ethics Committee, TCD, and were conducted in accordance with the principles of the Declaration of Helsinki.

2.2.1.1 Sample Size and Study Power. A recent meta-analysis (Jordao et al., 2019) demonstrated a significant between-groups difference in mind-wandering frequency, reporting an average large effect size (Hedges' g = -.89). Using this parameter and an alpha of .05, 34 participants per group provided a .95 power for a two-tailed independent samples t-test. Calculations for the partial Pearson's r

correlations (total sample size of 60 participants, controlling two variables, with an alpha of .05) revealed power values of .89 and .99 to detect medium ($r_{\text{partial}}= \pm .4$) and large ($r_{\text{partial}}= \pm .6$) effects, respectively. While these calculations were conducted after data collection, the effect sizes used are independent of this dataset and thus, do not have the same issues with bias as "post hoc" power calculations using obtained effect sizes.

2.2.2 Materials and Procedures

2.2.2.1 Session 1: Background Neuropsychological Measures. The test battery comprised assessments of *cognitive function*: National Adult Reading Test (NART; Nelson & Willison, 1991), Tests of Everyday Attention (TEA; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1996), Stroop Color and Word test (Golden & Freshwater, 2002), and the Controlled Oral Word Association Test (COWAT; Benton, Hamsher, & Sivan, 1994; Spreen & Strauss, 1998). Participants completed self-report questionnaires assessing *negative affect* using the Hospital Anxiety and Depression Scale (HADS; Zigmond & Snaith, 1983) and *daily life attentional difficulties* with the Connor's Adult Attention-Deficit/Hyperactivity Disorder (ADHD) Rating Scale (CAARS; Conners, Erhardt, & Sparrow, 1999). Details on the neuropsychological measures are provided in Table **S.2.1 (**§2.5 *Supplemental Material*).

2.2.2.2 Session 2: Behavioral Task. Participants returned to the lab on a separate day for the behavioral session that included a computerized sustained attention task with embedded ES probes. Concurrent electroencephalography (EEG) and pupillometry were recorded to investigate age-related differences in the temporal dynamics of momentary attentional fluctuations; the results of which are reported in *Chapters 3* and *4* of this thesis.

2.2.2.2.1 ***Gradual Contrast Change Detection with Experience Sampling (GradCCD-ES) Task.*** The GradCCD-ES task (McGovern et al., 2018; O'Connell et al., 2012) required participants to continually monitor a flickering annulus stimulus (25Hz) to detect intermittent targets, characterized as smooth and gradual contrast changes, to assess sustained attention. The checkerboard annulus stimulus comprised 8° outer and 3° inner radii with interchanging light and dark radial segments, against a dark grey background. The linear contrast reductions unfolded gradually from 65% to 35% over 1.6 seconds and returned to baseline over 0.8 seconds (Figure **2.1**). The targets occurred pseudo-randomly with inter-trial intervals (ITI) of three-, five-, or 7-seconds. The target stimuli were presented in the center display of a 40cm cathode-ray tube (CRT) monitor operating at 100Hz with 1024x768 resolution using Matlab software version R2016b (MATLAB, 2016) and Psychtoolbox-3 interface (Brainard, 1997; Pelli, 1997). Participants sat opposite the monitor in a dark, sound-attenuated room, and fixated on the central point to identify target contrast changes. As soon as participants noticed the annulus contrast decreasing, they made a speeded left-button press with their right index finger. Participants performed 8 blocks; each lasted approximately 8 minutes and included 48 target trials (totaling 384 targets). Participants carried out two brief practice blocks prior to the main experiment to ensure adequate comprehension of the procedures. Behavioral performance indices included: a) Hit Rate (proportion of correctly identified targets), b) RT for correct target trials (in seconds), c) RT coefficient of variance (CoV) for correct trials, calculated as the standard deviation of RT divided by the mean RT, multiplied by 100, and d) the number of False Alarms. Outcomes were averaged across the task for each participant.

To capture mind-wandering events in real time, the task was intermittently interrupted by built-in ES probes. When a probe appeared, the task halted temporarily, and participants were instructed to “Choose the response that best describes your [their] mental state right before this screen appeared”. Participants responded with a keyboard press (numbers 1-3) as to whether they had been 1) “Focused on the task”, 2) “Unintentionally lost focus on the task”, or 3) “Intentionally disengaged from the task” in the moments prior to the probe (see Seli, Cheyne, et al., 2015). Once the probe was answered, the task resumed. Each block contained 16 probes (128 in total). The probes occurred pseudo-randomly with a minimum constraint of two-trial separation imposed to minimize task interruptions, facilitate possible occasions for mind-wandering, and curtail probe predictability.

Prior to task administration, participants were provided with an instruction sheet (Appendix **E**) containing written explanations of the various probe responses, examples of each condition, and the protocol for responding to the probes during the task (adapted for use with permission from the Seli lab; see Seli, Cheyne, et al., 2015). The focused category was explained as:

> “If you are focused on the task, this means that just before the question screen appeared, you were paying attention to some aspect related to the task. For example, you may have been looking for a target, thinking about making a

> button press, wondering about your performance, or how long the task will last, and so on. These types of thoughts are: ‘focused on the task’.”

The mind-wandering conditions were described as follows:

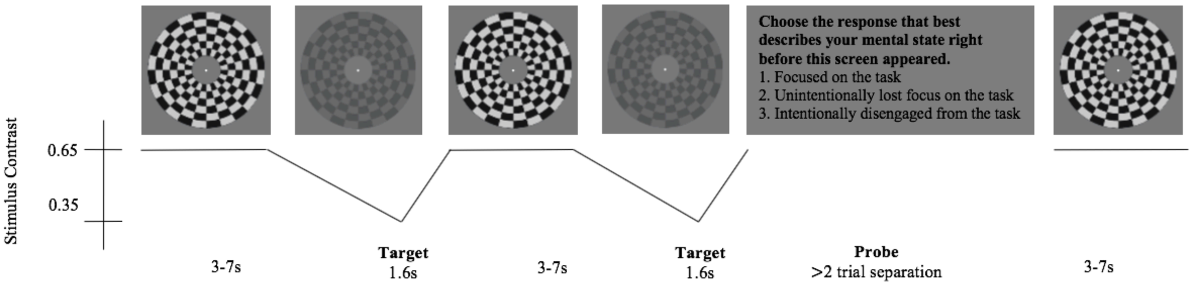
> “You may also experience task-unrelated thoughts. This means that just before the question screen appeared you were thinking about something other than the task. For example, you might be thinking about your grocery list, or about your transport home, an upcoming holiday, or you might be recounting a conversation you had with a friend that morning, and so on. Any thoughts like these that are entirely unrelated to the task are known as “task-unrelated thoughts”. Another important distinction is that these task-unrelated thoughts can occur because you unintentionally or intentionally thought about things other than the task. Your mind may have unintentionally drifted away despite your best effort to engage with the task. For example, have you ever had the experience of reaching the end of a paragraph and realising that you did not take in anything you were reading? Despite you trying, your mind was elsewhere, unintentionally. Alternatively, on other occasions you may have made the decision to intentionally disengage from the task in order to think about something else. This is more guided thought. For example, you might disengage from the task at hand to plan your to do list for that evening.”

Trained research assistants were available to answer any questions that participants had regarding the different probe categories, to provide further clarifications and examples if requested, and to check the participants’ interpretations of the probe conditions. Further, to engender honest reporting, participants were reassured that mind-wandering is a normal, natural, and frequent feature of everyday cognition, and that thinking about things other than the here-and-now also frequently occurs during lab task participation. Participants were encouraged by the research assistants to answer the probes honestly.

ES outcomes included the frequency and percentage of each probe response: a) Focus, b) Unintentional, and c) Intentional mind-wandering, as well as d) a composite Total Mind-Wandering frequency (summed frequency of Unintentional and Intentional mind-wandering responses). These measures were averaged across the total task for each participant.

Figure 2.1

Experimental Schematic of the Gradual Contrast Change Detection Task with Experience Sampling Probes



Choose the response that best describes your mental state right before this screen appeared.
1. Focused on the task
2. Unintentionally lost focus on the task
3. Intentionally disengaged from the task

Note. Participants continuously monitored the flickering annulus stimulus for gradual contrast changes, representing a stimulus contrast reduction from 65% to 35% over 1.6 seconds, and responded to intermittent experience sampling probes asking about current mental state.

2.2.2.2.2 ***Task-Related Motivation Measures.*** The Stanford Sleepiness Scale (SSS; Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973) was administered prior to the task to assess alertness. The Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999) was administered pre- and post-task to measure task-induced motivation changes, see Table **S.2.1** (§2.5 *Supplemental Material*).

2.2.3 Data Management

Data from 68 participants, who completed the study per-protocol, were initially assessed for normality (by inspecting skewness and kurtosis values, histograms, and Kolmogorov-Smirnov tests). Outliers, defined as data points extending greater than three times the IQR within a particular outcome measure, were removed and excluded from subsequent analyses (representing less than .05% of the values in each group). Two participants had a combined total of three missing CAARS items. Subscale total scores for these participants were adjusted according to the number of items answered (Conners et al., 1999).

2.2.4 Statistical Analysis Plan

To assess Hypotheses **One** and **Two** that examined between-group differences in behavioral performance and subjective ES probe responses, a series of two-tailed independent *t*-tests were conducted. Where Levene's test for equality of variance was significant, the appropriate tests with corrected degrees of freedom (df) were reported. Where normality was violated, a non-parametric test equivalent, Mann-Whitney *U* test, was conducted and the associated medians and IQR reported. A test statistic was deemed significant if the *p*-value was less than .05. For each comparison, Cohen's *d* was calculated as a measure of effect size and interpreted by rule of thumb as representing small ($d = .2$), medium ($d = .5$), or large ($d = .8$) effects (J. Cohen, 1988). Bayesian analyses were also applied to the group comparisons to establish the presence or absence of a group effect, using a default scaling parameter of .707. Bayes Factor (BF) provided a relative measurement of the predictive ability of the null versus the alternative hypothesis (Dienes, 2014). The Bayesian approach was applied here to support the frequentist between-group comparisons; specifically, in situations where a non-statistically significant result was observed, BF demonstrated whether there was support for the null hypothesis of no group difference (i.e. evidence of absence) or whether there was a dearth of evidence (i.e. absence of evidence) (Dienes, 2014). Guidelines for the strength of the evidence in favor of the alternative hypothesis were classified as weak/inconclusive ($BF_{10} = .33\text{-}3$), moderate ($BF_{10} = 3\text{-}10$), or strong ($BF_{10} > 10$). A BF value lower than a third indicated support for the null hypothesis, that no effect was present (Dienes, 2014).

For Hypothesis **Two** a further 2x3 mixed repeated measures analysis of variance (ANOVA) was performed to evaluate subjective mind-wandering frequency with respect to the between-subjects factor of "Age Group" (younger and older adults) and within-subjects factor of "Probe Response" (Focus, Unintentional, and Intentional Mind-Wandering). Where the assumption of sphericity was violated, as identified by a significant Mauchly's test, the Greenhouse Geisser correction (epsilon, ε) was applied and the adjusted degrees of freedom and associated p-values were reported. A significant omnibus *F* test for an interaction term was followed up by tests of simple effects (Bonferroni-corrected) to determine the direction of the differences.

Two-tailed partial Pearson's *r* correlations, controlling for age group and NART Errors, were performed to test Hypotheses **Three** and **Four** that predicted significant differential associations between ES probe responses, and behavioral and neuropsychological outcomes, respectively. For Hypothesis **Five**, parallel mediation models were conducted to evaluate Age Group and Mind-Wandering (Unintentional and Intentional) effects, and the relative role of putative mediators, derived from theoretical models. Variables representing cognitive function, task demand, affective, and motivational factors were included as mediators. For all mediation analyses, 95% Bootstrap confidence intervals (using 10,000 bootstrapped samples) were used for statistical inference, providing credible intervals for the specific indirect effects.

SPSS Version 24 (IBM; Chicago, IL, United States), SPSS Process Macro v3.3 model 4 (Hayes, 2013), and JASP software (JASP Team, 2019) were used to run the frequentist, mediation, and Bayesian analyses, respectively. Prism 8 (GraphPad) was used for graphical representations.

2.3 Results

2.3.1 Sample Characteristics

The final sample comprised 34 older adults (20 female) with a mean age of 70.97 years (*SD* = 3.54, range 65-78 years) and 34 younger adults (16 female) with a mean age of 21.71 years (*SD* = 4.59, range 18-35 years). The groups did not significantly differ on gender, $x^2(1, N = 68) = .94, p = .331$, phi (Φ) = -.12, $BF_{10} = .47$, or years of education, $t(60.99) = 1.47, p = .148$ (two-tailed), $d = .36$, $BF_{10} = .62$ (see Table **S.2.2** for sociodemographic characteristics, §2.5 *Supplemental Material*).

2.3.2 Group Comparisons on the Background Neuropsychological Measures

Descriptive statistics for group comparisons on key neuropsychological variables are summarized in Table **S.2.3** in §2.5 *Supplemental Material.* A suite of independent samples *t*–tests demonstrated statistically significant between-group differences on *cognitive function*. Older adults were slower to detect TEA Telephone Search targets, $t(60.68)= -6.31, p < .0005$, 95% CI [-1.55, -.80], $d = 1.53$, $BF_{10} = 370837.20$, and demonstrated longer search times when weighted for tone-counting accuracy, $t(32.61)= -6.32, p < .0005$, 95% CI [-4.03, -2.07], $d = 1.51$, $BF_{10} = 187696.93$, and a larger dual-task decrement, $t(35.86)= -4.23, p < .0005$, 95% CI [-2.19, -.77], $d = 1.04$, $BF_{10} = 283.19$. There was no support for group differences in Visual Elevator accuracy, $t(65) = -.11, p = .916$, 95% CI [-.82, .73], $d = .03$, $BF_{10} = .25$, or Stroop Word trial duration, $t(66) = -1.48, p = .144$, 95% CI [-7.32, 1.09], $d = .36$, $BF_{10} = .6$. Older adults did, however, take significantly longer to complete the Stroop Color, $t(66) = -4.14, p < .0005$, 95% CI [-20.51, -7.16], $d = 1.00$, $BF_{10} = 218.88$, and Color-Word, $t(66) = -6.00$, $p < .0005$, 95% CI [-51.74, -25.91], $d = 1.46$, $BF_{10} = 121177.62$, trials. Correspondingly, there was strong evidence that older adults were more susceptible to Stroop Interference, $t(44) = 3.15, p = .003$, 95% CI [3.17, 14.44], $d = 1.06$, $BF_{10} = 12.80$. Moreover, older adults produced fewer words on Categorical Verbal Fluency, $t(66) = 3.27, p= .002$, 95% CI [2.67, 11.03], $d = .79$, $BF_{10} = 19.66$, but were not significantly different from younger adults on the Phonemic condition, $t(57.41) = -.99$, $p= .325$, 95% CI [-7.81, 2.63], $d = .24$, $BF_{10} = .38$. All statistically significant results were indicative of poorer cognitive performance by older adults, apart from the NART, where older adults produced fewer errors, $t(66) = 2.94, p = .005$, 95% CI [1.77, 9.29], $d = .71$, $BF_{10} = 8.66$. This latter finding remained when data from non-native English speakers were removed and re-analysed; hence, results from the total sample are reported.

Despite poorer cognitive performance, older adults experienced less *negative affect*, reporting lower levels of HADS Anxiety, $t(59.91) = 3.96$, $p < .0005$, 95% CI [1.55, 4.74], $d = .96$, $BF_{10} = 127.51$, and Depression, $U = 403.50$, $Z = -2.16$, $p = .031$, $d = .54$, $BF_{10} = 1.96$. Further, there were significant group differences on CAARS *daily life attentional difficulties*; older adults expressed fewer issues with self-perceived inattention and memory, $t(45.75) = 3.09$, $p = .003$, 95% CI [.74, 3.50], $d = .74$, $BF_{10} = 9.41$, reduced hyperactivity/restlessness, $t(56.79) = 6.34$, $p < .0005$, 95% CI [2.68, 5.15], $d = 1.54$, $BF_{10} = 421009.79$, as well as fewer problems with self-concept, $t(59.06) = 3.51$, $p = .001$, 95% CI [1.27, 4.63], $d = .85$, $BF_{10} = 37.03$. The groups did not significantly differ with respect to their perceived impulsivity or emotional lability, $t(66) = 1.53$, $p = .130$, 95% CI [-.23, 1.76], $d = .37$, $BF_{10} = .67$. Overall, there was strong evidence for a group difference in subjective experience of ADHD-related symptoms, with older adults reporting fewer difficulties, $t(60.73)= 4.55$, $p < .0005$, 95% CI [2.79, 7.17], $d = 1.10$, $BF_{10} = 785.65$. Only one younger adult reported a formal ADHD diagnosis and *t*-scores for all participants fell below the threshold for clinically elevated symptoms (Robertson et al., 1996).

Finally, the *task-related motivation* measures revealed older adults reported greater SSS alertness pre-task than their younger counterparts, $U = 315.00$, $Z = -3.44$, $p = .001$, $d = .85$, $BF_{10} = 8.71$. DSSQ group comparisons showed older adults found the task more engaging; that is, they experienced less task-induced motivation losses relative to younger adults, $t(66) = -2.89$, $p = .005$, 95% CI [-6.52, -1.19], $d = .69$, $BF_{10} = 7.73$. There was no significant between-group difference regarding task-induced distress, $t(65)= 1.46$, $p = .149$, 95% CI [-.75, 4.88], $d = .36$, $BF_{10} = .62$, but there was weak evidence for increased task-induced worry in younger adults, $t(66)=2.32$, $p =.024$, 95% CI [.41, 5.48], $d = .56$, $BF_{10} = 2.35$.

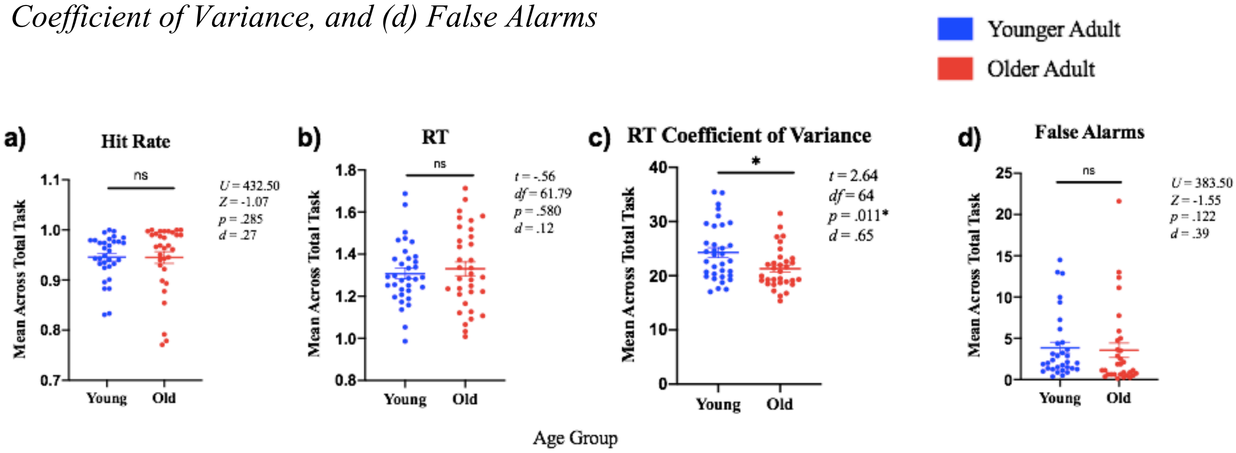
2.3.3 Hypothesis One: There will be No Marked Age-Related Decrements in Performance on the GradCCD-ES Task

Independent *t*-test and Mann-Whitney *U* analyses demonstrated relative group parity in GradCCD-ES task performance (Table **2.1**). There were no significant between-groups differences observed in Hit Rate, $U = 432.50$, $Z = -1.07$, $p = .285$, $d = .27$, $BF_{10} = .37$, False Alarms, $U = 383.50$, $Z = -1.55$, $p = .122$, $d = .39$, $BF_{10} = .67$, or mean RT, $t(61.79)$

= -.56, p = .580, 95% CI [-.11, .06], d = .12, BF_{10} = .28, across the task. There was, however, moderate evidence in support of a group difference in RT CoV; namely, older adults demonstrated significantly less performance variability than younger adults, t(64) = 2.64, p =.011, 95 % CI [.72, 5.24], d = .65, BF_{10} = 4.45 (see Figure **2.2**).

Figure 2.2

Scatterplots of Individual Level Data Points for Between-Group Comparisons on Behavioral Performance Indices: (a) Hit Rate, (b) Reaction Time (RT), (c) RT Coefficient of Variance, and (d) False Alarms



Note. Scatterplots present between-group performance differences in (a) Hit Rate, (b) Reaction Time (RT), (c) RT Coefficient of Variance (CoV), and (d) False Alarms. Graphs for RT and RT CoV display mean (standard error of the mean, SEM); Hit Rate and False Alarms graphs display median (IQR).

ns = non-significance; *p < .05

2.3.4 Hypothesis Two: Older Adults will Report Fewer Incidences of Unintentional and Intentional Mind-Wandering Throughout the Task

Descriptive statistics for the group ES probe responses are displayed in Table **2.1** and Figure **2.3**. Older participants reported greater levels of Focus than younger participants, t(66) = -3.42, p = .001, 95% CI [-4.12, -1.08], d = .83, BF_{10} = 28.74. Younger and older adults reported Mind-Wandering for approximately 45% and 27% of the probes, respectively. There was strong evidence to support a group difference in Total Mind-Wandering frequency, with older adults exhibiting a lower propensity to mind-wander overall, than their younger counterparts, t(65) = 3.88, p <.0005, 95% CI [1.38, 4.30], d = .95, BF_{10} = 102.14. Specifically, older adults experienced fewer incidences of Unintentional, t(66) = 2.43, p = .018, 95% CI [.24, 2.48], d = .59, BF_{10} =

2.93, and Intentional, $t(65) = 4.65$, $p < .0005$, 95% CI [.86, 2.15], $d = 1.13$, $BF_{10} = 1087.82$, Mind-Wandering than younger participants.

A 2x3 mixed repeated measures ANOVA was performed to complement the independent *t*-test comparisons on probe response frequency. Consistent with the prediction that groups would differ regarding mind-wandering frequency, a significant Group x Probe interaction was observed, $F_{1.25, 81.21} = 12.58$, $p < .0005$, $\eta p^2 = .16$, $\varepsilon = .63$. Separate within-subjects repeated measures ANOVAs demonstrated a significant effect of Probe Response for both younger, $F_{1.37, 45.24} = 47.55$, $p < .0005$, $\eta p^2 = .59$, $\varepsilon = .69$, and older, $F_{1.13, 36.26} = 131.09$, $p < .0005$, $\eta p^2 = .80$, $\varepsilon = .57$, adult groups. For younger adults, Bonferroni-corrected pairwise comparisons showed that younger adults significantly differed with respect to the frequency of Focus and Unintentional Mind-Wandering responses (mean difference = 4.00, $p < .0005$, 95% CI [1.84, 6.16]), Focus and Intentional Mind-Wandering responses (mean difference = 6.63, $p < .0005$, 95% CI [4.88, 8.38]), as well as Unintentional and Intentional Mind-Wandering responses (mean difference = 2.63, $p < .0005$, 95% CI [1.53, 3.72]). Similarly, older adults' response frequencies were significantly different between Focus and Unintentional Mind-Wandering (mean difference = 8.18, $p < .0005$, 95% CI [5.81, 10.55]), Focus and Intentional Mind-Wandering responses (mean difference = 10.97, $p < .0005$, 95% CI [9.23, 12.71]), and Unintentional and Intentional Mind-Wandering responses (mean difference = 2.79, $p < .0005$, 95% CI [1.88, 3.71]).

Further, follow-up univariate analyses were performed to investigate the Group effect at each level of the within-subjects factor of Probe Response. Younger and older adult groups significantly differed regarding their response frequency for Focus, $F_{1, 66} = 11.69$, $p = .001$, $\eta p^2 = .15$ (group mean difference = -2.59, $p = .001$, 95% CI [-4.12, -.108] and Unintentional Mind-Wandering, $F_{1, 66} = 5.91$, $p = .018$, $\eta p^2 = .08$ (group mean difference = 1.36, $p = .018$, 95% CI [.24, 2.48]. The group difference in Intentional Mind-Wandering frequency was particularly pronounced, $F_{1, 65} = 21.66$, $p < .0005$, $\eta p^2 = .25$ (group mean difference = 1.50, $p < .0005$, 95% CI [.86, 2.15], with older adults reporting significantly fewer incidences of Intentional Mind-Wandering than their younger counterparts.

Table 2.1

Behavioral Performance Indices and Experience Sampling Probe Responses on the Gradual Contrast Change Detection Task for Younger and Older Adult Participants

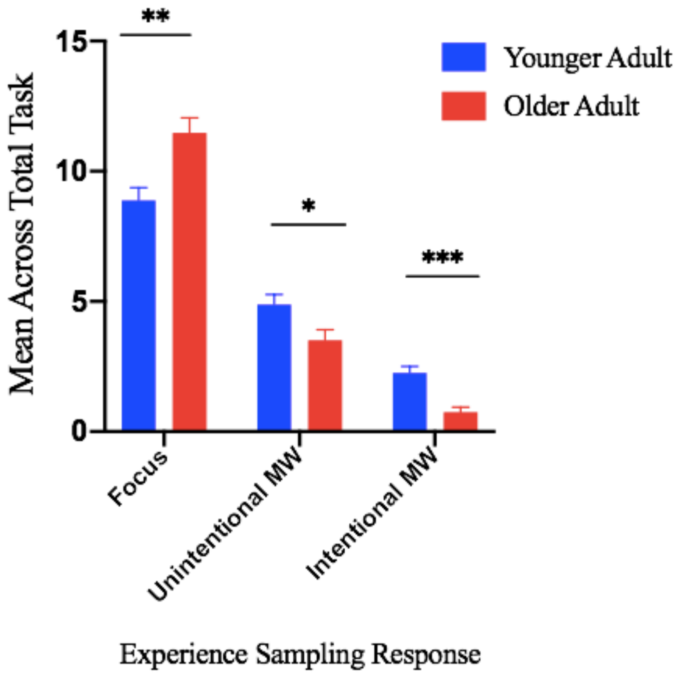
Variable	Young (*n* = 34)	Old (*n* = 34)
	M (*SD*)	*M* (*SD*)
Behavioral Performance		
Hit Rate, median (IQR), Young: *n* = 32, Old: *n* = 32	.95 (.05)	.97 (.07)
Reaction Time	1.31 (.15)	1.33 (.19)
Reaction Time CoV, * Young: *n* = 34, Old: *n* = 32	24.29 (5.22)	21.32 (3.80)
False Alarms, median (IQR), Young: *n* = 32, Old: *n* = 31	2.06 (3.19)	1.13 (4.13)
Experience Sampling		
Focus**	8.88 (2.91) 55.47%	11.47 (3.34) 71.71%
Unintentional MW*	4.88 (2.27) 30.47%	3.51 (2.35) 21.94%
Intentional MW***, Old: *n* = 33	2.25 (1.51) 14.06%	.75 (1.10) 4.66%
Total MW***, Old: *n* = 33	7.13 (2.91) 44.53%	4.28 (3.08) 26.78%

Note. CoV, Coefficient of Variance; IQR, Interquartile range; M, mean; MW, Mind-Wandering; n, Number of observations; SD, Standard deviation.

**p* < .05; ***p* < .01; ****p* < .001

Figure 2.3

Grouped Bar Chart Showing Differences on the Experience Sampling Probe Responses between Younger and Older Adult Participants



Note. Graph displays mean (SEM). MW, Mind-Wandering.
*$p < .05$; **$p < .01$; ***$p < .001$

2.3.5 Hypothesis Three: Unintentional and Intentional Mind-Wandering will Negatively Impact Concurrent Task Performance

Partial Pearson correlations were conducted to determine the relationship between probe responses and behavioral performance indices, controlling for Age Group and NART Errors (see Table **2.2**). There was a statistically significant positive association between Focus and Hit Rate, $r_{\text{partial}}(56) = .41$, $p = .001$, and a negative relationship between Focus and False Alarms, $r_{\text{partial}}(56) = -.28$, $p = .034$. Unintentional Mind-Wandering was associated with reduced Hit Rate, $r_{\text{partial}}(56) = -.42$, $p = .001$, while Intentional Mind-Wandering was positively related with False Alarms, $r_{\text{partial}}(56) = .28$, $p = .035$. Repeated partial correlations controlling for Age Group only showed negligible differences to the reported results (see Table **S.2.4**, §2.5 *Supplemental Material*).

Follow-up exploratory simple mediation models showed RT CoV, but not RT, mediated the Intentional Mind-Wandering and False Alarms relationship (mediated effect = .47, 95% CI .08 to .92). Namely, higher incidences of Intentional Mind-Wandering were associated with more False Alarms, linked in part to their more variable performance (higher RT CoV). Note, an additional analysis did not find a corresponding indirect effect of RT CoV mediating Unintentional Mind-Wandering and False Alarms. Further, neither RT nor RT CoV indirectly influenced the Unintentional Mind-Wandering and Hit Rate relationship (see Figure **2.4**).

Table 2.2

Partial Pearson's r Correlation Coefficients for the Relationships between Experience Sampling Probe Responses and Behavioral Performance Indices, Controlling for Age Group and NART Errors (N= 56)

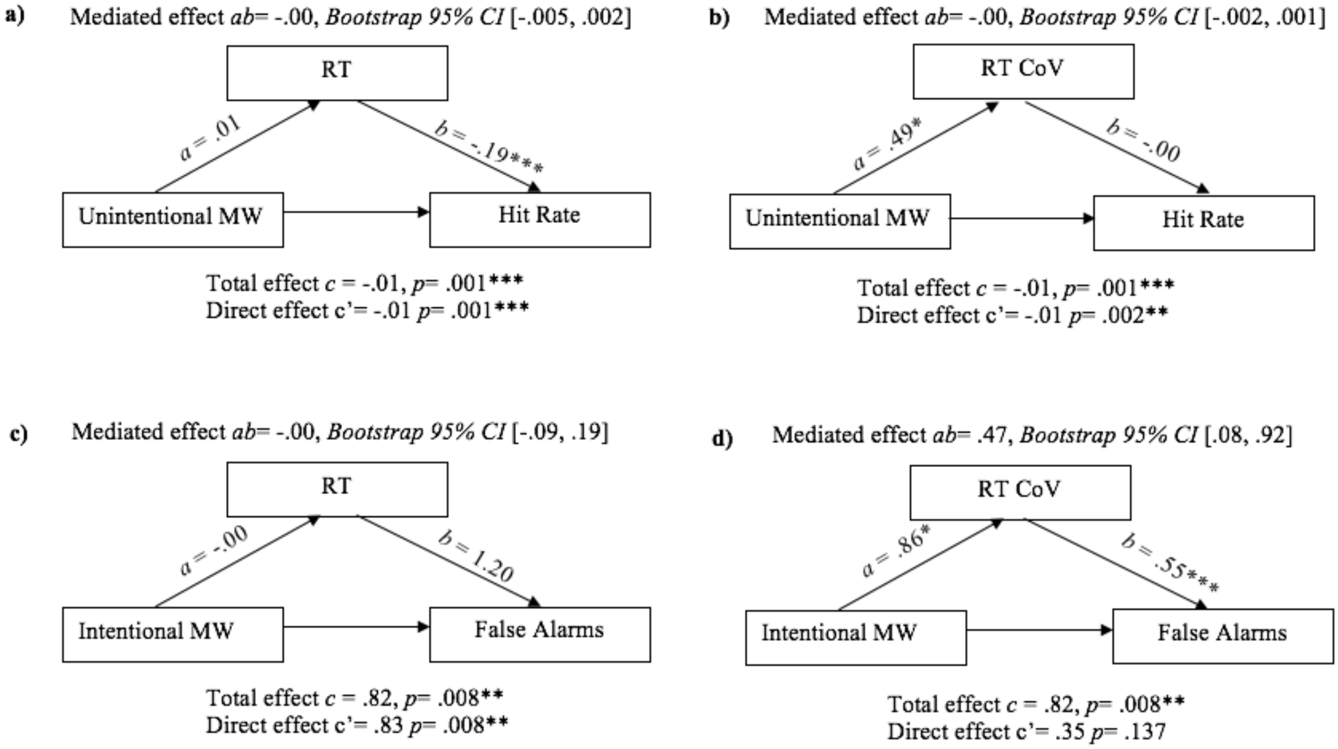
Variable	1	2	3	4	5	6	7	8
1. Focus	-	-.91***	-.70***	-1.00***	.41**	-.12	-.22	-.28*
2. Unintentional MW		-	.34**	.91***	-.42**	.16	.18	.21
3. Intentional MW			-	.70***	-.21	.00	.18	.28*
4. Total MW				-	-.41**	.12	.22	.28*
5. Hit Rate					-	-.59***	-.18	-.45***
6. RT						-	-.39**	-.05
7. RT CoV							-	.79***
8. False Alarms								-

Note. CoV, Coefficient of Variance; MW, Mind-wandering; n, number of observations; NART, National Adult Reading Test; RT, Reaction Time.

**p* < .05; ***p* < .01; ****p* < .001

Figure 2.4

Statistical Diagrams of Exploratory Simple Mediation Models Testing the Effects of Mind-Wandering on Behavioral Performance Outcomes. Mediation Models Display the Effects of (a) Unintentional Mind-Wandering on Hit Rate Mediated by Reaction Time (RT), (b) Unintentional Mind-Wandering on Hit Rate Mediated by RT Coefficient of Variance (CoV), (c) Intentional Mind-Wandering on False Alarms Mediated by RT, and (d) Intentional Mind-Wandering on False Alarms Mediated by RT CoV



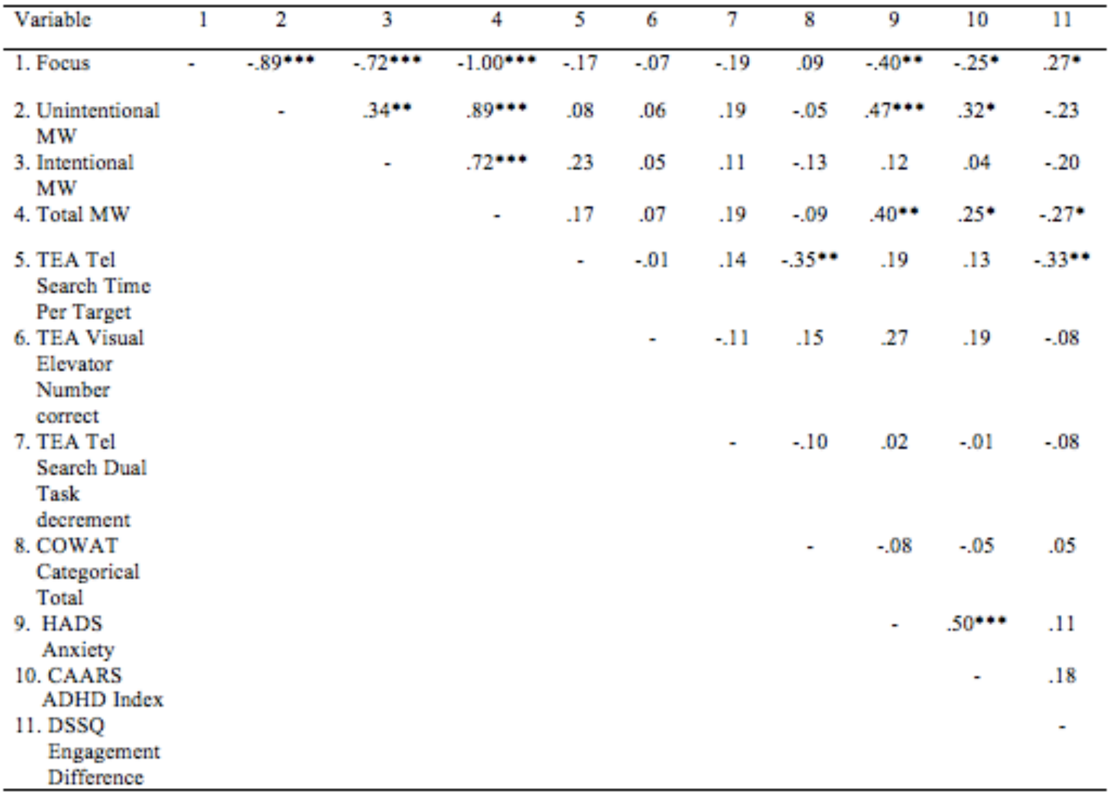
Note. CI, Confidence Interval; CoV, Coefficient of Variance; MW, Mind-Wandering; N, Number of observations; RT, Reaction Time. The mediation parameters show that the effect of Unintentional Mind-Wandering on Hit Rate was not mediated by either (a) RT or (b) RT CoV. Further, the effect of Intentional Mind-Wandering on the number of False Alarms was not mediated by (c) RT but was significantly mediated by (d) RT CoV.

2.3.6 Hypothesis Four: Unintentional and Intentional Mind-Wandering Will be Differentially Associated with Key Neuropsychological Outcomes

Partial Pearson's *r* correlations, adjusted for Age Group and NART Errors, found Focus to be negatively associated with HADS Anxiety, r_{partial} (60) = -.40, *p* = .001, and CAARS ADHD Index, r_{partial} (60) = -.25, *p* = .047, and positively associated with DSSQ Engagement Difference, r_{partial} (60) = .27, *p* = .037. After controlling for covariates, Unintentional Mind-Wandering was significantly positively correlated with greater anxiety, r_{partial} (60) = .47, $p < .0005$, and more ADHD symptoms, r_{partial} (60) = .32, *p* = .012. Intentional Mind-Wandering, conversely, was not associated with the key neuropsychological variables. See Table **2.3** for correlational coefficients. There were no major differences when partial correlations controlled for Age Group only (see Table **S.2.5**, §2.5 *Supplemental Material*).

Table 2.3

Partial Pearson's r Correlation Coefficients for the Relationships Between Experience Sampling Probe Responses and Key Neuropsychological Measures, Controlling for Age Group and NART Errors (*N* = 60).



Variable	1	2	3	4	5	6	7	8	9	10	11
1. Focus	-	-.89***	-.72***	-1.00***	-.17	-.07	-.19	.09	-.40**	-.25*	.27*
2. Unintentional MW		-	.34**	.89***	.08	.06	.19	-.05	.47***	.32*	-.23
3. Intentional MW			-	.72***	.23	.05	.11	-.13	.12	.04	-.20
4. Total MW				-	.17	.07	.19	-.09	.40**	.25*	-.27*
5. TEA Tel Search Time Per Target					-	-.01	.14	-.35**	.19	.13	-.33**
6. TEA Visual Elevator Number correct						-	-.11	.15	.27	.19	-.08
7. TEA Tel Search Dual Task decrement							-	-.10	.02	-.01	-.08
8. COWAT Categorical Total								-	-.08	-.05	.05
9. HADS Anxiety									-	.50***	.11
10. CAARS ADHD Index										-	.18
11. DSSQ Engagement Difference											-

Note. ADHD, Attention-Deficit/Hyperactivity Disorder; CAARS, Conners' Adult ADHD Rating Scale; COWAT, Controlled Oral Word Association Test; DSSQ, Dundee Stress State Questionnaire; HADS, Hospital Anxiety and Depression Scale; MW, Mind-wandering; TEA, Tests of Everyday Attention; Tel, Telephone. *p < .05; **p < .01; ***p < .001

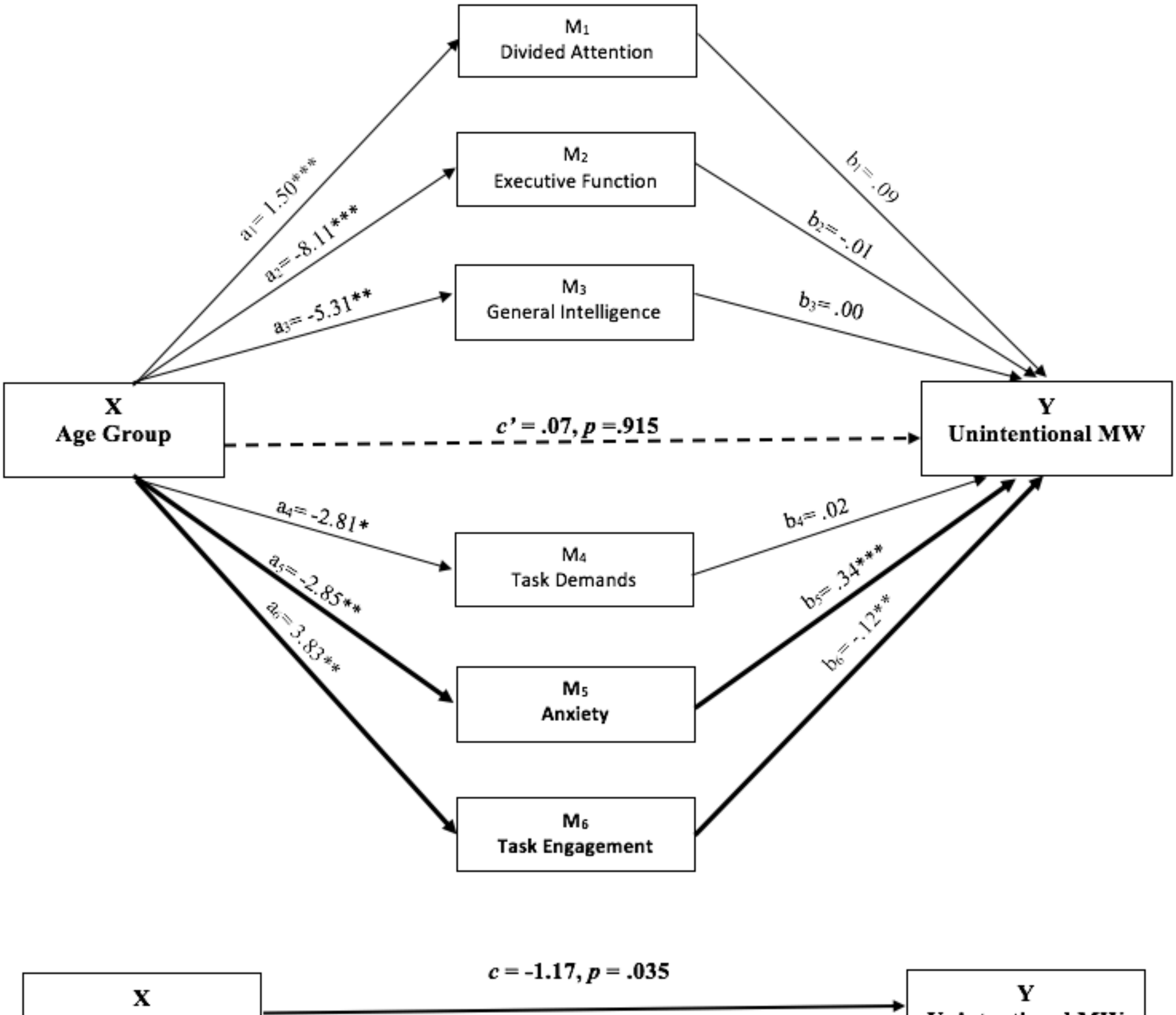
2.3.7 Hypothesis Five: Distinct Neuropsychological Factors Will Mediate the Age Effect for Unintentional and Intentional Mind-Wandering

Bootstrap confidence intervals were used to explore the role of six parallel mediators, derived from four competing theories (cognitive function, task demands, negative affect, and motivation) in mediating the age and mind-wandering effect. Separate parallel mediation analyses were conducted for Unintentional and Intentional Mind-Wandering outcomes. For *Unintentional* Mind-Wandering, the total effect ($c = -1.17$, $t(62) = -2.15$, $p = .035$) showed Age Group to be a significant predictor, ignoring the mediators. Controlling for the mediators, the direct effect of Age Group on Unintentional Mind-Wandering was not significant; there was no evidence that Unintentional Mind-Wandering differed as a function of age when the mediators were statistically controlled, $c' = .07$, $t(56) = .11$, $p = .915$. This indicated an indirect only effect through HADS Anxiety (mediated effect = -.98, 95% CI -1.61 to -.41) and DSSQ Engagement Difference (mediated effect = -.47, 95% CI -1.08 to -.08). Older adults reported fewer incidences of Unintentional Mind-Wandering related to their lower level of anxiety and greater task engagement. No other indirect effects were significant. This is consistent with hypothesized frameworks suggesting the roles of affective and motivational factors. The specific indirect effect contrast did not show a significant difference in the strength of these mediators (effect = -.51, 95% CI -1.31 to .33). The overall model accounted for approximately 40% of the variance explained in unintentional mind-wandering ($r^2 = .3968$, $p < .0005$), see Figure **2.5**.

For *Intentional* Mind-Wandering, both the total ($c = -1.51$, $t(61) = -4.42$, $p < .0005$) and direct ($c' = -1.51$, $t(55) = -2.89$, $p = .006$) effects were significant. The direct effect showed Age Group was related to Intentional Mind-Wandering independent of any mediators. Further, there were no significant indirect effects mediating this relationship, see Figure **2.6**.

Figure 2.5

A Statistical Diagram of the Parallel Mediation Model Testing the Effect of Age Group on Unintentional Mind-Wandering with Six Mediators (N = 64).



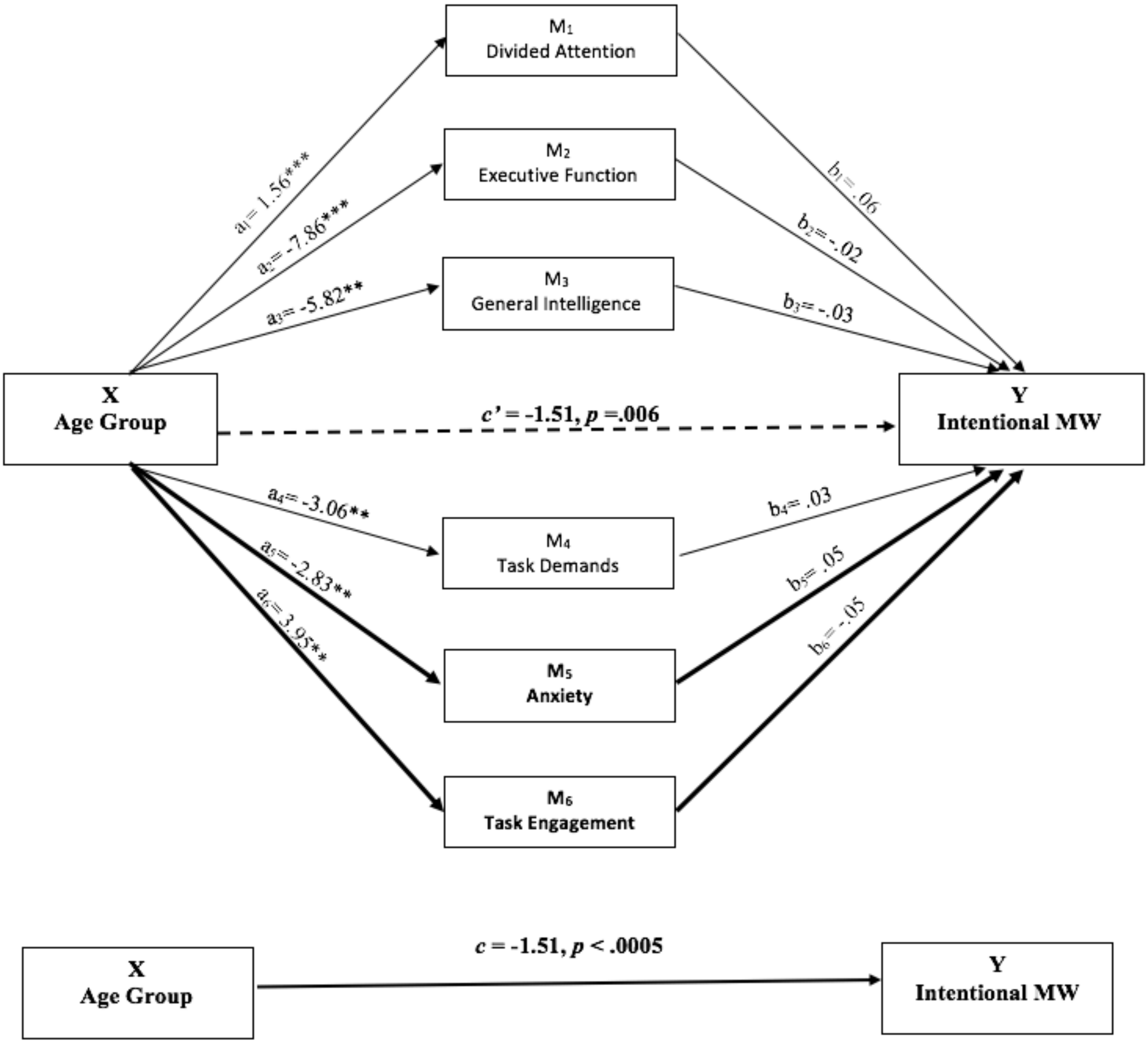
Note. M_1 Divided Attention (TEA Telephone Search Dual Task Decrement); M_2 Executive Function (COWA Category total); M_3 General Intelligence (NART Errors); M_4 Task Demands (RT CoV); M_5 Anxiety (HADS Anxiety); M_6 Task Engagement (DSSQ Engagement difference).

c = Total effect; *c'* = Direct effect; MW, Mind-wandering.

**p* < .05; ***p* < .01; ****p* < .001

Figure 2.6

A Statistical Diagram of the Parallel Mediation Model Testing the Effect of Age Group on Intentional Mind-Wandering with Six Mediators (N = 63).



Note. M_1 Divided Attention (TEA Telephone Search Dual Task Decrement); M_2 Executive Function (COWA Category total); M_3 General Intelligence (NART Errors); M_4 Task Demands (RT CoV); M_5 Anxiety (HADS Anxiety); M_6 Task Engagement (DSSQ Engagement difference).

c = Total effect; *c'* = Direct effect; MW, Mind-wandering.

**p* < .05; ***p* < .01; ****p* < .001

2.4 Discussion

The present study investigated whether the frequency and phenomenology of mind-wandering changed as a function of age and examined the neuropsychological mechanisms mediating age-related differences in Unintentional and Intentional Mind-Wandering. In addition to replicating the consistently observed age-related decrease in Unintentional and Intentional mind-wandering, our research offers three novel findings.

1. We show that only Unintentional, but not Intentional, Mind-Wandering is predicted by affective and motivational models of age-related mind-wandering.
2. We demonstrate that Intentional Mind-Wandering may reflect an adaptive exploratory state that younger adults engage in more frequently than older adults, without incurring a relative cost to task performance.
3. Our study is the first, to our knowledge, to concurrently contrast competing theories of mind-wandering to directly compare the relative contributions of dominant models in the field.

These contributions are based on a multi-faceted methodological approach that assayed mind-wandering during a non-demanding task and presented targets as gradually unfolding contrast changes in a single perceptual feature, rather than fast sudden-onset discrete stimuli that demand rapid information processing or exogenous attention capture.

Despite a natural tendency for both groups to frequently engage in mind-wandering during a simple sustained attention task, older adults exhibited less Unintentional and Intentional Mind-Wandering than their younger counterparts. The larger effect size observed for the intentional group difference underscored a more pronounced proclivity in younger adults to deliberately disengage from the task. This corroborates previous studies evincing an age-accompanied decrease in unspecified mind-wandering (Frank et al., 2015; Giambra, 1989; Irish et al., 2019; Jackson & Balota, 2012; Jordao et al., 2019; Krawietz et al., 2012; Maillet & Schacter, 2016; Maillet et al., 2020; Seli et al., 2020; Shake et al., 2016) and adds to the growing body of research demonstrating age-related reductions in unintentional and intentional mind-wandering (Grodsky & Giambra, 1990; Seli, Maillet, et al., 2017).

There was relative group equivalence in behavioral performance, with the exception of a moderate age-related decrease in RTV. The Exploitation/Exploration oscillation strategy suggests that temporal fluctuations between goal-directed thinking and mind-wandering are modulated by an inner drive (Sripada, 2018). High RTV has been propounded as an index of exploratory mind-wandering, capturing the dynamic, and perhaps impulsive, alternation between task and competing intentions. Thus, our observed age-related reduction in between-trial RTV suggests steadier attentional engagement by older adults.

This finding replicated an effect originally reported by McGovern et al. (2018) who employed a variant of the present task and considered the possible roles of engagement and fluctuating attention in driving the age RTV discrepancy. They indirectly substantiated this claim through analyses of neurophysiological signals relating to sensory evidence accumulation (Centro-Parietal Positivity or CPP; O'Connell et al., 2012) and endogenous attentional engagement (posterior alpha band activity; Dockree et al., 2017; Hanslmayr et al., 2007; Kelly & O'Connell, 2013; O'Connell et al., 2009). Specifically, McGovern et al. (2018) reported greater variability in CPP build-up coupled with more variable posterior alpha band activity in younger adults relative to older adults, indicative of a higher degree of attentional fluctuation. Given higher variability in younger adults was demonstrated in studies that did (the present study) and did not (McGovern et al., 2018) include ES procedures, this finding does not appear to be a by-product of interrupting performance through probes, but rather a marker of oscillating attention. Indeed, previous research has proposed a pronounced exploration bias in younger adults (Mata et al., 2013) and demonstrated more marked RTV in individuals with ADHD compared to controls (e.g. Castellanos et al., 2005; Tamm et al., 2012). Taken together, our results suggest older adults exploited greater task focus and procured a relative behavioral advantage via more stable attentional performance. If there is a trade-off between goal-directed thinking and more explorative mind-wandering, as proffered by the oscillation strategy, then it appears older adults are less inclined to intentionally disengage and explore the mind-wandering space.

Our exploratory partial correlations, controlling for Age Group and IQ, showed focused states were associated with greater Hit Rate and fewer False Alarms. Unintentional Mind-Wandering related to reduced Hit Rate, while Intentional Mind-Wandering related to False Alarms. This latter relationship was mediated by RTV; namely, Intentional Mind-Wandering was associated with more False Alarms accounted, in part, by increased performance instability. The probes were differentially but meaningfully related to behavioral concomitants and showed mind-wandering to incur a negative effect on performance, in accordance with previous studies (e.g.

Cheyne et al., 2009; McVay & Kane, 2009; Mooneyham & Schooler, 2013; Smallwood, McSpadden, Luus, et al., 2008). This corroborates a functional divergence in mind-wandering intentionality (Seli, Risko, Smilek, et al., 2016) and demonstrates the benefit of distinguishing heterogeneous mind-wandering experiences.

What can we understand about mind-wandering dynamics from their relationships with task performance? We submit that these differential associations are in line with the exploitation/exploration strategic theory of mind-wandering (Sripada, 2018); namely, frequent unintended involuntary disruptions to evidence accumulation, through Unintentional Mind-Wandering, led to performance decrements (missed targets). Intentional Mind-Wandering, conversely, may have allowed for dual-tasking, wherein some resources were exploited toward the task and others marshalled in favor of mind-wandering. Given the easy nature of the task, participants may have modulated their Intentional Mind-Wandering relative to task demands without reducing their accuracy. However, this deliberate dropping in and out of an exploratory state, especially by younger adults, may have increased the variability of their responding (indexed by high RTV) and led to more False Alarms. Given that the higher variability in younger adults did not incur a substantial performance cost, they may have more resources available to implement an optimal oscillation strategy, enabling greater exploration through mind-wandering.

Our neuropsychological assessments verified an age-related decline across various cognitive domains, in line with research showing reduced cognitive resources with advancing age (Braver & West, 2008; Foster et al., 2007). Conversely, older adults reported less anxiety, less depression, and fewer daily-life attentional difficulties than younger adults. Moreover, older adults were more alert ahead of the task and reported less task-induced motivation depreciation. This supports reports of greater positive affect and increased task interest in older adults (Jackson & Balota, 2012; Krawietz et al., 2012; Parks et al., 1989). Notably, our cognitive measures were not associated with mind-wandering after controlling for age group and IQ. Similarly, Shake et al. (2016) found working memory capacity to be unrelated to mind-wandering after covarying age and text interest. Correspondingly, our partial correlations revealed Focus to be associated with less anxiety, fewer ADHD symptoms and less task-induced motivation loss. Conversely, Unintentional Mind-Wandering was associated with increased anxiety and ADHD symptoms. Interestingly, Intentional Mind-Wandering was not correlated with the neuropsychological outcomes. This highlights how conflation of mind-wandering types may mask unique associations.

What factors influence the inclination to mind-wander in younger but not older adults? Our parallel mediation analyses found anxiety and task engagement mediated the Age Group and Unintentional Mind-Wandering relationship, whereas no indirect effects by the posited mediators were observed for Intentional Mind-Wandering. Older adults curbed their Unintentional Mind-Wandering, influenced, at least partially, by less negative affect and greater motivation than younger adults. Neither the cognitive nor task demand factors influenced this relationship which is striking given the widely hypothesized mind-wandering accounts implicating executive resources (McVay & Kane, 2010; Smallwood & Schooler, 2006). Instead, our results elucidate the roles of dispositional factors, supporting affective (e.g. Frank et al., 2015; Klinger, 1971) and motivational (e.g. Jackson & Balota, 2012) accounts, in contributing to age-differences in Unintentional Mind-Wandering.

Although Intentional Mind-Wandering was also reduced in the older group, this effect was not similarly mediated by dispositional factors. This is in accordance with Seli, Maillet, et al. (2017) who reported a negative correlation for both age groups between motivation and unintentional mind-wandering, but not for motivation and intentional mind-wandering. We advance that older adults marshal their more limited executive resources toward the primary task to avoid risking a more balanced ‘exploit/explore’ oscillation strategy. In support, we showed a lack of indirect effects influencing Intentional Mind-Wandering, a sustained direct effect of Age Group, and a key RTV group difference; together this favours a more restricted oscillation strategy with age. The reported mediations simultaneously tested the roles of multiple putative mechanisms in integrated models, but these models neither account for all possible intervening variables nor facilitate explicit causal claims. Other factors not currently investigated, such as cognitive fatigue, may also partially account for these observed findings. Although related to motivation, cognitive fatigue coupled with tedium may have led participants, particularly younger adults, to deliberately disengage from the task. Indeed, one of the espoused benefits of mind-wandering is relief from boredom (Mooneyham & Schooler, 2013). Further, given the low-task demands and lack of novelty employed by the current task, any moderating impact of older adults’ reduced capacity for rule-switching, or poorer memory for response requirements, may have been minimised.

Previous research has shown that after controlling for affect (Frank et al., 2015) and interest/motivation (Frank et al., 2015; Krawietz et al., 2012; Seli et al., 2020; Shake et al., 2016), age differences in mind-wandering decreased. Our study extended previous designs that analysed motivation captured pre-task (Seli et al., 2020) or retrospectively (Frank et al., 2015; Krawietz et al., 2012; Shake et al., 2016), by analysing pre-to-post change scores to index task-induced motivation differences. Moreover, by including multiple mediators in our intentionality models, we dissociated several prominent theories, and showed the additive value of affective and motivation factors, thereby providing further insights into the factors that influence Unintentional Mind-Wandering. Overall, our findings show how distinguishing between the presence, or absence, of intentionality yields deeper insights into the impact of age on mind-wandering.

2.4.1 ***Methodological Considerations and Avenues for Future Research***

Despite current developments, we acknowledge several methodological limitations with recommendations for future research. Firstly, natural environments may provide broader scope for investigating mind-wandering compared to circumscribed lab environments, where individuals have stronger demand characteristics placed on them to perform. If the oscillation strategy is seen as an optimal approach to balance two modes of thought: exploring self-generated thoughts during mind-wandering versus focusing on current opportunities, then this might be best captured in open-ended, unstructured natural environments, with more freedom to explore. Within the quotidian, individuals engage in self- or other-imposed tasks, but also in situations where no explicit goal/task is defined (Murray et al., 2020). Preliminary field research by Maillet et al. (2018) has demonstrated age-attenuated mind-wandering and a positive association between negative affect and mind-wandering during daily activities. Moreover, a recent study with students, found that despite broadly similar patterns of off-task thought content and neural architecture across lab and daily life contexts, lab-sampled thoughts were more oriented toward other people than those from daily life (Ho et al., 2020). Future approaches should investigate if everyday mind-wandering propensity changes with age, contextualised by the richness of everyday experience, to pinpoint the mechanisms underlying such changes within a real-world environment. Incorporating field ES (Ho et al., 2020; Kane et al., 2017; Maillet et al., 2018; McVay et al., 2009) and non-invasive lifelogging technology (e.g. Gurrin, Smeaton, & Doherty,

2014) may augment our mechanistic understanding of fluctuating attention and its consequences across ecologically valid activities.

Secondly, despite the instrumental utility of ES for advancing the exploration of mind-wandering, there are associated challenges. It may be that content, rather than process, is more consciously penetrable for self-reports (Nisbett & Wilson, 1977), or that the very act of introspection may alter the quality of the experience being assessed (Schooler, 2002). The value of phenomenological reports, i.e. what it feels like to be in a particular experience/state, however, is not dependent on a conscious understanding of the higher-order cognitive processes. Participants may, through reflective recovery of the process (which is subjective and “first-personal”), make a judgment as to whether their thoughts were deliberately intended. Indeed, the dissociable correlations between Unintentional and Intentional Mind-Wandering and external outcomes (Corbetta & Shulman, 2002; Golchert et al., 2017; Seli, Ralph, et al., 2017; Seli, Risko, et al., 2017; Seli, Risko, Smilek, et al., 2016; Seli, Smallwood, et al., 2016) demonstrates the validity of intentionality judgments and the inherent value of first-person responses.

Moreover, self-reported mind-wandering may be influenced by how it is defined or perceived. Although varying response options and social desirability bias represent possible moderating factors, age-related differences in mind-wandering remain even when a) thoughts concerning performance, namely task-related interference, are measured separately (Maillet & Schacter, 2016), b) variations in probe framing are included (Jordao et al., 2019), or c) incentives for reporting mind-wandering are provided (Zedelius, Broadway, & Schooler, 2015). This suggests that other factors are driving the age-reduction in mind-wandering. Additionally, it may be argued that prior training on probe categories ahead of the task primed participants to ascribe greater importance to monitoring their mental states (Smallwood & Schooler, 2006). However, age-differences in mind-wandering have persisted across probe- (Frank et al., 2015) and self-caught (Grodsky & Giambra, 1990) procedures, and the validity of mind-wandering self-reports has been established against behavioral concomitants (McVay et al., 2013), eye-movements (Frank et al., 2015), and neural correlates (Golchert et al., 2017). In the present study, the probes were used to circumvent potential meta-cognitive limitations in older adults (Maillet & Schacter, 2016). Metacognitive processes, however, warrant further investigation as a possible source of age-related changes in mind-wandering.

Thirdly, the HADS was employed to better understand the role of affect in age-related mind-wandering. This measure, however, does not fully capture the conceptually related “current concerns” construct, which indexes the quantity and content of non-trivial concerns/active personal goals. It is challenging to distinguish affective from non-affective concerns in order to investigate the relative explanatory power of both current concerns and affective accounts. More research is needed with a diverse younger population to disentangle the impact of current concerns on mind-wandering and determine if it is the number of concerns, the content of concerns, or the affective saliency of concerns that contribute to increased mind-wandering in younger adults.

Finally, our older adults ranged in age from 65 to 78 years old (“young-old”) and were highly educated. Cognitive decline is particularly pronounced in those of more advanced age, i.e. older adults on the older end of the continuum, (Borella, Carretti, & De Beni, 2008), and with poorer education (Stern, Alexander, Prohovnik, & Mayeux, 1992). Clustering older adult age groups may mask the precise impact of executive resources or task demands on age-related mind-wandering (Gyurkovics, Balota, & Jackson, 2018; Jordao et al., 2019; Zavagnin et al., 2014). A recent meta-analysis observed a moderating effect of the mean age of the older group on the age-reduction in mind-wandering (Jordao et al., 2019). Additionally, mind-wandering rates were comparatively lower in mild cognitive impairment (MCI) (Niedźwieńska & Kvavilashvili, 2018), early stage Alzheimer’s disease (Gyurkovics et al., 2018; although see O'Callaghan, Shine, Hodges, Andrews-Hanna, & Irish, 2019), frontotemporal dementia (O'Callaghan et al., 2019), and Parkinson’s disease (Geffen et al., 2017) compared to healthy older adults. Therefore, our surprising absence of executive deficits contributing to mind-wandering in healthy older adults raises the question as to whether, or at what timepoint, cognitive resources begin to degrade the propensity for, or content of, spontaneous thought in MCI and Alzheimer’s disease. The ability to preserve these states for longer is an important facet of self-awareness and one’s humanity and identity in the face of dementia (O'Callaghan et al., 2019). Longitudinal approaches may capture mind-wandering changes across a broader age continuum and with progressive degeneration.

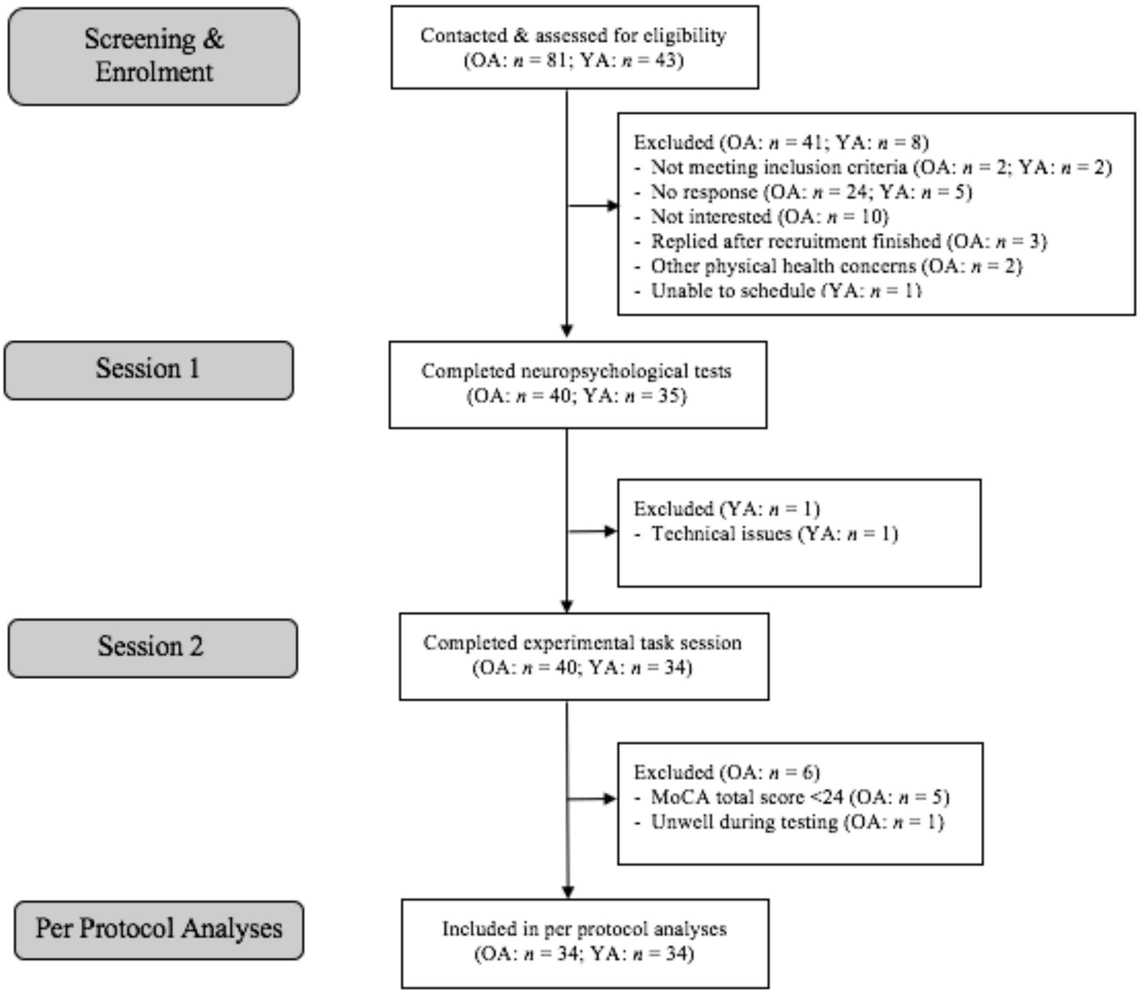
2.4.2 Conclusions

Considering the documented global trend of population aging, clarifying the extent to which aging influences key mental processes is paramount. Accordingly, the complex relationship between mind-wandering and aging has garnered research attention. Despite its ubiquity, it remains an under-examined phenomenon because of its inherent ephemeral and covert phenomenology. Although, a robust and perhaps, paradoxical, age-accompanied decrease in mind-wandering has been reported, the crucial dynamics and factors involved have been largely precluded from the cognitive aging literature. Our study enabled consideration of different mind-wandering dimensions by providing additional insights into how unintentional and intentional mind-wandering change with age. We adjudicated between prominent theories, providing positive support for affective and motivational accounts as influencing the age-related diminution in unintentional mind-wandering, with reasons to be less persuaded by executive resource theories. Additionally, we propound a more exploitative oscillation strategy in older adults as mitigating the effects of their reduced cognitive resources to explain their decreased tendency to intentionally mind-wander. Consideration of dispositional and strategic factors in future examinations may shed light on the impact of aging on unintentional and intentional mind-wandering.

2.5 Supplemental Material

Figure S.2.1

Participant Consort Flow Diagram.



Note. *n*, number of observations; OA: Older adults; YA: Younger adults.

Table S.2.1

Details on the Neuropsychological Measures

	Cognitive Function
National Adult Reading Test (NART; Nelson & Willison, 1991)	The NART is a word reading test used to estimate premorbid IQ. Participants read aloud 50 irregular words, of increasing difficulty, scored for pronunciation accuracy. The number of pronunciation errors committed was recorded.
Tests of Everyday Attention (TEA; Robertson et al., 1996)	The TEA is a battery of tests assessing aspects of attentional functioning. Participants completed three TEA subtests: a) Visual Elevator (attentional switching), b) Telephone Search (visual selective attention), and c) Telephone Search while Counting (sustained and divided attention). In the Visual Elevator task, participants counted a series of visually presented elevator floors, in upward and downward directions, to identify the number of the final floor. The total number of correct trials was noted. For the Telephone Search, participants scanned a sample telephone directory sheet for pairs of matching symbols. The average time per correctly identified target was recorded. In the Telephone Search while Counting task, participants performed an alternate version of the previous subtest, identifying matching symbol pairs in a simulated telephone directory, concurrently to counting strings of audio tones played from a CD player. The average time per target weighted for tone counting accuracy (sustained attention) was calculated and then subtracted from the time per target from the previous trial to devise a dual-task decrement score (divided attention).
STROOP Color and Word test (Golden & Freshwater, 2002)	The Stroop test was incorporated as a measure of selective attention, processing speed, and susceptibility to cognitive interference. Participants performed two congruous conditions (the Word and Color trials) and one incongruous condition (the Color-Word trial). In each condition, participants read aloud a stimulus sheet, comprising 100 items, as quickly as possible. In the Word trial (W), participants read a list of color words items (“Blue”, “Green”, or “Red”) printed in black ink. The color trial (C) consisted of the letters ‘XXXX’ printed in blue, green or red ink. Here, participants were tasked with naming the color ink. In the Color-Word trial (CW), the color

	words were printed in incongruent ink colors (e.g. the word “Red” was printed in blue ink). Participants were required to identify the color ink the word was printed in and suppress their instinct to read the word. The time taken to complete the 100 items in each condition was recorded. A further measure of “Interference” was derived by subtracting the predicted color-word score from the raw colour-word score
Controlled Oral Word Association Test (COWAT; Benton et al., 1994; Spreen & Strauss, 1998)	Participants were tasked with generating as many words as possible, within 60-second timeframes, from given phonemic (“F”, “A”, “S”; letter fluency) or semantic (“animals” and “boys” names; category fluency) criteria to assess executive function. Summed acceptable words across phonemic and semantic trials were calculated.
Negative Affect	
Hospital Anxiety and Depression Scale (HADS; Zigmond & Snaith, 1983)	The HADS is a 14-item self-report scale measuring psychological distress symptoms occurring over the previous week and comprises two subscales with 7 items relating to anxiety (HADS Anxiety), and 7 items on depression (HADS Depression). Participants rated each item on a four-point response scale (0-3). Item responses were summed to create subscale totals, each with a maximum score of 21.
Daily Life Attentional Difficulties	
Conners’ Adult ADHD Rating Scale (CAARS; Conners et al., 1999)	The CAARS is a measure of the presence and severity of Attention-Deficit/Hyperactivity Disorder (ADHD) related symptoms. Participants completed the short self-report form, a 26-item symptom rating scale comprising statements referring to recent behaviors and problems, rated on a four-point Likert scale, ranging from 0 “Not at all, never” to 3 “Very much, very frequently”. Four domain scores were derived from the scale items, including a) inattention/memory problems, b) hyperactivity/restlessness, c) impulsivity/emotional lability and d) problems with self-concept, with an additional e) 12-item ADHD index.
Task-Related Motivation	
Stanford Sleepiness Scale (SSS; Hoddes et al., 1973)	The SSS is a single-item question on current subjective level of sleepiness with a seven-point Likert response range, from 1 “Feeling active, vital, alert, wide awake” to 7 “No longer fighting sleep, sleep onset soon, having dream like thoughts”.

The Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999)	The short-version of the DSSQ is a 30-item multidimensional self-report scale assessing task-related engagement, distress, and worry. Prior to the target detection task, participants were asked to rate each item on a five-point scale, from 0 “Definitely false” to 4 “Definitely true”, based on how they were feeling in that moment. Participants repeated the scale following completion of the task; this time, assessing how they felt while performing the task. DSSQ difference scores between the two time-points (post-task minus pre-task) were calculated to measure state changes induced by the task. Negative scores indicated task-induced decline, whereas positive scores indicated task-induced increase.

Note. The neuropsychological test battery was administered to all participants by well-trained Research Assistants using a standardized protocol in a quiet well-lit testing room, lasting approximately 45-60 minutes. Descriptive statistics of their performance are provided in Table **S.2.3** (§*2.5 Supplemental Material*). The number of observations for the Stroop ‘Interference’ measure was reduced as the 45-second time limit used in the calculation of its component raw and predicted color-word scores, was introduced midway into the data collection period. Specific key neuropsychological variables used for hypothesis testing analyses included TEA Telephone Search Time per target, TEA Visual Elevator number correct, TEA Telephone Search dual-task decrement, COWAT Categorical total, HADS Anxiety, CAARS ADHD Index, and DSSQ Engagement Difference.

Table S.2.2

Baseline Sociodemographic Characteristics for Younger and Older Adult Participants

Variable	Young (*n* = 34)	Old (*n* = 34)
	M (SD)	*M* (SD)
Age, years	21.71 (4.59)	70.97 (3.54)
Age range, years	18-35	65-78
Gender, *n*	20 Female, 14 Male	16 Female, 18 Male
Marital status, *n* (%)		
Co-habiting	0	1 (2.90%)
Engaged	0	2 (5.90%)
Married	0	23 (67.60%)
Separated/divorced	0	2 (5.90%)
Single/Never married	34 (100%)	4 (11.80%)
Widowed	0	2 (5.90%)
Full-time education, years	16.21 (2.41)	15.19 (3.24)
Highest qualification, *n* (%)		
Doctor of Philosophy	1 (2.90%)	1 (2.90%)
Masters	1 (2.90%)	6 (17.60%)
Undergraduate	4 (11.80%)	12 (35.30%)
Diploma/Certificate	3 (8.80%)	6 (17.60%)
Leaving Certificate	25 (73.50%)	7 (20.60%)
Junior Certificate	0	1 (2.90%)
Primary	0	1 (2.90%)
Employment status, *n* (%)		
Paid/self-employed	1 (2.90%)	2 (5.9%)
Retired	0	29 (85.30%)
Semi-retired	0	3 (8.80%)
Student	33 (97.10%)	0
Living situation, *n* (%)		
Alone	2 (5.90%)	8 (23.50%)
Alone with children	0	1 (2.90%)
With family	11 (32.40%)	0
With friends	11 (32.40%)	0
With partner and/or children	1 (2.90%)	24 (70.60%)
With unrelated persons	9 (26.50%)	1 (2.90%)
MoCA Total Score	N/A	27.47 (1.52)

Note. M, mean; MoCA, Montreal Cognitive Assessment; *n*, Number of observations; N/A, Not applicable; SD, Standard deviation.

Table S.2.3

Descriptive Statistics on Key Neuropsychological Variables for Younger and Older Adults

Variable	Young (n = 34)	Old (n = 34)
	M (SD)	*M* (SD)
Cognitive Function		
NART Errors**	16.94 (6.03)	11.41 (9.18)
TEA Visual Elevator Correct, Old: n = 33	8.35 (1.59)	8.39 (1.58)
TEA Tel. Search Time per Target***	2.86 (.65)	4.04 (.88)
TEA Tel. Search while Counting Time per Target Weighted*** Young: n = 32	2.96 (.59)	6.01 (2.75)
TEA Tel. Search Dual Task Decrement*** Young: n = 33, Old: n = 33	.24 (.48)	1.73 (1.96)
Stroop Word Total Time	48.37 (7.92)	51.49 (9.38)
Stroop Color Total Time***	64.65 (10.48)	78.48 (16.44)
Stroop Color-Word Total Time***	97.59 (21.08)	136.42 (31.26)
Stroop Interference** Old: n = 12	7.78 (8.48)	-1.03 (7.82)
COWAT Phonemic Total	41.21 (8.41)	43.79 (12.65)
COWAT Categorical Total**	45.03 (7.38)	38.18 (9.73)
Negative Affect		
HADS Anxiety***	6.53 (3.77)	3.38 (2.71)
HADS Depression, median (IQR)*	5.00 (8.00)	2.00 (4.00)
Daily Life Attentional Difficulties		
CAARS A Inattention/ Memory Problems** Old: n = 30	6.35 (3.63)	4.23 (1.55)
CAARS B Hyperactivity/ Restlessness***	6.79 (3.01)	2.88 (1.97)
CAARS C Impulsivity/ Emotional Lability	3.47 (2.36)	2.71 (1.69)
CAARS D Problems with Self-Concept**	7.15 (4.01)	4.21 (2.80)
CAARS E ADHD Index***	12.88 (5.14)	7.90 (3.79)
Task-Related Motivation		
SSS, median (IQR)**	2.00 (1.00)	2.00 (1.00)

DSSQ Engagement Difference**	-6.97 (4.99)	-3.12 (5.97)
DSSQ Distress Difference, Young: *n* = 33	3.09 (5.82)	1.03 (5.72)
DSSQ Worry Difference*	4.71 (4.58)	1.76 (5.82)

Note. CAARS, Connor's Adult ADHD Rating Scale; COWAT, Controlled Oral Word Association Test, DSSQ, Dundee Stress State Questionnaire; HADS, Hospital Anxiety and Depression Scale; IQR, Interquartile range; M, mean; NART, National Adult Reading Test; *n*, Number of observations; SD, Standard deviation; SSS, Stanford Sleepiness Scale; TEA, Tests of Everyday Attention, Tel, Telephone.

*p < .05; **p < .01; ***p < .001

Table S.2.4

Partial Pearson's r Correlation Coefficients for the Relationships between Experience Sampling Probe Responses and Behavioral Performance Indices, Controlling for Age Group (N= 57)

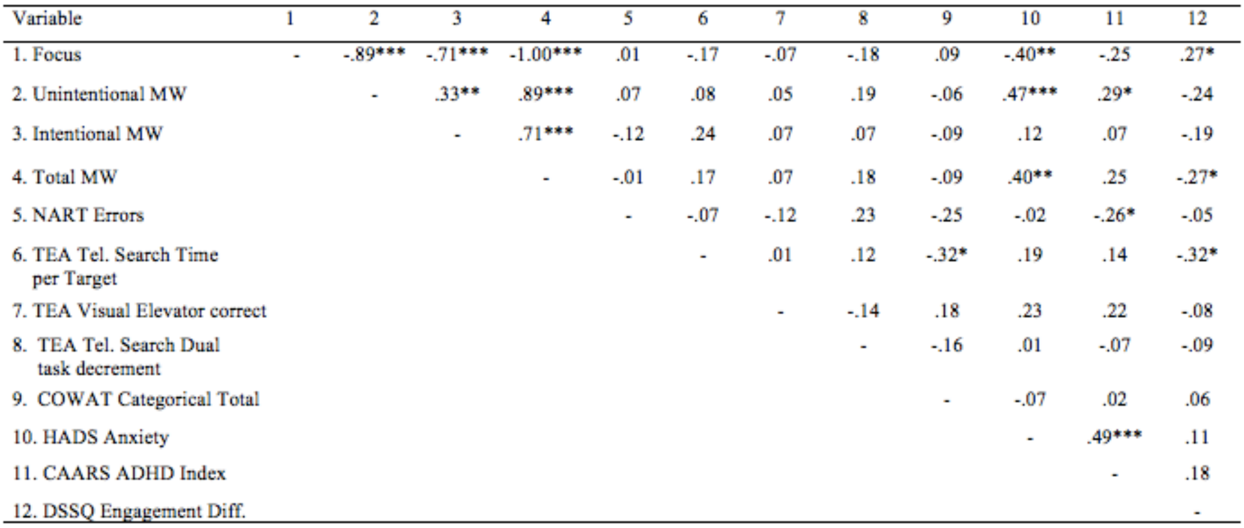
Variable	1	2	3	4	5	6	7	8
1. Focus	-	-.90***	-.69***	-1.00***	.41**	-.12	-.21	-.28*
2. Unintentional MW		-	.32*	.90***	-.42**	.17	.18	.21
3. Intentional MW			-	.69***	-.21	-.01	.16	.26*
4. Total MW				-	-.41**	.12	.21	.28*
5. Hit Rate					-	-.59***	-.18	-.44***
6. RT						-	-.38**	-.04
7. RT CoV							-	.79***
8. False Alarms								-

Note. CoV, Coefficient of Variance; MW, Mind-wandering; N, number of observations; RT, Reaction Time.

*p < .05; **p < .01; ***p < .001

Table S.2.5

Partial Pearson's r Correlation Coefficients for the Relationships Between Experience Sampling Probe Responses and Key Neuropsychological Measures, Controlling for Age Group (N = 61)



Variable	1	2	3	4	5	6	7	8	9	10	11	12
1. Focus	-	-.89***	-.71***	-1.00***	.01	-.17	-.07	-.18	.09	-.40**	-.25	.27*
2. Unintentional MW		-	.33**	.89***	.07	.08	.05	.19	-.06	.47***	.29*	-.24
3. Intentional MW			-	.71***	-.12	.24	.07	.07	-.09	.12	.07	-.19
4. Total MW				-	-.01	.17	.07	.18	-.09	.40**	.25	-.27*
5. NART Errors					-	-.07	-.12	.23	-.25	-.02	-.26*	-.05
6. TEA Tel. Search Time per Target						-	.01	.12	-.32*	.19	.14	-.32*
7. TEA Visual Elevator correct							-	-.14	.18	.23	.22	-.08
8. TEA Tel. Search Dual task decrement								-	-.16	.01	-.07	-.09
9. COWAT Categorical Total									-	-.07	.02	.06
10. HADS Anxiety										-	.49***	.11
11. CAARS ADHD Index											-	.18
12. DSSQ Engagement Diff.												-

Note. ADHD, Attention-Deficit Hyperactivity Disorder; CAARS, Conners' Adult ADHD Rating Scale; COWAT, Controlled Oral Word Association Test; Diff, difference; DSSQ, Dundee Stress State Questionnaire; HADS, Hospital Anxiety and Depression Scale; MW, Mind-wandering; NART, National Adult Reading Test; N, number of observations; TEA, Tests of Everyday Attention; Tel, Telephone.

$*p < .05$; $**p < .01$; $***p < .001$

Chapter 3: Empirical Paper 2

Characterising the Electroencephalographic and Pupillometric Signatures of Mind-Wandering in Healthy Ageing

3.1 Introduction

3.1.1 Age-Related Differences in Mind-Wandering

Mind-wandering is an ephemeral, universal, and dynamic mental state, under the umbrella of spontaneous thought phenomena (Christoff et al., 2016), wherein thoughts transition from task-related or perceptually-guided thoughts to unrelated, self-generated mental content (Smallwood & Schooler, 2015). As a prominent feature of human cognition, mind-wandering is estimated to occupy between 25% and 50% of all conscious cogitations (Kane et al., 2007; Killingsworth & Gilbert, 2010; Klinger & Cox, 1987). Previous research has established a consistent and robust age-related diminution in the frequency of mind-wandering across a diverse range of lab, online, and daily-life settings (see meta-analysis Jordao et al., 2019; see review Maillet & Schacter, 2016).

In our previous work (*see Chapter 2* of this thesis, or Moran et al., 2021), we replicated this finding of reduced mind-wandering as a function of age and highlighted the influential role of dispositional factors (out of the factors investigated), notably affect and motivation, mediating its advent. Although younger and older adults differed regarding standardised tests of executive function and attention, these cognitive variables did not statistically mediate the relationship between age group and mind-wandering propensity (Moran et al., 2021). An age-related behavioural difference in reaction time variability (RTV), a known index of oscillatory attention cycles (Esterman et al., 2013), was observed which indicated strategic differences in how younger and older adults approached the task. Taken together, our findings highlighted the need to examine strategic factors in future investigations of age-related mind-wandering. The focus of the current chapter, therefore, is to better understand how ageing influences the strategic trade-off between opposing demands of task focus and mind-wandering as expressed by the "exploitation/exploration trade-off" model (Sripada, 2018), against a backdrop of reduced executive function with age.

3.1.2 Exploitation/Exploration: A Strategic Model of Mind-Wandering

The "*exploitation/exploration trade-off*" (Sripada, 2018) posits an antagonistic alternation between "exploitative" goal-directed processes and "explorative" modes of thinking, namely mind-wandering. In exploitation, an agent capitalises on current resources and familiar options in the pursuit of a goal; whereas in exploration, an agent engages in a widening search for unknown alternatives and potentially more promising opportunities. Exploitative goal-directed thinking is associated with the successful coordination of attention, working memory, and cognitive control for goal fulfilment (Botvinick & Cohen, 2014; Evans, 2008). Explorative mind-wandering may also be beneficial in some situations, for example, for creative incubation, pattern learning, novelty-seeking, problem-solving, and autobiographical memories (Baird et al., 2012; Mata et al., 2013; Mooneyham & Schooler, 2013).

Optimal decision-making and effective performance require balanced and flexible regulation between these exploit/explore strategies on a trial-by-trial basis in response to changing contextual demands or temporal uncertainties. RTV has been propounded as a quantitative index of this strategic optimisation and modulatory temporal alternation between task and other competing intentions. Specifically, high RTV has been observed during mind-wandering and low RTV during focused, goal-directed thinking (Cheyne et al., 2009; Esterman et al., 2013; Mooneyham & Schooler, 2013; Smallwood, McSpadden, Luus, et al., 2008). Rather than a precise dichotomy, these two serial modes of thought likely reflect a continuum, whereby actions appear comparatively more exploitative or exploratory relative to the given context.

The exploitation/exploration framework when applied to the cognitive ageing literature may elucidate the role of different oscillatory dynamics in age-related mind-wandering patterns. To that end, preliminary research has demonstrated an exploration bias in younger adults during a set of lab-based foraging tasks (Mata et al., 2013) and an age-related reduction in performance variability (RTV) in sustained attention tasks, suggestive of older adults adopting a more exploitative oscillatory approach (McGovern et al., 2018; Moran et al., 2021). Alongside dispositional factors, namely positive affect and better task-engagement by older adults (Moran et al., 2021), reduced age-related executive resources (Braver & West, 2008; Foster et al., 2007) may curb older adults' ability to alternate between competing strategies, contributing to their decreased tendency to explore the mind-wandering space. However, the degree to which the natural ageing process interacts with this capacity for optimal strategic regulation, and the posited underlying mechanisms, remains largely unknown.

3.1.3 Candidate Mechanisms Underlying Oscillatory Attentional Shifts

The information processing mechanisms that underlie the aforementioned strategic model cannot be fully understood by behavioural assays alone. The high temporal resolution of physiological recordings provides a means to trace discrete and dissociable neural signals that reflect the transitions between goal-directed thinking and endogenously driven mind-wandering as they unfold in real time. Specifically, different stages of processing have been examined using electrophysiological methods within the context of ageing, through signals that reflect fluctuations in attentional engagement, as well as target processing markers, such as sensory representations, evidence accumulation, and motor action preparation (McGovern et al., 2018). However, the relationships of such electrophysiological indices to different mind-wandering propensities in younger and older adults have yet to be investigated.

3.1.4 Key Neurophysiological Components of Fluctuating Attentional Engagement

3.1.4.1 Alpha Frequency: Oscillatory Attention. Modulation of alpha-band activity over posterior scalp regions is a widely used electrophysiological index of endogenous attention, reflecting top-down inhibitory control and higher-order attentional processes (Clayton, Yeung, & Cohen Kadosh, 2015; Dockree et al., 2017; Hanslmayr et al., 2007; Kelly, Lalor, Reilly, & Foxe, 2006; Kelly & O'Connell, 2013; O'Connell et al., 2009; Thut, Nietzel, Brandt, & Pascual-Leone, 2006). Alpha amplitude provides a robust predictor of attentional lapses (O'Connell et al., 2009), as does alpha variability (Dockree et al., 2017), and is sensitive to subjective states of mind-wandering (Compton et al., 2019). Oscillatory alpha activity preceding behavioural processing also predicts performance decrements across a range of tasks (Macdonald et al., 2011; Mazaheri, Nieuwenhuis, van Dijk, & Jensen, 2009; O'Connell et al., 2009; Thut et al., 2006; van Dijk, Schoffelen, Oostenveld, & Jensen, 2008).

Research has increasingly demonstrated that during alpha synchronization, controlled monitoring of the external task is inhibited as an individual disengages from the task to mind-wander or to deploy attention elsewhere (the "alpha-inhibition hypothesis", Klimesch, 2012). Indeed, parieto-occipital alpha power has been shown to be reduced when participants attended to external visual input (e.g. Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998) but to be elevated during tasks involving other sensory modalities (e.g. Foxe, Simpson, & Ahlfors, 1998; Linkenkaer-Hansen, Nikulin, Palva, Ilmoniemi, & Palva, 2004) and those requiring internally-directed cognition (e.g. Braboszcz & Delorme, 2011). In relation to ageing specifically, attenuated pre-target alpha variability in older adults compared to younger adults has been documented (McGovern et al., 2018), suggesting a pattern of steadier attentional engagement with age. As such, alpha power may provide insight into the dynamics of shifting attentional states in younger and older adults.

3.1.4.2 Pupil Diameter.

3.1.4.2.1 Attentional Allocation. Pupil dilation has been traditionally considered an indirect measure of the intensity of attentional allocation, cognitive load, mental effort, and the intensity of processing during cognitive tasks (Alnaes et al., 2014; Beatty, 1982; Kahneman, 1973; Kahneman & Beatty, 1966, 1967). More recently, endogenous baseline pupil diameter (PD) and task-evoked pupillary responses have been utilised as covert indices tracking fluctuating attentional states (Aston-Jones & Cohen, 2005; Joshi et al., 2016). However, research on the specific pupillometric signatures of mind-wandering has yielded contradictory findings. Whereas some studies have demonstrated an association between larger baseline PD and off-task thoughts and/or poorer sustained attentional performance (proxies for mind-wandering) (Franklin, Broadway, et al., 2013; Smallwood et al., 2012), other studies have shown the opposite pattern (Grandchamp, Braboszcz, & Delorme, 2014; Hopstaken, van der Linden, Bakker, & Kompier, 2015; Mittner et al., 2014; Unsworth & Robison, 2016). The shared effects of time-on-task on both PD and on task performance may shed light on these inconsistencies, particularly within the context of demanding vigilance paradigms (Grandchamp et al., 2014; Hopstaken et al., 2015; van den Brink, Murphy, & Nieuwenhuis, 2016; Van Orden et al., 2000). For instance, after controlling for time-on-task effects, baseline PD follows a Yerkes-Dodson inverted u-shaped function (Yerkes & Dodson, 1908), predicting optimal task engagement and performance with intermediate PD levels. Further, the temporal derivative of PD (i.e. the pupil dilation changes within each temporal window) was linearly related to task performance, independent of time-on-task effects (van den Brink et al., 2016). These findings support PD as a promising candidate measure, sensitive to fluctuations in the attention-arousal system (Franklin, Broadway, et al., 2013; Grandchamp et al., 2014; Unsworth & Robison, 2016, 2018). However, the relationship between mind-wandering and ageing, as reflected through distinct PD patterns, requires greater empirical scrutiny.

3.1.4.2.2 An Indirect Measure of Locus Coeruleus Neuromodulation.

Endogenously-driven pupillary responses have also been indirectly linked to psychophysiological activity in the locus coeruleus (LC) neuro-modulatory system (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Murphy et al., 2014; Murphy et al., 2011). This system is implicated in arousal and vigilance (e.g. Berridge & Waterhouse, 2003; Coull, Jones, Egan, Frith, & Maze, 2004; Smith & Nutt, 1996) through the release of noradrenaline (NA), with more fine-grained roles identified in attentional control and behavioural flexibility (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Chamberlain & Robbins, 2013; Sara & Bouret, 2012). Ascending neuromodulatory systems, such as the LC-NA, represent one potential mechanism through which brain states may flexibly alternate between serial modes of thought (O'Callaghan et al., 2021). The LC-NA system has been suggested as a neural modulator, akin to an “internal pacemaker”, regulating the temporal oscillatory dynamics involved in the exploitation/exploration trade-off (Sripada, 2018). The “adaptive gain theory” suggests that these strategic exploit/explore states are modulated according to LC dynamics (Aston-Jones & Cohen, 2005), alternating between a slow tonic LC mode (reflecting baseline activity and sustained information processing) and a fast phasic LC mode (reflecting task-specific processing) (Berridge & Waterhouse, 2003; Chamberlain & Robbins, 2013; Laeng, Sirois, & Gredeback, 2012; Sirois & Brisson, 2014; Yerkes & Dodson, 1908). The association between pupil size and momentary fluctuations in LC-NA activity is tempered by the indirect quality of the supporting evidence (Aston-Jones & Cohen, 2015); however a more recent study conducted by Joshi and colleagues (2016) demonstrated a direct relationship between single-unit LC firing rates and pupil diameter in non-human primates (Joshi, Kalwani, & Gold, 2016). Joshi et al. (2016) showed that the co-variation of LC activity and pupil dilations, and the associated release of NA throughout the brain, was indicative of underlying changes in arousal over distinct timescales in macaque monkeys. These authors failed to replicate the tonic and phasic firing modes that had previously been reported by Aston-Jones and Cohen (2005), but instead showed a linear relationship between LC and pupil size, suggesting that PD and LC activity co-fluctuate in line with underlying changes in arousal and attentive engagement.

Emerging consensus promotes PD as a useful indirect measure of LC-NA activity (Alnaes et al., 2014; Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Joshi et al., 2016; Murphy et al., 2014; Murphy et al., 2011) with neuromodulatory influence following a Yerkes-Dodson inverted u-shape relationship with task performance. Specifically, relatively low (hypo-arousal, small baseline PD) or high (hyper-arousal, large baseline PD) tonic NA levels culminate in reduced alertness and greater distractibility (i.e. "exploration"), respectively. Tonic levels at both extremes are associated with little or absent phasic activity, behavioural decrements, and poor attentional control. Conversely, with moderate tonic NA levels, phasic bursts occur in response to task stimuli and these distinct LC firing patterns are conducive to "exploitative" task focus, facilitating optimal performance (Aston-Jones & Cohen, 2005; O'Callaghan et al., 2021). Indeed, momentary attentional lapses have been preceded by periods of relatively elevated and reduced baseline pupil sizes (McGinley et al., 2015; Murphy et al., 2011; Smallwood et al., 2012; Unsworth & Robison, 2016; Van Orden et al., 2000), while attenuated phasic pupil responses to stimulation have been observed during mind-wandering, as discussed above (Smallwood et al., 2011). Less research has examined dynamic PD patterns associated with exploitation/exploration processes specifically; although, Jepna and Nieuwenhuis (2011) demonstrated that baseline PD was larger prior to exploratory behaviours and was predictive of individual differences in explorative tendencies during a gambling task. Together, these findings suggest that regulation of tonic and phasic LC-NA activity is critical in shifting attentional states.

An alternate model of mind-wandering by Mittner and colleagues (2016) posits how neuromodulation from the LC may be critical for changing cortical dynamics, in particular the Default Mode Network (DMN), which itself relates strongly to EEG alpha (Knyazev, Slobodskoj-Plusnin, Bocharov, & Pylkova, 2011). According to this model (Mittner et al., 2016), depending on whether the task promotes internal or external orientation, exploitative phasic LC activity may be related to both goal-directed thinking and mind-wandering, whereas the explorative tonic LC mode is associated with an additional "off-task" state managing the transitions between these two states. Despite evolving theoretical frameworks, the role of the LC-NA mediating attentional shifts is increasingly substantiated. For instance, a recent pharmacological study observed methylphenidate (MPH), a drug used to treat attention disorders, increased noradrenaline and dopamine transmission culminating in suppressed alpha activity and reduced alpha variability, coupled with improved task performance and better target processing (Dockree et al., 2017). It follows that the LC-NA system acts on top-down endogenous attentional mechanisms, regulating behaviour and performance by gating sensory processing for successful goal-maintenance and coordinating the balance between optimal exploitative and explorative modes of thinking according to contextual demands (Aston-Jones & Cohen, 2005; Hauser, Fiore, Moutoussis, & Dolan, 2016; Jepma & Nieuwenhuis, 2011; Joshi et al., 2016). However, the presence of inconsistencies in the literature regarding the precise pupil dynamics associated with alternating attentional states and mind-wandering episodes and the uncertain role of other factors such as time-on-task trends, external task demands, or cognitive ageing, need to be resolved.

3.1.5 Perceptual Decoupling: Attenuated Neurocognitive Processing and Enhanced Endogenous Attention

Mind-wandering is often conceptualised as a “perceptual decoupling” process (Antrobus et al., 1970; Smallwood & Schooler, 2006, 2015), wherein executive resources are decoupled from sensory processing of the immediate perceptual environment in favour of endogenous processes. Converging evidence has supported an influence of top-down attentional control in attenuating perceptual processing and disrupting the integrity of task performance. Specifically, disrupted sensorimotor processing and reduced alertness have been observed during periods of mind-wandering, indexed by attenuated electrophysiological responses to external events (Baird, Smallwood, Lutz, & Schooler, 2014; Barron et al., 2011; Braboszcz & Delorme, 2011; Kam et al., 2011; Macdonald et al., 2011; O'Connell et al., 2009; Smallwood, Beach, et al., 2008), changes in pupillary responses (Smallwood et al., 2011), and poorer or more variable concurrent behavioural performance (e.g. Cheyne et al., 2006; McVay & Kane, 2009; Mooneyham & Schooler, 2013; Smallwood, McSpadden, & Schooler, 2008; Unsworth & McMillan, 2013). Indeed, previous research has demonstrated that faster RTs with steeper perceptual evidence accumulation build-up rates tend to be accompanied by reduced alpha power (Kelly & O'Connell, 2013). Moreover, progressive pre-stimulus alpha changes have been shown to precede lapsed attention and often co-occurred with reduced target processing (Dockree et al., 2017;

O'Connell et al., 2009), and subjective low-attentional focus states (MacDonald et al 2011). These findings support momentary interruptions to target anticipation during periods of synchronised alpha activity.

Disrupted behavioural performance and suppressed neurocognitive processing of external events are therefore evident during the decoupled state, suggesting that perceptual decoupling may represent one promising mechanism through which mind-wandering is facilitated (Smallwood, 2013; Smallwood & Schooler, 2006). Mind-wandering may gate perceptual processing to insulate internal streams of information from external distractions or it may withdraw limited resources from the perceptual processing of the external task (see Franklin, Mrazek, et al., 2013; Kam & Handy, 2013; Smallwood, 2013). Previous studies, however, have only managed to measure perceptual decoupling using discrete sudden-onset stimuli that do not represent the evolution of continuous, unfolding perceptual information alongside the wandering mind.

3.1.6 Key Neurophysiological Components of Perceptual Decision-Making

As so far stated, attentional fluctuations prior to a target may impact visual sensory processing, and cognitive and decision-making processes, leading to disrupted performance. We henceforth discuss different components implicated in the process of converting incoming sensory evidence into a motor response (a process referred to as perceptual decision-making), specifically highlighting signals that index evidence accumulation, sensory evidence representation, and motor preparation processes.

3.1.6.1 Centro-Parietal Positivity: Decision Formation. The centro-parietal positivity (CPP) event-related potential (ERP) is a supramodal and abstract decision signal that traces the time-course of evidence accumulation, irrespective of task-relevant sensory-motor demands, independent of evidence modalities, and in the absence of a required decision-formed motor response (Kelly & O'Connell, 2013; O'Connell et al., 2012; Twomey, Kelly, & O'Connell, 2016). In line with sequential sampling models (Laming, 1968; Link & Heath, 1975; Ratcliff, 1978; Usher & McClelland, 2001), the CPP displays a proportional build-up rate that scales with evidence strength peaking at response execution (Kelly & O'Connell, 2013; O'Connell et al., 2012). The CPP build-up rate precedes effector-selective motor preparation signals and as such is a useful marker of the intermediate stage between sensory encoding and motor preparation (Kelly & O'Connell, 2013). The CPP represents the cumulative evidence component of perceptual decision formation, distinct from signals that reflect sensory evidence and motor preparation components.

The CPP is functionally equivalent to the classic centroparietal P300 (P3b) potential (Dockree et al., 2017; O'Connell et al., 2012; Twomey, Murphy, Kelly, & O'Connell, 2015), a component which has been researched in ageing and shown to decrease in amplitude and increase in peak latency with advancing age (Fjell & Walhovd, 2001; Polich, 1996, 1997; Rossini, Rossi, Babiloni, & Polich, 2007). Specifically, attenuated external processing, through reduced P3 amplitudes, has been observed during periods of mind-wandering and low attentional focus (Barron et al., 2011; Macdonald et al., 2011; Smallwood, Beach, et al., 2008). Reciprocally, enhanced attentional engagement (i.e. via suppressed alpha activity) from MPH administration has coincided with increased P3 amplitudes prior to target processing, although no similar effect was observed on an electrophysiological assay of basic visual stimulus processing (Dockree et al., 2017). Together these findings suggest that endogenous attentional mechanisms impact the temporal accrual of sensory evidence.

A reliable age-related widening of decision boundaries has been previously demonstrated (Forstmann et al., 2011; Ratcliff, Thapar, & McKoon, 2001, 2003, 2006b, 2010; Spaniol, Voss, & Grady, 2008; Starns & Ratcliff, 2010). This may be due, at least in part, to older adults adopting more conservative decision policies and requiring more evidence before committing to a decision (e.g. Forstmann et al., 2011; Rabbitt, 1979); brain structural age-related differences, for example reduced white matter tracts in pre-supplementary motor areas and striatum (Forstmann et al., 2011); or an age-dependent slowing in sensory encoding and/or motor execution processes (Ratcliff et al., 2001, 2003; Ratcliff, Thapar, & McKoon, 2006a; Ratcliff et al., 2006b, 2010; Thapar, Ratcliff, & McKoon, 2003). However, the degree to which attentional fluctuations influence such indices of decision formation in ageing is less well known. Although, reduced between-trial variability in the build-up of the CPP and alpha-band signals were observed in older adults compared to younger adults (McGovern et al., 2018), which indicates more consistent and exploitative attentional engagement with age. Therefore, the CPP may be an important marker for investigating oscillatory attention patterns and their relation to target processing in ageing.

3.1.6.2 Steady-State Visually Evoked Potential: Sensory Evidence Representation. The steady-state visually evoked potential (SSVEP) is a continuous oscillation in the early visual cortex elicited as a time-locked response to repetitive visual stimulation (Di Russo et al., 2007; Muller & Hillyard, 2000). The SSVEP signal provides a cortical representation of sensory evidence, generating a continuous neural readout of momentary sensory encoding and bottom-up visual stimulus processing over time. The amplitude of the SSVEP indexes the degree to which sensory input informs contrast-dependent perceptual decisions and is predictive of response timing and accuracy (O'Connell et al., 2012; Steinemann, O'Connell, & Kelly, 2018). Moreover, the SSVEP has been shown to be sensitive to visuospatial attention allocated to flickering stimuli (Di Russo, Spinelli, & Morrone, 2001; Morgan, Hansen, & Hillyard, 1996; Muller & Hillyard, 2000). In a previous study investigating age-related differences in perceptual decision-making, SSVEP amplitudes were attenuated in older adults compared to younger adults, but when normalised to account for baseline differences, both groups reliably traced stimulus changes over time (McGovern et al., 2018). The influence of mind-wandering on the integrity of sensory evidence accumulation for younger and older adults, however, remains under-researched.

3.1.6.3 Mu/Beta: Motor Preparation. Preparatory motor activity, i.e. prior to a manual response, is indexed by mu/beta-band (8-30Hz) oscillatory activity over motor regions in the contralateral hemisphere to the responding hand. Beta-power desynchronises prior to motor responses and demonstrates build-to-threshold dynamics at the motor level, consistent with the characteristics of an effector-selective decision signal (Donner, Siegel, Fries, & Engel, 2009; Kelly & O'Connell, 2013; Murphy, Boonstra, & Nieuwenhuis, 2016; O'Connell et al., 2012). Speed conditions further alter the onset of motor preparation (Steinemann et al., 2018), suggesting that motor preparation is sensitive to strategic adjustments of the decision policy. Age-related changes in motor-level processing show stronger desynchronization of mu/beta band activity in older adults (Crone et al., 1998; Pfurtscheller, 1981; Quandt et al., 2016; Sailer, Dichgans, & Gerloff, 2000); although, McGovern and colleagues (2018) found no differences in normalised left hemisphere beta (LHB) activity between younger and older adults. These findings demonstrate the potential utility of mu/beta spectral amplitude changes as a marker of evolving motor preparation that may provide insight into the unresolved dynamics underscoring the influence of attentional fluctuations on perceptual decision-making and behavioural performance in younger and older adults.

3.1.7 The Present Study

The present study aimed to investigate the extent to which younger and older adults strategically prioritise competing task-relevant goals versus self-generated thoughts during a non-demanding, continuous sustained attention task. Against a backdrop of reduced executive function in older adults, it is proposed that younger and older adults employ different task performance strategies to mitigate potential performance costs. Specifically, we hypothesise that older adults marshal their resources to the task by strategically consigning more of their limited resources to maintain an exploitative performance strategy and more conservative decision policy (Sripada, 2018). By contrast, we hypothesise that younger adults will permit greater shifts to exploratory states during the task. These potentially different means to the same end will be investigated here by examining known electrophysiological and psychophysiological markers of (a) attentional engagement (pre-target alpha and PD), (b) perceptual decoupling (probe-aligned SSVEP, alpha, and PD), and (c) perceptual decision-making (target-aligned CPP, SSVEP, and LHB). Tracing key attentional and decision signals will help ascertain the mechanistic basis of strategic transient shifts in brain states, dually affected by competing sensory input and intrinsic processes, to augment our understanding of the mind-wandering experience for younger and older adults.

The current study employed the gradual contrast change detection task with built-in experience sampling probes (Grad-CCD-ES; McGovern et al., 2018; Moran et al., 2021; O'Connell et al., 2012) and concurrent EEG and pupillometry recordings to capture mind-wandering under non-demanding experimental conditions. Six key features of the Grad-CCD-ES that enabled the investigation of mind-wandering are discussed. First, participants monitored a continually presented annulus stimulus for smooth, gradually evolving, and temporally unpredictable feature changes over long and tedious blocks. This extended traditional methodological approaches that typically measure transient responses that are exogenously evoked by perceptually salient, sudden-onset, discrete, and often predictably occurring targets (e.g. a distinct symbol). The gradual stimulus changes in the present task minimised the need for rapid information processing and response demands, thereby placing greater reliance on endogenous attentional control and continued readiness. Second, the steady and gradually evolving target transitions removed momentary sensory-evoked signals from the ERP and stimulus-evoked pupillary responses, thereby enabling isolation of the individual dynamics of shifting attentional states as they occurred in real-time. Third, longer inter-trial-intervals (ITIs) were incorporated to minimise possible phasic contamination of the pupil measurements from stimulus-evoked pupil responses arising from previous trials. Fourth, the rapid, synchronous on-off flicker of the visual annulus stimulus at 25Hz generated an SSVEP, tracking the representation of the stimulus contrast and providing a neural read-out of momentary sensory processing against which changes that occur with on and off-task subjective states could be recorded. Fifth, the manual button press response to target identification enabled preparatory motor activity to be tracked over contralateral pre-motor structures. Sixth, the task was pseudo-randomly interrupted by ES probes asking participants to self-report their current attentional states at discrete moments in time.

The advantage of the present approach, therefore, is the triangulation of subjective, behavioural, and neurophysiological methods. The paradigm is thus well-suited to tracing and mechanistically dissociating the transitions between top-down endogenous and bottom-up stimulus-evoked processes to explore how mind-wandering impacts perceptual decision-making and task performance over time and how these processes are affected differentially by ageing.

3.2 Methodology

3.2.1 Participants

Thirty-five younger adults (aged 18- 35 years) and 40 community-dwelling healthy older adults (aged 65- 80 years) participated in this study. Younger adults were recruited from the student population in Trinity College Dublin (TCD), while older adults were recruited from a research participant panel. All participants reported normal or corrected-to-normal vision, no personal or family history of neurological or psychiatric illness, no personal or family history of brain injury or unexplained fainting, no sensitivity to flickering light, and no recent history of drug, alcohol, or pharmaceutical abuse. Two younger participants were later excluded owing to technical data acquisition issues. Five older adults were excluded as they scored lower than 24 on the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), suggesting possible cognitive impairment (O'Caoimh et al., 2016), and one further older participant was excluded due to illness during testing.

Due to excessive EEG and/or ocular artifacts, participants' *electroencephalographic* data were either removed from both the target- *and* probe-related analyses (younger adults, n = 6; older adults, n = 1), the target analyses *only* (younger adults, n = 2; older adults, n = 3), or the probe analyses *only* (younger adults, n = 2; older adults, n = 3). Further, participants' *pupillometric* data were excluded from the target- *and* probe-related analyses owing to excessive artifacts or missing data (younger adults, n = 1; older adults, n = 3). The sample sizes included in each analysis are detailed with each result.

The final sample of participants for whom we had data available for at least one of the neurophysiological analyses (EEG and/or pupillometry) comprised 34 younger adults (16 female, mean age 21.71 years, standard deviation (*SD)* = 4.59) and 34 older adults (20 female, mean age 70.97 years, *SD* = 3.54). The groups did not significantly differ on gender, $x^2(1, N = 68) = .94, p = .331$, or years of full-time education, $t(60.99) = 1.47, p = .148$ (two-tailed). Younger adults reported an average of 16 years of education (*SD* = 2.41) and older adults reported 15 years (*SD* = 3.24). Participants were offered partial course credit or a €20 gratuity to cover travel costs. Participation was entirely voluntary, and all participants provided written informed consent to the procedures that were approved by the School of Psychology Research Ethics

Committee, TCD, and were conducted in observance of the Declaration of Helsinki principles and the European General Data Protection Regulations.

3.2.2 Materials and Procedures

Participants performed a computerised sustained attention task, namely the GradCCD-ES task (McGovern et al., 2018; Moran et al., 2021; O'Connell et al., 2012) with concurrent EEG and pupillometry recording. These data were collected alongside a comprehensive neuropsychological test battery as part of a broader study that explored the neuropsychological factors mediating age-related differences in mind-wandering phenomenology. Results pertaining to the neuropsychological and behavioural analyses were previously disseminated (see thesis *Chapter 2*, or Moran et al., 2021).

3.2.2.1 Gradual Contrast Change Detection with Experience Sampling (GradCCD-ES) Task. Healthy younger and older adult participants performed the GradCCD-ES task (McGovern et al., 2018; Moran et al., 2021; O'Connell et al., 2012) in a darkened and sound-attenuated room, sitting at a distance of ~57cm from the presentation computer with their head supported by a chinrest to minimise head and eye movements. The visual annulus stimulus was presented in the centre display of a 40cm cathode-ray tube (CRT) monitor that operated at 100Hz refresh rate with 1024x768 resolution. Stimulus presentation and participant response collection regimes were controlled via the Psychtoolbox-3 interface (Brainard, 1997; Pelli, 1997) and MATLAB R2016b software, (MATLAB, 2016). Participants fixated on the centre of the screen and monitored a continuously presented, flickering checkerboard annulus stimulus (outer radius = 8°, inner radius = 3°) with alternating light and dark radial segments on a dark grey background. The on-off flicker of the checkerboard stimulus at 25Hz gave rise to a steady-state visually evoked potential (SSVEP) in the EEG, which acted as a measure of momentary sensory encoding (O'Connell et al., 2012). Participants identified intermittent targets, that took the form of gradual reductions in stimulus contrast from 65% to 35% over 1.6 seconds followed by a return to baseline after a further 0.8 seconds. Targets occurred periodically with ITIs of three, five, or 7-seconds selected randomly across trials to minimize target predictability. As soon as participants detected the target transition, they responded with a speeded mouse button press with their right index finger (Figure **3.1**).

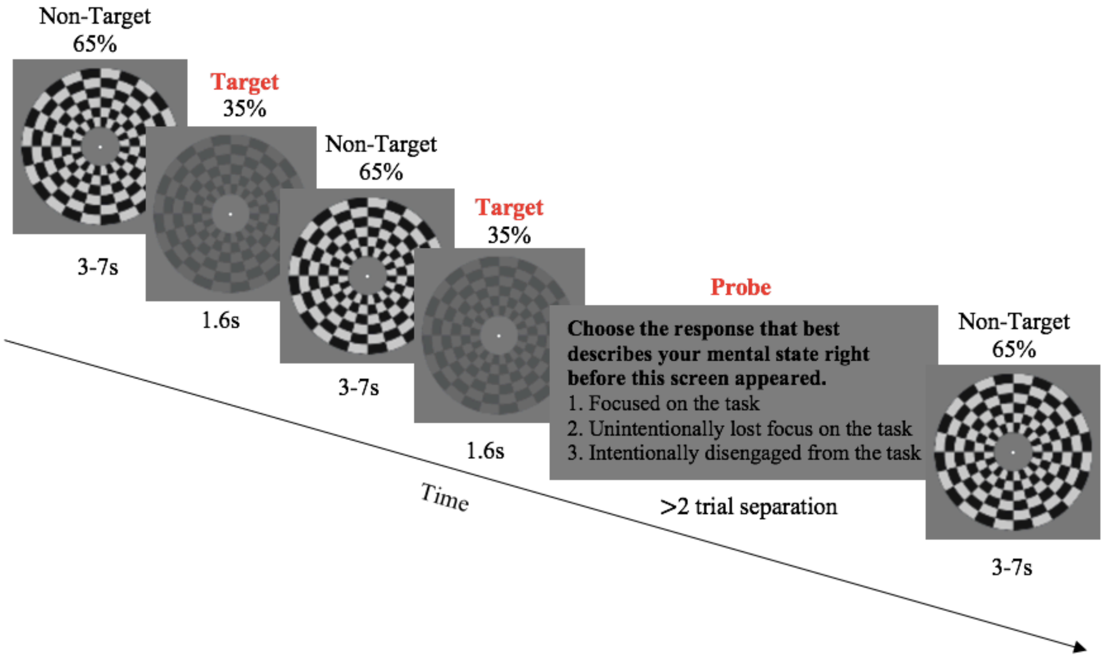
The task was pseudo-randomly interrupted by built-in ES probes (minimum two-trial separation) that asked participants to classify their current mental state. Prior to the onset of each probe, the checkerboard stimulus offset was followed by a blank screen for 500ms. The probe screen then instructed participants to "Choose the response that best describes your [their] mental state right before this screen appeared". Participants indicated with a keyboard press (1-3) as to whether they had been 1) "Focused on the task", 2) "Unintentionally lost focus on the task", or 3) "Intentionally disengaged from the task" in the moments before the onset of the probe (following Seli, Cheyne, et al., 2015). The task resumed immediately following a probe response.

Prior to the main experiment, participants were provided task and probe instructions with mind-wandering examples. Two brief practice blocks (including three trials and one probe) were administered to participants to ensure adequate understanding of the experimental procedures. Prior to each experimental block, the eye-tracking system was calibrated and validated, and then the task was initiated on the display computer. Eight blocks of the main task were performed; each block contained 48 target trials and 16 probes and spanned approximately 8 minutes. Participants availed of short breaks in between blocks.

All behavioural performance and subjective ES indices were averaged across the total task for each participant. The behavioural outcomes extracted comprised a) Hit Rate (proportion of correctly identified targets), b) RT for correct trials (in seconds), c) between-trial RT Coefficient of Variance for correct trials (RT CoV; the standard deviation of RT divided by mean RT), and d) the number of False Alarms. Subjective outcomes included the frequency of a) Focused and b) composite total Mind-Wandering reports (sum of Unintentional and Intentional mind-wandering responses). In the broader study (Moran et al., 2021), mind-wandering experiences were dissociated as a means of classifying the phenomenology of mind-wandering and examining age-related patterns, and corollaries, of different types of self-generated thought. The present report, however, investigated age-related neurophysiological patterns of on- (Focus) and off-task (Mind-Wandering) states, given that perceptual decoupling attributes no specific claims regarding intentionality. Moreover, concatenation of Unintentional and Intentional responses was performed to minimise data attrition in the neurophysiological analyses arising from low trial counts due to the infrequency of intentional mind-wandering reports, particularly for older adults.

Figure 3.1

Experimental Schematic Depicting the Gradual Contrast Change Detection Task with Experience Sampling Probes.



Note. Participants continuously monitored the flickering annulus for gradual contrast changes, characterised as a stimulus contrast reduction from 65% to 35% over 1.6 seconds, and responded to intermittent experience sampling probes asking them about their current mental state. For the present report, Unintentional and Intentional mind-wandering probe responses were collapsed to form a composite ‘Mind-Wandering’ variable.

3.2.3 EEG Acquisition and Pre-Processing

Continuous EEG was acquired by an ActiveTwo system (BioSemi, The Netherlands) using 128 scalp electrodes, according to the equiradial system montage, and digitised at 512Hz. Vertical eye movements were recorded by two electrooculogram (EOG) electrodes positioned above and below the left eye. Data analyses were performed using custom scripts in MATLAB version r2016b (MATLAB, 2016) incorporating EEGLAB functions for importing data files and spherical spline interpolation of noisy channels (Delorme & Makeig, 2004). Continuous EEG data were detrended to suppress slow drifts and low-pass filtered at 40Hz using a zero-phase non-causal Hamming Windowed-Sinc Finite Impulse Response (FIR) filter [‘eegfiltnew’ function] to mitigate high frequencies. Data were then re-referenced offline to the average reference of all

128 electrodes. Data were segmented into fixed-length stimulus-locked epochs, according to the particular signal investigated and the time period of interest. Probe event triggers (i.e. probe presentation and response) were extracted from the behavioural files and converted to timestamps for use in the probe-aligned analyses as these were not present in the electrophysiological outputs (.bdf files) due to a technical error.

For *target-aligned analyses*, epochs were time-locked to target onset using windows of either a) -2000ms to 200ms (for pre-target Alpha) or b) -250ms to 1925ms (for decision-related signals). The target-aligned epochs were baseline corrected relative to the average signal in the 200ms pre-target window. Regarding the *probe-aligned analyses*, data were segmented into epochs of -2000ms before to 200ms after probe presentation, and baseline corrected relative to the -2000 to -1800ms pre-probe interval (pre-probe SSVEP and Alpha).

Single ERP trials are sensitive to EOG or noise transients stemming from electrical interference from the recording environment, muscle activity, skin potentials, blinks, and ocular movements. In the present study, trials containing artifacts were rejected if the bipolar vertical EOG signal (upper minus lower) exceeded an absolute value of 250μV at any point during the epoch or if the scalp electrodes surpassed an artifact threshold of 100μV. For probe-aligned data, artifact rejection was restricted to the posterior channels (A-lead) given that the signals of interest for the probe-aligned analyses arise predominantly in the posterior region of the brain. To minimise trial loss during pre-processing procedures, channels with extreme variance and/or high artifact counts were interpolated such that no more than 10% of channels were interpolated across the whole session for each participant. Following channel inspection and interpolation, participants with excessive trial loss, resulting in fewer than 30 trials remaining per variable, were removed from subsequent analyses (see § *Participants*). Moreover, for the probe-related analyses, a further exclusion criterion was implemented such that participants with fewer than 10 total valid trials after pre-processing procedures available for the Focused (younger adult, *n* = 1) or Mind-Wandering (younger adult, *n* = 1; older adults, *n* = 10) conditions were excluded from these analyses.

All single-trial data were transformed into current source density (CSD; J. Kayser & Tenke, 2006). This conversion was implemented to reduce spatial overlap between functionally distinct components, attenuate the spatial blurring effects of volume conduction, and minimise the projection of fronto-central negativity to posterior centro-parietal channels (Kelly & O'Connell, 2013; Twomey et al., 2015).

3.2.4 Pupillometry Acquisition and Pre-Processing

An EyeLink 1000 eye-tracking system (SR Research Ltd, Canada), with desktop mount and infrared camera and illuminator, was used for real-time monocular tracking at a sampling rate of 1000Hz. Pupil size of the left eye was continuously recorded over the duration of each experimental block. A chin rest was used to aid head stability and minimize extraneous movements or off-screen fixations. The eye-tracker was calibrated and validated prior to each block using a 9-point fixation sequence.

Pupillometric data were extracted and pre-processed using MATLAB (version 9.2 2017a) software. Firstly, the ".edf" eye-tracker files were converted to ".mat" format and the PD time series, sampling frequency, start times, and blink indices were extracted. Stimulus event markers (i.e. target onset and probe presentation) were extracted from the behavioural files and converted to timestamps, as these were not present in eye-tracker output due to a technical error. Raw pupil data are commonly subject to artifacts or gaps from blinks or off-screen fixations (Alnaes et al., 2014; Sirois & Brisson, 2014). As such, a custom algorithm using MATLAB was employed to identify blinks (e.g. half-blinks and pupil occlusion from eyelids or eyelashes) to add to the blink indices identified by the manufacturers' inline algorithm (see also van den Brink et al., 2016). Blink indices (extracted from .edf files) were expanded by 50ms on either side to supplement the custom identification algorithm. Blinks and other artifacts, once marked, were removed and interpolated with a 2nd degree polynomial curve-preserving function. Visual inspection was also performed on all pupil data to verify the resulting pupil time series. Sessions that were deemed unfit for use (e.g. EyeLink failed recording and artifacts produced by correction of anomalies such as prolonged eye-closing or sudden sustained changes in amplitude) were marked for rejection and were not used in further analyses [see § *Participants*].

Pupil signals were low pass filtered at 6Hz (Butterworth filter, 40th order, double-filtered/zero-phase shift) to remove higher frequency jitter and noise, including the steady-state flicker frequency. Further, the pupil time series were *z*-score normalised (within- individual) prior to analysis. All single trials containing greater than 30% interpolated data points were rejected for both the target- and probe-aligned analyses. As with the electrophysiological analyses, "Unintentional" and "Intentional" mind-wandering responses were aggregated to form a total "Mind-Wandering" variable that was compared against "Focus". Participants with fewer than 10 trials in the mind-wandering condition remaining after pre-processing procedures were further excluded from analysis [younger adults, n = 1; older adults, n = 7].

For *target-aligned analyses*, the pre-target and post-target epochs were extracted from -2000ms to 0ms, and 0ms to 4000ms, respectively, and were baseline corrected with mean amplitudes calculated over the -200ms to 0ms pre-target window. Moreover, *probe-aligned* epochs were extracted from -2000ms to 0ms, time-locked to probe presentation, and were baseline corrected with mean amplitudes calculated from the -2000ms to -1800ms pre-probe interval. Pupil size was baseline corrected on a trial-by-trial basis and these baseline corrected values were analysed rather than absolute measurements to account for possible inter-individual differences in baseline pupil size and to attenuate habituation or the relative decline of pupil size over time (Sirois & Brisson, 2014).

3.2.5 Signal Analysis

ERP componentry and oscillatory measures of EEG activity, and pupil dilation measures were investigated relative to target and probe stimuli onsets. Grand-averaged waveforms were generated and latency measurement windows were determined through visual inspection of the temporal and spatial extents of the components, and amplitude measures were isolated in accordance with previous research (see Alnaes et al., 2014; Dockree et al., 2017; Loughnane et al., 2019; McGovern et al., 2018; O'Connell et al., 2012; Sirois & Brisson, 2014; Twomey et al., 2015). SSVEP, Alpha, and PD were examined with respect to both target and probe stimuli, while the CPP and Mu/Beta signals traced decision-related activity relative to target onset only. Data extraction and analysis procedures for each signal are henceforth discussed.

3.2.5.1 Alpha: Attentional Engagement.

3.2.5.1.1 Target Analysis. Alpha (8-14Hz) was examined prior to target onset as an oscillatory measure of endogenous attentional engagement. Alpha amplitudes were extracted from a cluster of parietal and occipital channels (B6 and B7 for younger adults; A16 and B7 for older adults) as determined by the maximal amplitude activity of mean alpha power evident from the separate group scalp topographies [window: -2000ms to 0ms, relative to target onset]. For each participant, the mean pre-target alpha amplitude was calculated over 20 cycles of the SSVEP (800ms). The between-trial variability of pre-target alpha for each group was indexed by the CoV, quantified as the standard deviation of alpha amplitude divided by mean alpha activity. Alpha CoV was extracted for each participant as the primary alpha measure.

3.2.5.1.2 Probe Analysis. Attentional modulation antecedent to probe onset was measured across the whole epoch by posterior alpha band activity (8-14Hz) at channels A9, A10, B6, and B7 (younger adults) and B7 and B8 (older adults), identified from the grand-averaged scalp topographies of mean alpha activity [window: -1800ms to 0ms, relative to probe presentation]. The mean alpha amplitudes for each participant were calculated using a static Fast Fourier Transformation (FFT) over 20 cycles of the SSVEP (800ms) relative to each probe response. The CoV of alpha power was then calculated for each probe condition, namely pre-Focus and pre-Mind-Wandering (combined alpha amplitudes for the Unintentional and Intentional responses) and extracted as the primary alpha measure.

3.2.5.2 PD: Attentional Engagement.

3.2.5.2.1 Target Analysis. Normalised PD was measured pre- and post-target onset as a proxy psychophysiological marker of attentional engagement and LC-NA activity (Aston-Jones & Cohen, 2005; van den Brink et al., 2016). For the *pre-target* normalised PD analyses, mean amplitudes were calculated across a temporal window of -2000ms preceding target evidence onset for each participant. Further, the trajectory of the pre-target normalised pupil changes was quantified by the pre-trial slopes. Slopes were approximated with linear least squares fit on the individual epoched signals from -2000ms to 0ms, and the mean slopes were calculated across all trials for each participant. To examine *post-target* normalised PD, both mean and peak amplitudes were extracted for each group from a window of 0ms to 4000ms, with respect to target onset, to gauge phasic pupil response to target.

3.2.5.2.2 Probe Analysis. For *pre-prob*e normalised PD, mean amplitudes were extracted from a window of -1800ms to -800ms prior to Focus and Mind-Wandering conditions to avoid the checkerboard offset occurringat -500ms.

3.2.5.3 CPP: Decision Formation.

***3.2.5.3.1 Target Analysis**.* The domain-general CPP ERP component was recorded relative to target onset to trace the time-course of sensory evidence accumulation and perceptual decision formation over target evolution, independent of preparatory motor dynamics (Kelly & O'Connell, 2015; O'Connell et al., 2012). ERPs were generated by averaging single-trial epochs for each participant, that were combined to form grand-averaged target-locked CPP waveforms per group and low-pass filtered using a fourth-order digital Butterworth filter at 8Hz for display only. The CPP was derived from a single scalp electrode site (channel A4) for both groups, identified from the grand-averaged response-locked scalp topographies as the region of maximal positive component activity [window: -150ms to -50ms relative to response] based on visual inspection. Two younger and two older adult participants displayed negative-going CPPs with the selected electrode site; however, given that there was the same number of participants affected across groups, these data were included in the grand-averaged data.

Amplitude measures of the ERP component were extracted from a broad latency window of 500ms to 1750ms relative to target onset; these measures included the peak magnitude (maximum positive voltage) and peak latency (timing of maximum positive voltage). The onset latency (start time) of the CPP was measured using a running point-by-point one-tailed *t*-test approach across time looking at divergence from zero in a positive direction, examined separately for younger and older groups. For each group, the CPP onset latency was identified as the initial time-point when the signal amplitude significantly diverged from zero ($p < .05$) and showed continuity of statistical significance above zero for at least the proceeding 50ms (see Loughnane et al., 2019; Loughnane et al., 2016). The build-up rate of the CPP was quantified as the slope of a straight line fitted to the unfiltered stimulus-aligned ERP waveforms over a window of 250ms to 750ms post-target evidence onset. The temporal extent of the CPP was measured in line with previous research showing that stimulus changes require several hundred milliseconds before impacting the CPP build-up rate (Kelly & O'Connell, 2013, 2015; Loughnane et al., 2016; O'Connell et al., 2012).

3.2.5.4 SSVEP: Sensory Evidence Encoding.

3.2.5.4.1 Target Analysis. The occipital SSVEP, driven by the intensity of the on-off stimulus flicker at a constant and rapid rate of 25Hz, provided a continuous oscillatory measure that tracked basic visual stimulus processing and sensory evidence encoding. The SSVEP for channel selection was computed using a static FFT over a 20-cycle window (800ms) of the stimulus flicker frequency to reduce contamination by spectral leakage. Signal-to-noise (SNR) grand-averaged scalp topographies [window: -100ms to 0ms, relative to target onset] were generated by dividing the power of the stimulus flicker frequency by the two adjacent frequencies in the frequency scale (i.e. 27.5Hz and 22.5Hz) to enhance the specificity of the topographies. Guided by the regions of maximal SSVEP activity on the SNR topographies, amplitudes were averaged across three (A17, A21, A30) or two (A21, A22) channels, for younger and older groups respectively, centred on standard site POz for both groups.

The temporal evolution of the SSVEP (25Hz) across the target-locked epoch was calculated using the standard short-time Fourier transform (STFT) procedure with a sliding boxcar window length of 400ms for capturing an integer number of 10 cycles of the SSVEP frequency with a 20ms step size. SSVEP measurements for each participant were normalised by dividing by the mean activity in the 250ms pre-target window. Normalised SSVEP target-locked mean amplitudes were extracted from a window of 500ms to 1600ms relative to target onset to track sensory encoding until the point of peak physical evidence at 1600ms. The build-up rate was calculated as the slope of a straight line fitted to the unfiltered ERP waveforms over a window of 350ms to 850ms.

3.2.5.4.2 Probe Analysis. The static FFT was measured within an 800ms pre-probe window for channel selection, starting at approximately -1600ms and ending at -800ms for each probe response, avoiding the checkerboard offset occurring at -500ms. Guided by the grand-averaged SNR scalp topographies [window: -1800ms to -1500ms, relative to probe onset], SSVEP amplitudes were averaged across three (A17, A21, A30) or two (A21, A22) channels, for younger and older groups respectively, centred on standard site POz for both groups.

The temporal evolution of the SSVEP (25Hz) across the probe-locked epoch was calculated using the STFT procedure with a boxcar window length of 400ms capturing an integer number of 10 cycles of the SSVEP frequency with a 26ms step size. The probe SSVEP measurements were not subjected to normalisation or further baseline-correction, hence between-group analyses of pre-probe SSVEP were not performed. Grand-average SSVEP waveforms were generated for the different probe responses; namely, Focus and Mind-Wandering. Amplitude measures were extracted from a window of -1800ms to -800ms prior to Focus and Mind-wandering trials and included the mean amplitude and amplitude variability (CoV, calculated as the standard deviation of SSVEP amplitudes divided by the mean activity). The build-up rates of the SSVEP (slope) prior to each probe response were also calculated over approximately -1800ms to -800ms, relative to probe presentation.

3.2.5.5 Mu/Beta: Motor Preparation.

3.2.5.5.1 Target Analysis. Effector-selective motor preparation was indexed by oscillatory power in the mu/beta bands (8 to 30Hz, excluding the 25Hz stimulus flicker frequency) over motor regions in the left hemisphere (contralateral to the responding right hand). Based on the stimulus-locked grand-averaged topographies [window: -100ms to 100ms, relative to mean target response], LHB was averaged over three channels for older adults (D18-D20) and measured from one channel for younger adults (D19), centred for both groups on standard left hemisphere motor site C3.

The time-course of LHB power was measured using the standard STFT with a sliding boxcar window size fitting 10 cycles of the SSVEP frequency and 20ms step size. LHB amplitudes were normalised relative to the 250ms pre-stimulus window for each participant. Target-locked normalised LHB mean amplitudes were examined within the window 500ms to 1250ms relative to target onset, and the slope was measured over a target-aligned window of 350ms and 850ms. Additionally, group differences in normalised LHB mean amplitudes and slopes were investigated within the window 1000ms to 1350ms relative to target onset.

3.2.6 Data Management and Statistical Analysis

Data normality was assessed using the Kolmogorov-Smirnov test. Extreme outliers, defined as values extending greater than three times the interquartile range (IQR) within a particular outcome measure per group, were precluded from further analysis. Outliers comprised fewer than 1.5% of all data points for both younger and older groups. Group comparisons on the spectral and time-based EEG and pupillometric measures were assessed by a series of two-tailed independent *t*-tests. Where Levene's test for the equality of variances was violated, a Mann Whitney *U* test was performed and associated tests with corrected degrees of freedom and median and IQR values reported. To compare signal characteristics prior to different probe states, paired samples *t*-tests were conducted separately for each group.

An exploratory 2x2 mixed repeated measures analysis of variance (ANOVA) was conducted to investigate the interaction between a between-subjects factor of "Age Group" and within-subjects factor of "Probe Response" on SSVEP CoV amplitudes. Where the ANOVA revealed a non-significant interaction, the main effects for the between- and within-subjects factors were interpreted. Significant main effects were followed up with post-hoc pairwise comparisons (paired samples *t*-tests) to locate the source of the differences; Bonferroni-corrected *p*-values were reported to correct for multiple comparisons.

Exploratory two-tailed partial Pearson's *r* correlations, controlling for age group, examined possible associations between neurophysiological and behavioural outcomes. A *p*-value of less than .05 determined statistical significance. For each group comparison, Cohen's *d* effect size was calculated and interpreted as representing small ($d = .2$), medium ($d = .5$), or large ($d = .8$) effects (Cohen, 1988).

Power analyses for the independent *t*-tests revealed that our sample sizes of 25 younger and 30 older adults for the electrophysiological analyses, and 33 younger and 31 older adults for the target pupil analyses, were sufficient to detect large ($d = .8$) effects with greater than .83 and .88 probabilities, respectively. Calculations for the exploratory Pearson's *r* correlations, with one variable controlled (Age Group), an alpha cut-off of .05, and an approximate sample size of 50 participants, provided .83 and .99 power values to detect medium ($r_{\text{partial}}= +/-.4$) and large ($r_{\text{partial}}= +/-.6$) effects, respectively. Although these calculations were performed after data collection, the effect sizes used were independent of the dataset and, therefore, not subject to the same biases as "post-hoc" power calculations computed with achieved effect sizes.

Bayesian analyses were also applied to complement the frequentist analyses to determine the presence or absence of a between-groups effect and to support, particularly, interpretation of non-significant results. Bayes Factor (*BF*), with a default scaling parameter of .707, yielded a relative measurement evaluating if the strength of the evidence favoured the predictive ability of the null over the alternative hypothesis (Dienes, 2014). The evidence in favour of the null was interpreted as weak or inconclusive (BF_{10} = .33-3), moderate (BF_{10} = 3-10), or strong ($BF_{10} > 10$). A BF_{10} of less than one third provided evidentiary support for the null hypothesis; namely, that no group effect was present. SPSS Version 24 (IBM; Chicago, IL, United States) and JASP software (JASP Team, 2019) were used to conduct the frequentist and Bayesian analyses. Bar chart figures were generated in Prism 8 (GraphPad).

3.3 Results

3.3.1 Behavioural Performance

Behavioural performance indices and ES probe descriptive statistics for the total sample of 34 older and 34 younger adults (namely, those participants with data included in at least one of the neurophysiological analyses) are presented in greater detail elsewhere (see thesis *Chapter 2*, or Moran et al., 2021). In brief, younger and older adults demonstrated commensurate performance on the contrast detection task. No statistically significant between-group differences were observed in mean RT, $t(61.79) = -.56$, $p = .580$, 95 % CI [-.11, .06], $d = .12$, $BF_{10} = .28$, Hit Rate which was near ceiling for both groups, $U = 432.50$, $Z = -1.07$, $p = .285$, $d = .27$, $BF_{10} = .37$, or the number of False Alarms, $U = 383.50$, $Z = -1.55$, $p = .122$, $d = .39$, $BF_{10} = .67$. The groups did significantly differ, however, with respect to RT CoV; specifically, older adults responded to targets less variably than their younger counterparts, $t(64) = 2.64$, $p = .011$, 95 % CI [.72, 5.24], $d = .65$, $BF_{10} = 4.45$. Additionally, older adults were less inclined to report total Mind-Wandering incidences than younger adults, $t(65) = 3.88$, $p < .0005$, 95 % CI [1.38, 4.30], $d = .95$, $BF_{10} = 102.14$. Taken together, these results suggest that older adults exploited greater focus on the task, incurring a relative behavioural advantage via more stable performance (see also McGovern et al., 2018).

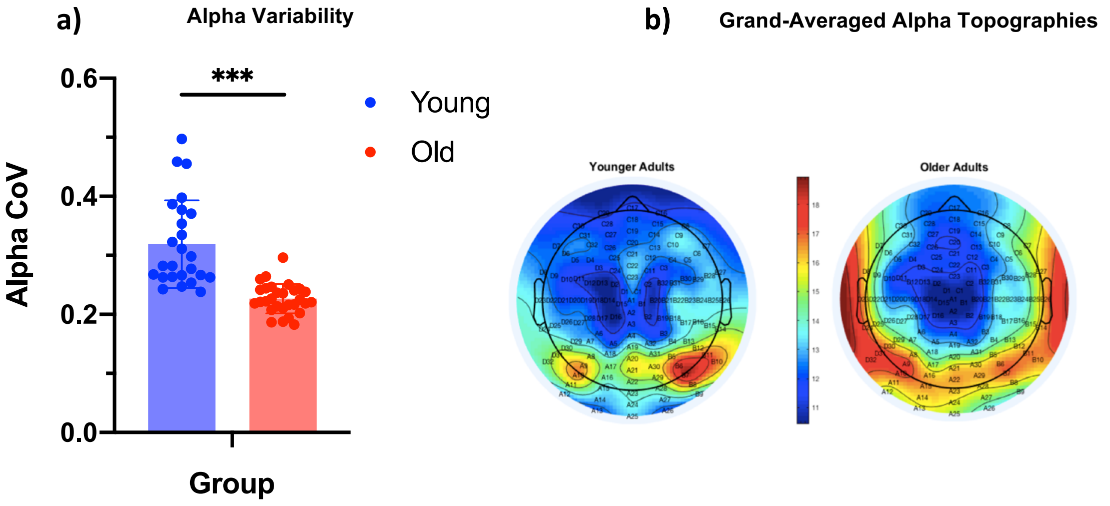
3.3.2 Target-Aligned Neurophysiological Measures of Fluctuating Attentional Engagement

Neurophysiological markers of fluctuating attentional engagement (pre-target alpha and PD) were measured relative to target onset for both age groups. Descriptive statistics for the between-group comparisons on the target-aligned EEG and pupil measures are displayed in Table **3.1**. The total number of valid trials included in the target-aligned alpha analyses differed significantly between younger and older adults (see Table **S.3.1**, §*3.5 Supplemental Material*). However, between-group analyses with a subset of randomly selected participants (representing 70% of the cases, with matched trial numbers across groups) found similar results to those using the total sample; therefore, the latter analysis using the total sample is reported. Further, trial counts for PD were matched across groups (see Table **S.3.1**, §*3.5 Supplemental Material*).

3.3.2.1 Pre-Target Alpha. Stimulus-independent endogenous neural activity in spectral alpha power was explored prior to target onset during a window devoid of task-evoked responses. A large and significant difference in pre-target attentional modulation, assayed by alpha CoV, was observed between age groups, $t(28.69) = 5.95$, $p < .0005$, 95% CI [.06, .12], $d = 1.72$, $BF_{10} = 168138.38$. Older adults exhibited less variable alpha-band activity prior to target onset than their younger counterparts (Figure **3.2**).

Figure 3.2

Bar Chart Comparing (a) Pre-Target Alpha Variability and (b) Alpha Power Scalp Topographies for Younger and Older Adult Participants



Note. (a) Bar chart comparing pre-target alpha variability (Coefficient of Variance, CoV) between younger and older adults. Error bars represent the standard error of the mean (SEM). (b) Grand-averaged topographies of mean occipital alpha power measured -2000ms to 0ms preceding target onset for each group. There was no clear alpha peak for older adults, consistent with age-associated reductions in alpha power and their steadier attentional engagement toward the task.

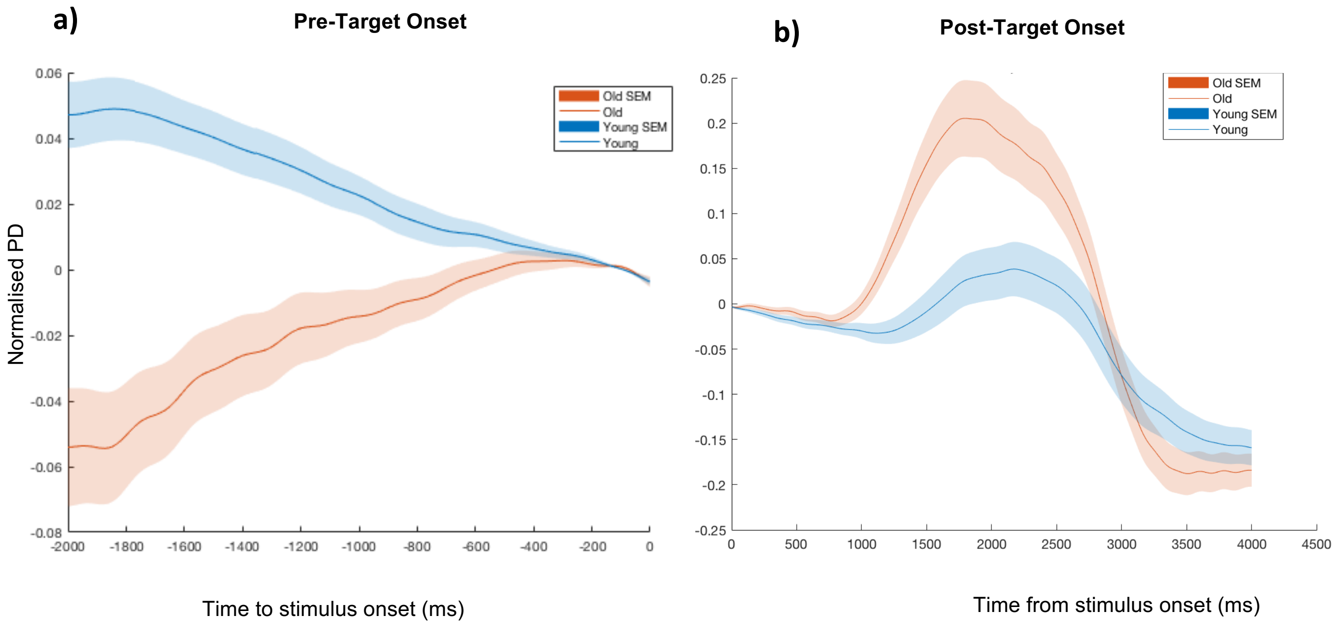
*** $p < .001$

3.3.2.2 Target-Related Changes in PD. An age-related reduction in the mean amplitude of the normalised PD in the two seconds preceding target onset was observed, $t(50.41) = 4.25$, $p < .0005$, 95% CI [.02, .06], $d = 1.08$, $BF_{10} = 351.62$. The groups further differed with respect to the rate of pupil dilation changes, quantified by the mean slope, over the pre-target period, $t(62) = -5.71$, $p < .0005$, 95% CI [-.03, -.01], $d = 1.43$, $BF_{10} = 36145.73$ (Figure **3.3a**). Both groups display dynamic pupil changes in anticipation of the target, with younger adults demonstrating a more reactive response, shifting attentional engagement toward the task just in time prior to the onset of the target, and older adults displaying a more preparatory and attentively engaged mode, as shown by the gradual rise in PD over the pre-target interval.

The grand-averaged normalised PD waveforms over the *post-target* onset window tracked the full extent of the pupil response to targets, showing a reduction in arousal, marked by a reduction in normalised PD following peak evidence and response for both groups. Older adults demonstrated higher mean amplitudes, $t(62) = -2.22$, $p = .030$, 95% CI [-.09, -.01], $d = .56$, $BF_{10} = 1.98$, and higher peak amplitudes, $t(61) = -3.45$, $p = .001$, 95% CI [-.23, -.06], $d = .87$, $BF_{10} = 30.00$, relative to the shoulder of the response curve compared to younger adults (Figure **3.3b**). Together, these target-aligned pupil differences indicate that younger and older adults employ different task-related strategies. Younger adults appeared to drop out of an "exploratory" state, gradually reducing their PD prior to target onset; in contrast, older adults more efficiently modulated their focus according to task demands.

Figure 3.3

Target-Aligned Grand-Averaged Pupil Diameter Waveforms (a) Pre- and (b) Post-Target Onset for Younger and Older Adult Participants



Note. Grand-averaged waveforms of normalised pupil diameter (PD) separated by group measured within a (a) *pre-target* window of -2000ms to 0ms and (b) *post-target* window of 0ms to 4000ms, where 0ms represents target onset. Shaded areas indicate the SEM of data points.

Table 3.1

Descriptive Statistics for the Spectral and Time-Based Features of the Target-Aligned Neurophysiological Measures of Attentional Engagement for Younger and Older Adults

Variable	Young		Old	
	n	*M* (*SD*)	*n*	*M* (*SD*)
Attentional Engagement				
Pre-Target Alpha CoV***	25	.32 (.07)	29	.23 (.03)
Pre-Target PD Mean Amp***	33	.02 (.03)	31	-.02 (.05)
Pre-Target PD Slope***	33	-.01 (.01)	31	.01 (.01)
Post-Target PD Mean Amp*	33	-.04 (.09)	31	.01 (.02)
Post-Target PD Peak Amp**	33	.12 (.16)	30	.26 (.18)

Note. Amp, Amplitude; CoV, Coefficient of Variance; M, mean; n, number of observations; PD, Pupil Diameter; SD, Standard Deviation. Target alpha amplitude measure [window: -2000ms to 0ms]; Pre-target PD amplitude and slope measures [window: -2000ms to 0ms]; Post-target PD amplitude measures [window: 0ms to 4000ms].

p* < .05; ** *p* < .01; * *p* < .001

3.3.3 Probe-Aligned Neurophysiological Measures of Perceptual Decoupling

Since perceptual decoupling is proposed to reflect the capacity to redeploy attention away from sensory input, the following were examined prior to different subjective attentional states within the pre-probe interval: 1) the unfolding SSVEP, representing sensory input, 2) alpha, indexing sensory inhibition during attentional withdrawal from a primary task, and 3) PD, with its known relationship to exploitation/exploration dynamics linked to LC-NA function (see Table **3.2**).

Trial counts were similarly matched across Focus and Mind-Wandering conditions for younger adults but not for older adults (see descriptive statistics and within-group trial count comparisons in Table **S.3.2**, §*3.5 Supplemental Material*), which is consistent with the low incidence of mind-wandering observed in the older group. In these cases, we supplement the frequentist approach by specifically highlighting the Bayesian values for the older adult probe signal comparisons to determine whether the observed non-significant findings are due to issues of statistical power (i.e. absence of evidence) or whether they support no effect (i.e. evidence of absence) (Dienes, 2014).

3.3.3.1 Pre-Probe SSVEP. *Within-group* comparisons of the SSVEP preceding Focused and Mind-Wandering states revealed no significant differences in the slope for either younger, $t(21) = .03, p = .977$, 95% CI [-.04, .04], $d = .01$, $BF_{10} = .22$, or older, $t(17) = -.38, p = .708$, 95% CI [-.05, .03], $d = .09$, $BF_{10} = .26$, participants. Bayesian analyses provided evidentiary support for the null hypothesis of no difference in SSVEP slope as a function of probe condition for either group. Contrary to expectation, higher mean SSVEP amplitudes were observed prior to mind-wandering compared to focused states for younger adults, $t(22) = -2.93, p = .008$, 95% CI [-.85, -.15], $d = .61$, $BF_{10} = 6.12$. No difference, however, was observed across conditions for older adults, $t(19) = 1.55, p = .138$, 95% CI [-.09, .60], $d = .35$, $BF_{10} = .65$, the BF value signals that this finding may be inconclusive (Figure **3.4**).

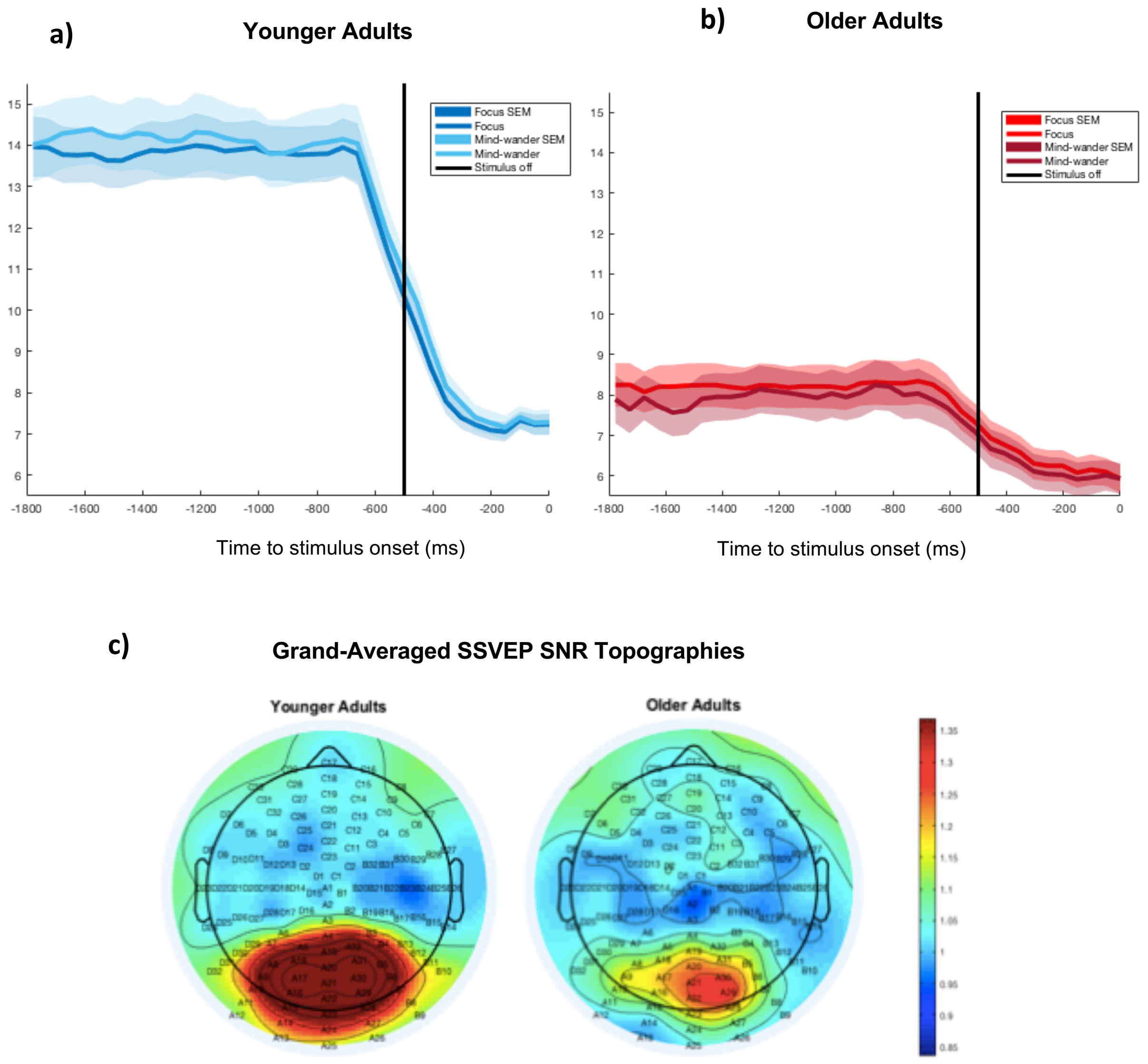
An exploratory *within-group* analysis revealed a significant difference in SSVEP amplitude CoV between Focus and Mind-Wandering for younger adults, $t(21) = -2.45, p = .023$, 95% CI [-.02, -.00], $d = .52$, $BF_{10} = 2.47$, but not for older adults, $t(18) = -1.02, p = .323$, 95% CI [-.02, .01], $d = .23$, $BF_{10} = .37$ (representing a weak or inconclusive effect). Younger participants showed greater variability in the pre-Mind-Wandering sensory signal compared to pre-Focus, suggesting that they may pursue more intermittent sensory encoding when engaged in a relatively exploratory off-task mode of thinking. Older adults, conversely, showed similar sensory evidence representation during Focused and Mind-Wandering states, providing some preliminary support for a more consistently exploitative task approach with age (Table **3.2**).

A follow up exploratory 2x2 mixed repeated measures ANOVA revealed no significant interaction between Age Group and Probe Response Condition with respect to SSVEP CoV amplitudes, $F_{1, 39} = .87, p = .358, \eta p^2 = .02$. The main effect for Probe Response was significant, $F_{1, 39} = 5.82, p = .021, \eta p^2 = .13$, indicating that irrespective of group, SSVEP CoV differed between Focused and Mind-Wandering conditions. The Bonferroni corrected pairwise comparison showed greater variability pre-Mind-Wandering than pre-Focus, independent of Group. Additionally, irrespective of probe response, younger and older adults significantly differed regarding SSVEP CoV, $F_{1, 39} =$

33.85, $p < .0005$, $\eta p^2 = .47$, with older adults displaying greater variability in the general pre-probe sensory signal than younger adults.

Figure 3.4

Probe-Aligned Grand-Averaged Signal Waveforms Showing Sensory Encoding (SSVEP) for (a) Younger and (b) Older Adult Participants and (c) Grand-Averaged Scalp Topographies



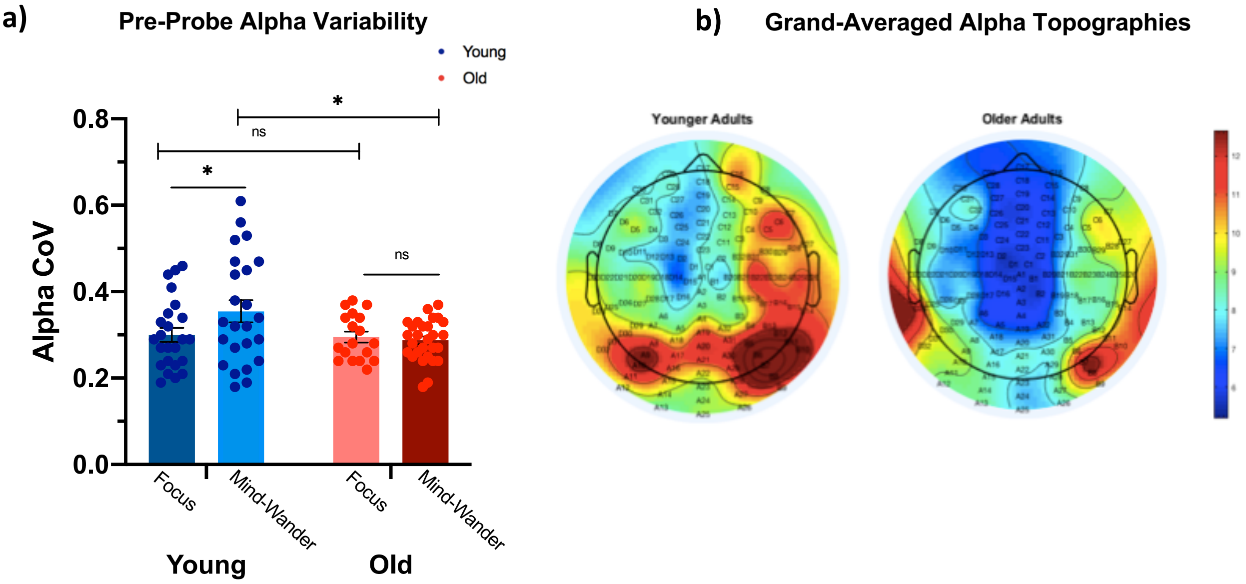
Note. Separate grand-averaged waveforms of the steady-state visually evoked potential (SSVEP) prior to Focused and Mind-Wandering states for (a) younger and (b) older adults, relative to probe onset at 0ms. SSVEP amplitude and slope measures were extracted from a temporal window of -1800ms to -800ms, avoiding the checkerboard stimulus offset at -500ms (denoted by the vertical black line). Shaded areas represent the SEM of data points. (c) Grand-averaged scalp topographies of the signal-to-noise (SNR) SSVEP signal were measured from -1800ms to -1500ms preceding probe onset for younger and older adults and showed a positive component over occipital regions.

3.3.3.2 Pre-Probe Alpha. *Within-group* paired samples *t*-tests observed significant greater alpha variability for Mind-Wandering compared to Focused conditions for younger adults, $t(22) = -2.09$, $p = .049$, 95% CI [-.08, -.00], $d = .44$, $BF_{10} = 1.35$, but this difference was not similarly documented in older adults, $t(17) = -1.58$, $p = .133$, 95% CI [-.05, .01], $d = .37$, $BF_{10} = .69$ (weak or inconclusive effect).

An exploratory *between-groups* analysis examined attentional modulation preceding probe presentation and demonstrated no significant difference between younger ($n = 24$, mean (M) = .30, $SD = .08$) and older adults ($n = 28$, $M = .29$, $SD = .05$) in Alpha CoV with respect to Focus, $t(36.07) = .71$, $p = .485$, 95% CI [-.02, .05], $d = .20$, $BF_{10} = .35$. There was, however, evidence to support a *between-groups* difference in alpha CoV prior to Mind-Wandering incidences, $t(32.61) = 2.09$, $p = .045$, 95% CI [.00, .12], $d = .59$, $BF_{10} = 1.22$. The reduced alpha variability in the older group ($n = 18$, $M = .29$, $SD = .05$), compared to younger adults ($n = 24$, $M = .35$, $SD = .12$), suggests a less marked shift away from an exploitative to an exploratory state with advancing age, even when mind-wandering (Table **3.2**, Figure **3.5**).

Figure 3.5

Bar Chart Comparing Pre-Probe Alpha Variability (a) and Alpha Power Scalp Topographies (b) for Younger and Older Adult Participants



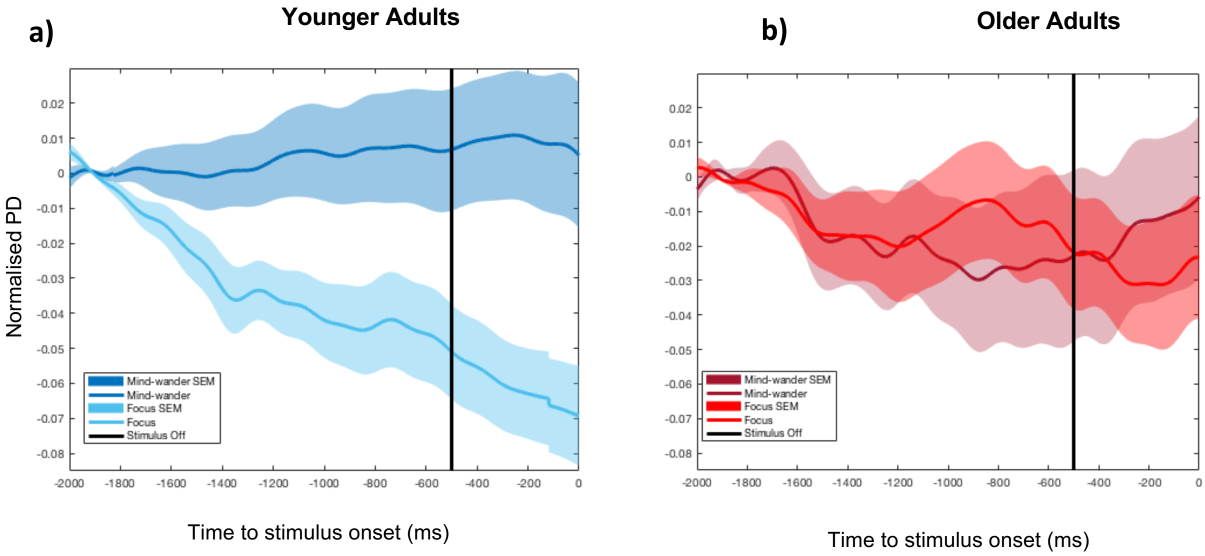
Note. (a) Bar chart comparing probe-aligned alpha variability (coefficient of variance, CoV) prior to Focused and Mind-Wandering states for younger and older adults. Younger adults exhibited greater alpha variability preceding Mind-Wandering compared to Focus but no difference between conditions was observed for older adults. Additionally, no between-groups difference was observed in pre-Focus alpha CoV, however, older adults demonstrated less alpha variability prior to Mind-Wandering than their younger counterparts. (b) Grand-averaged topographies of the mean alpha signal [-1800ms to 0ms] relative to probe presentation for younger and older adults.
ns: non-significant; *$p < .05$

3.3.3.3 Pre-Probe PD. A significant *within-groups* difference in mean normalised PD prior to Focus and Mind-Wandering was observed for younger adults, $t(31) = -2.49$, $p = .018$, 95% CI [-.06, -.01], $d = .44$, $BF_{10} = 2.67$, but not for older adults, $t(23) = .49$, $p = .625$, 95% CI [-.03, .06], $d = .10$, $BF_{10} = .24$. The BF for the older group effect provides evidence in favour of the null hypothesis, namely that there was no difference in PD between conditions for older adults.

No significant *between-groups* difference was observed in mean PD prior to Focus between younger ($n = 33$, $M = -.03$, $SD = .04$) and older ($n = 31$, $M = -.01$, $SD = .07$) adults, $t(62) = -1.21$, $p = .233$, 95% CI [-.05, .01], $d = .30$, $BF_{10} = .47$. Further, no difference was observed in pre-Mind-Wandering mean PD between younger ($n = 32$, $M = .00$, $SD = .06$) and older ($n = 24$, $M = -.02$, $SD = .09$) adults, $t(54) = 1.39$, $p = .170$, 95% CI [-.01, .06], $d = .38$, $BF_{10} = .61$. Overall, there appeared to be a ‘drop out of explorative mode’ pre-Focus which was more accentuated in younger adults, as shown by a general rise in their PD prior to mind-wandering in contrast with the general decrease in PD prior to Focus (Table **3.2**, Figure **3.6**).

Figure 3.6

Probe-Aligned Grand-Averaged Signal Waveforms Showing Attentional Engagement (Pupil Diameter) Prior to Focus and Mind-Wandering States for (a) Younger and (b) Older Adults



Note. Grand-averaged waveforms of normalised and baseline-corrected pupil diameter (PD) prior to Focused and Mind-Wandering states for (a) younger and (b) older adults relative to probe onset at 0ms. Amplitude measures were extracted across a temporal window of -1800ms to -800ms, to avoid the checkerboard stimulus offset at -500ms, denoted by the vertical black line. The checkerboard offset was followed by a 500ms blank screen before probe onset at 0ms. Shaded areas represent the SEM of data points.

Table 3.2

Within-Group Descriptive Statistics for the Spectral and Time-Based Features of Probe-Aligned Neurophysiological Measures of Perceptual Decoupling for Younger and Older Adult Participants

Variable	Young				Old			
	Focus		Mind-Wandering		Focus		Mind-Wandering	
	n	*M* (*SD*)	*n*	*M* (*SD*)	*n*	*M* (*SD*)	*n*	*M* (*SD*)
SSVEP Slope	22	.00 (.05)	22	.00 (.07)	18	-.01 (.05)	18	-.00 (.06)
SSVEP Mean Amp	23	13.76 (4.21)**	23	14.26 (4.51)**	20	8.23 (3.62)	20	7.98 (3.22)
SSVEP Amp CoV	22	.08 (.01)*	22	.10 (.02)*	20	.12 (.02)	20	.12 (.03)
Alpha CoV	23	.31 (.08)*	23	.34 (.12)*	18	.27 (.05)	18	.29 (.05)
PD Mean Amp	32	-.03 (.04)*	32	.00 (.06)*	24	-.01 (.07)	24	-.02 (.09)

Note. Amp, Amplitude; CoV, Coefficient of Variance; M, mean; n, Number of observations; PD, Pupil Diameter; SD, Standard deviation; SSVEP, Steady-State Visually Evoked Potential.

Pre-probe SSVEP slope and amplitude measures [window: -1800ms to -800ms]; Pre-probe Alpha amplitude measure [window: -1800ms to -800ms]; Pre-probe PD amplitude measure [window: -1880ms to -800ms].

* Significant within-groups difference at $p < .05$

** Significant within-groups difference at $p < .01$

3.3.4 Target-Aligned Neurophysiological Measures of Perceptual Decision-Making

Neural indices of perceptual decision formation (CPP), sensory evidence encoding (SSVEP), and motor preparation (Mu/Beta) were examined at the time of target evidence onset and tracked over target evolution for younger and older adults. Descriptive statistics for the spectral and time-based features of these decision-related signal measures as a function of age group are provided in Table **3.3**. Stimulus-locked signal waveforms aligned to target onset and grand-averaged scalp topographies for younger and older adults are displayed in Figure **3.7**. The number of valid trials contributing to these decision-related variables were not significantly different across groups (Table **S.3.1**, §*3.5 Supplemental Material*).

3.3.4.1 CPP During Target Evolution. Signal analyses demonstrated that the CPP at evidence onset did not vary with age (Figure **3.7a**). There were no significant differences between younger and older adults in the peak amplitude of the CPP, *t*(53) =

1.37, *p* = .175, 95% CI [-2.32, 12.42], *d* = .37, BF_{10} =.59, the peak amplitude latency, *t*(53) = -1.21, *p* = .230, 95% CI [-222.26, 54.68], *d* = .33, BF_{10} =.50, or the rate of evidence accumulation (as measured through the build-up rate of the CPP) *t*(32.76) = 1.23, *p* = .228, 95% CI [-.00, .02], *d* = .35, BF_{10} = .55. Both groups similarly and reliably integrated sensory evidence in line with target evolution until forming a decision threshold that peaked at response execution.

Differential group CPP onset latencies; namely, 708.98ms and 265.53ms for younger and older adults, respectively, revealed earlier initiation of sensory evidence accumulation for older adults. This pattern of earlier decision formation by older adults may reflect more exploitative, or conservative, perceptual evidence tracking with age and greater attentional readiness (Figures **3.7a** and **3.8**). Conversely, younger adults began integrating evidence of the stimulus change later, reacting when the contrast reduction became more salient.

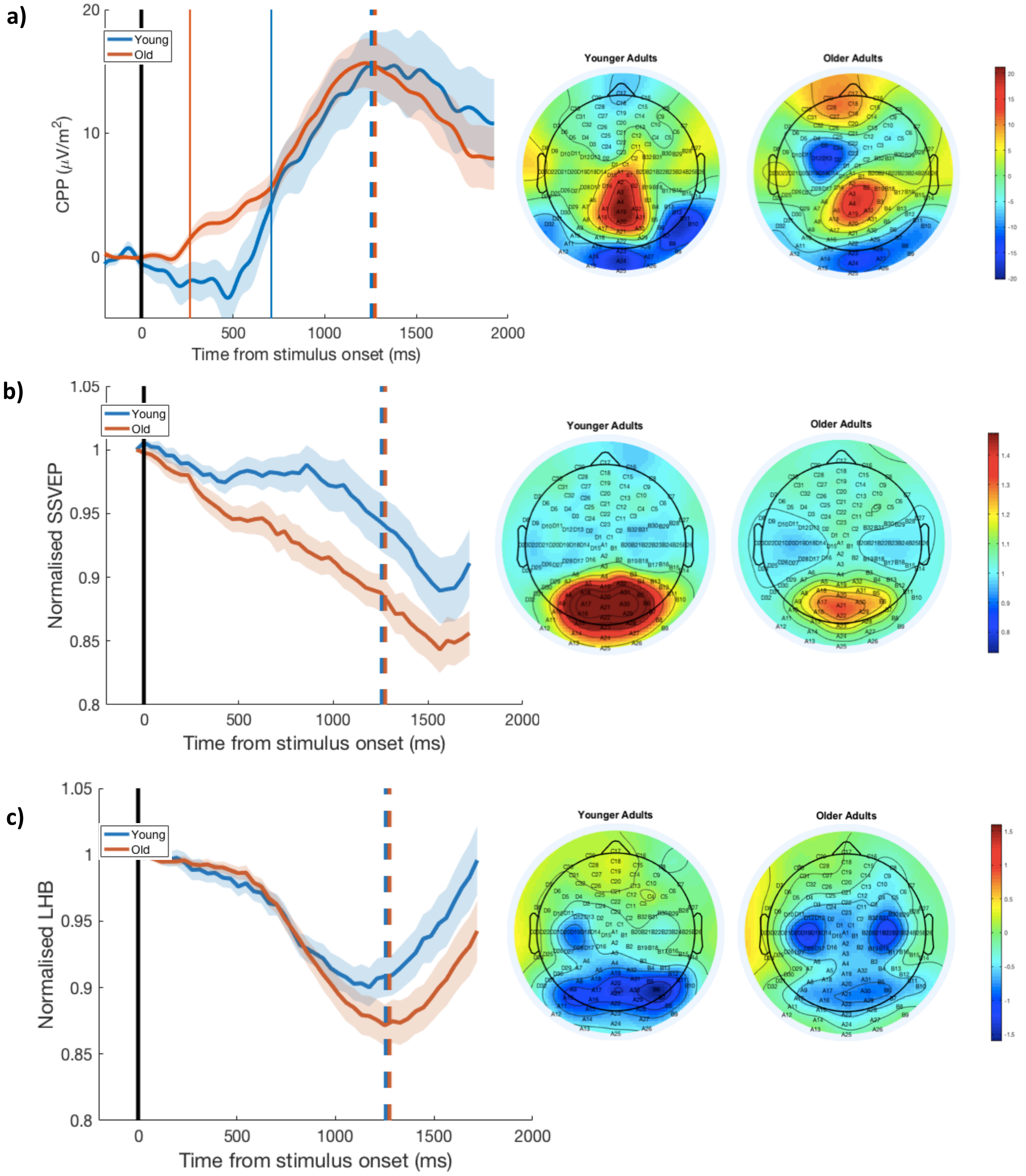
3.3.4.2 SSVEP During Target Evolution. The normalised SSVEP for both groups reliably traced the exogenously driven feature changes of the stimulus contrast. The grand-averaged target-aligned waveforms showed decreasing SSVEP magnitudes in line with the contrast reduction until full target evolution, i.e. peak physical evidence, at 1600ms (Figure **3.7b**). No group differences in the rate of sensory encoding, indexed by the normalised SSVEP slope, were observed, *t*(51) = 1.01 *p* = .317, 95% CI [-.00004, .00012], *d* = .28, BF_{10} = .42. A significant between-groups difference, however, in the mean amplitude of the normalised SSVEP was revealed, *t*(53) = 2.54, *p* = .014, [.01, .09], *d* = .69, BF_{10} = 3.63. Here, the SSVEP traced the stimulus contrast reduction so the finding of an age-related reduction in mean SSVEP represents better sensory encoding with age. The more pronounced drop in mean SSVEP amplitude for older adults suggests that they more faithfully tracked the downward trajectory of the visual stimulus throughout the target period than their younger counterparts.

3.3.4.3 LHB During Target Evolution. The effector-selective LHB showed qualitatively similar age-related patterns to the domain-general CPP; namely both groups demonstrated comparable decision-related activity antecedent to full target evolution (Figure **3.7c**). No significant differences in motor preparation were observed between younger and older adults either in the rate (slope), *t*(53) = .62, *p* = .539, 95% CI [-.00004, .0001], *d* = .17, BF_{10} = .32, or in the mean amplitude, *t*(53) = .51, *p* = .614, 95% CI [-.02, .03], *d* = .14, BF_{10} = .30, of normalised LHB over the target-locked waveforms.

Additional analyses were performed to investigate possible differences in normalised LHB amplitude over a target-locked time window around the time of mean RT (1000ms to 1350ms post-target onset). No significant differences in LHB mean amplitude were observed between younger and older adults, *t*(53) = 1.31, *p* = .196, 95% CI [-.01, .07], *d* = .36, BF_{10} = .55. There was, however, a marginally significant difference in the LHB slopes between groups, *t*(53) = 2.01 *p* = .049, 95% CI [.0000003, .0002], *d* = .55, BF_{10} = 1.43, with older adults showing greater beta desynchronization around the time of motor response via a more pronounced drop in the slope of normalised LHB than younger adults consistent with an exploitative approach (see Table **3.3** and Figure **3.7**). The BF, however, suggests that evidence for this effect is weak or inconclusive.

Figure 3.7

Target-Aligned Grand-Averaged Signal Waveforms (left) and Scalp Topographies (right) Showing (a) Decision Formation (CPP), (b) Sensory Encoding (SSVEP), and (c) Motor Preparation (Mu/Beta) for Younger and Older Adult Participants

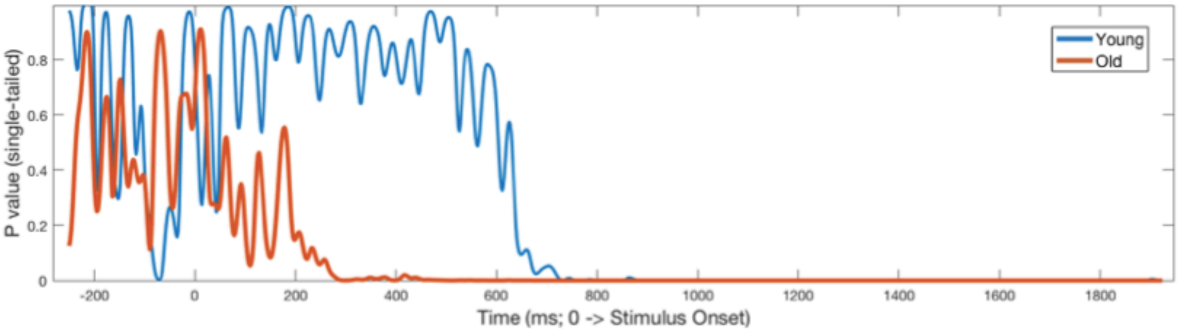


Note. Vertical lines at 0ms denotes the time of target stimulus onset. Dashed lines on the stimulus-locked waveforms represent the mean reaction time for each group.

Vertical coloured lines in Figure **3.7a** represent the CPP onset latencies for each group. Shaded areas indicate the SEM of data points. (a) Stimulus-locked CPP waveforms separated by group plotted relative to target onset (left). CPP onset latencies for older and younger adults at 265.63ms and 708.98ms, respectively, are indicated by vertical coloured lines. Grand-averaged topographies of the ERP signal -150ms to -50ms preceding response for each group showing a positivity over centroparietal areas (right). (b) Stimulus-locked normalised SSVEP waveforms separated by group plotted relative to target onset (left). Grand-averaged topographies of the signal-to-noise SSVEP signal measured -100ms to 0ms preceding stimulus onset for each group showing a large positive component over occipital regions (right). (c) Stimulus-locked normalised LHB waveforms separated by group plotted relative to target onset (left). Grand-averaged topographies of LHB signal measured -100ms to 100ms with respect to response for each group showing maximal activity over premotor regions in the left hemisphere (right).

Figure 3.8

CPP Onset: Running Point-by-Point t-Tests Against Zero Across the ERP Waveforms



Note. CPP Onset latencies were calculated for each group as the first time point the signal amplitude significantly exceeded zero in a positive direction ($p < .05$) and sustained this significant divergence over at least 50ms. The CPP Onset latency for younger adults occurred at 708.98ms while older adults' onset latency occurred earlier at 265.63ms. Figure **3.7a** shows the grand-averaged CPP waveforms from which these onset latencies were derived.

Table 3.3

Descriptive Statistics for the Spectral and Time-Based Features of Target-Aligned Neurophysiological Measures of Perceptual Decision-Making for Younger and Older Adult Participants

Variable	Young		Old	
	n	*M* (*SD*)	*n*	*M* (*SD*)
	Perceptual Decision-Making			
CPP Peak Amp	25	26.13 (15.93)	30	21.08 (11.26)
CPP Peak Latency, ms	25	1234.38 (223.31)	30	1318.16 (278.41)
CPP Slope	25	.01 (.02)	30	.01 (.01)
SSVEP Mean Amp*	25	.96 (.08)	30	.90 (.07)
SSVEP Slope	23	-.00002 (.0001)	30	-.00006 (.0002)
LHB Mean Amp	25	.94 (.05)	30	.93 (.05)
LHB Slope	25	-.0001 (.0001)	30	-.0001 (.0001)
LHB Mean Amp Additional	25	.91 (.07)	30	.88 (.08)
LHB Slope Additional*	25	.00002 (.0002)	30	-.0001 (.0001)

Note. Amp, Amplitude; CPP, Centro-Parietal Positivity; LHB Left Hemisphere Beta; M, mean; ms, milliseconds; n, number of observations; SD, Standard Deviation; SSVEP, Steady-State Visually Evoked Potential. CPP amplitude measures [window: 500ms to 1750ms]; CPP slope [window: 250ms to 750ms]; Target SSVEP amplitude measures [window: 500ms to 1600ms]; Target SSVEP slope [window: 350ms to 850ms]; LHB amplitude measures [window: 800ms to 1250ms]; LHB slope [window: 350ms to 850ms]; Additional LHB amplitude and slope measures [window: 1000ms to 1350ms].

$^*p < .05$

3.3.5 Exploratory Correlations Between Behavioural and Neurophysiological Measures

Exploratory partial correlations, controlling for Age Group, were performed to investigate the associations between behavioural performance indices and neurophysiological signals. After controlling for Age Group, Hit Rate was negatively associated with pre-target alpha CoV, $r_{\text{partial}}(48) = -.40$, $p = .004$, and with pre-Mind-Wandering mean PD, $r_{\text{partial}}(50) = -.29$, $p = .036$. Namely, better performance was related to steadier attentional engagement during the pre-target and pre-probe intervals, indexed by attenuated alpha variability and reduced pupil dilation. Additionally, Hit Rate was partially correlated with probe-aligned PD difference scores (i.e. the difference in mean PD from Mind-Wandering to Focused states), $r_{\text{partial}}(50) = -.33$, $p = .016$, suggesting that enhanced accuracy was associated with less shifting from exploitative to explorative modes.

Reciprocally, self-reported Mind-Wandering frequency was positively partially associated with pre-target mean SSVEP, $r_{\text{partial}}(51) = .27$, $p = .049$, pre-Mind-Wandering mean PD, $r_{\text{partial}}(53) = .28$, $p = .042$, and with probe-aligned PD difference scores, $r_{\text{partial}}(53) = .27$, $p = .047$. That is, less efficient target stimulus encoding, elevated pupil size, and more marked pupil changes between subjective attentional states were individually associated with greater mind-wandering propensity, independent of Age Group.

When age group was controlled, larger RTs (slower performance) were positively associated with widened and delayed decision policy indexed by higher CPP peak amplitudes, $r_{\text{partial}}(52) = .32$, $p = .018$, and delayed CPP peak amplitude latencies, $r_{\text{partial}}(52) = .41$, $p = .002$. Further, RT CoV was negatively associated with CPP peak amplitude latency, $r_{\text{partial}}(51) = -.32$, $p = .019$, and with post-target mean PD amplitude, $r_{\text{partial}}(59) = -.28$, $p = .030$. Fluctuating performance was therefore linked with a less robust response to target evolution, with earlier, and perhaps more impulsive, perceptual decision formation. Additionally, RT CoV was positively partially correlated with pre-Focus SSVEP CoV, $r_{\text{partial}}(46) = .29$, $p = .043$, and with probe-aligned PD difference scores, $r_{\text{partial}}(51) = .28$, $p = .045$. As such, performance variability was associated with more variability in the sensory signal prior to focused states, and with greater exploratory shifting during the pre-probe interval. Finally, the number of False Alarms was positively associated with the mean amplitude of normalised LHB, $r_{\text{partial}}(49) = .29$, $p = .041$. False Alarms were related to reduced beta desynchronisation, possibly indicating greater uncertainty or a more liberal threshold for motor response preparation and execution on the basis of less evidence. The behavioural outcomes were not further significantly correlated with any of the other neurophysiological signals.

3.4 Discussion

The present investigation examined background states of attention (alpha oscillations) and shifts in "exploit"/ "explore" modes (pupil changes) during a non-demanding sustained attention task within the context of ageing. We aimed to examine how such endogenous attention signal changes correspond to subjective attentional states captured by thought probes, and to characterise their effects on goal-relevant stimuli (evidence accumulation, sensory representation, and action) and behavioural performance for younger and older adults. We advance four key findings that indicate an age-related difference in oscillatory strategies, propounding a more exploitative task approach with advancing age.

1. Steadier attentional engagement preceding target onset was observed for older adults compared to their younger counterparts as seen by attenuated variability in the attentional signal and more robust phasic PD response to target.
2. Younger, but not older, adults exhibited perceptual decoupling through more intermittent sensory encoding, indexed by greater variability in the sensory and attentional signals prior to mind-wandering relative to focused states.
3. Older adults demonstrated earlier onset of evidence accumulation and better sensory representation of the target stimulus compared to younger adults. In further support of perceptual decoupling for younger adults, they show delayed and reduced representation of the sensory evidence as it evolved over the target trial. This suggests that younger adults were less adept at tracking the sensory evidence at the critical point where the contrast changes because they are more generally disengaged.
4. Increased attentional variability and attenuated task-related processing were associated with performance decrements and increased mind-wandering, independent of age group, suggesting the implications of transitional shifts between exploitative and explorative states.

Considering the potential implications of oscillatory attentional engagement, the age-related difference in mind-wandering propensity, and group equivalence in task performance, we tender that younger and older adults employed different strategies during the GradCCD-ES. Younger adults flexibly alternated between competing goal-directed and explorative strategies without incurring relative performance costs, despite their increased mind-wandering propensity and more variable sensory evidence encoding and attentional engagement. Older adults marshalled their more limited cognitive resources toward the task and showed less bias for exploration, even during mind-wandering. This was supported by their reduced mind-wandering tendency, steadier attentional engagement pre-target and pre-mind-wandering, and more conservative decision policy, compared to their younger counterparts.

3.4.1 Steadier Attentional Engagement with Advanced Age

Prior to target onset, older adults demonstrated more stable attentional engagement, as shown by their reduced posterior alpha band variability, coupled with attenuated mean normalised PD, and gradually increasing pupil dilation in anticipation of the target. These antecedent attentional markers were examined over a temporal window absent of task-dependent target changes, which enabled investigation of intrinsic neural activity that was less impeded by stimulus-evoked responses. Following target presentation, older adults exhibited higher mean and peak normalised PD amplitudes, suggesting that they tracked the full extent of target evolution with greater integrity. This is in line with Joshi et al. (2016) who showed a linear relationship between LC and pupil size, namely that greater PD is linked to more NA in the service of goals. Conversely, younger adults showed a steep decrease in PD prior to target onset, suggesting that they dropped out of an exploratory mode prior to target onset with further attenuated pupil response to targets. These age-related patterns are further substantiated by the behavioural finding of reduced RTV in older adults.

Together, these findings suggest a more restricted exploitative oscillation strategy with age, which confers a relative behavioural advantage for older adults through steadier performance and better attentional engagement. Indeed, a bias for explorative tendencies in younger adults has been previously reported (Mata et al., 2013). These findings also replicate an effect formerly observed by McGovern et al. (2018), in which less variable alpha activity and RT performance were documented in older adults compared to younger adults. This was demonstrated using a previous variant of the current task without the inclusion of probes and as such, the age-related discrepancy in attentional dynamics and strategic policies do not appear to be consequents of periodic task disruptions from ES procedures.

3.4.2 Younger Adults Show Perceptual Decoupling During Mind-Wandering

Signal analysis within the pre-probe interval provided support for perceptual decoupling (J. Smallwood & Schooler, 2006, 2015) in younger adults but not for older adults. Specifically, younger adults exhibited more intermittent sensory encoding (greater SSVEP CoV) in conjunction with more variable synchronisation of the attentional signal (alpha CoV) during self-reported mind-wandering states relative to focused states. Endogenous baseline PD was also analysed as a proxy psychophysiological measure of LC-NA neuromodulatory activity, representing a potential mechanism through which brain states may flexibly shift between competing exploit and explore modes. Younger adults displayed higher mean PD amplitudes prior to Mind-Wandering compared to Focus and appeared to drop out of an exploratory mode pre-Focus as evidenced by their more accentuated rise in PD prior to Mind-Wandering and decrease in PD prior to Focus.

Younger adults also displayed higher mean SSVEP prior to mind-wandering relative to focused states. Given that previous research has shown reduced electrophysiological responses to external events in perceptual decoupling, the reverse effect observed was therefore unexpected. However, we speculate that if the 25Hz sensory signal was processed with greater neural efficiency during focused states, then more desynchronised neural populations may have yielded a reduced SSVEP amplitude. Indeed, cognitive efficiency theories often predict that reduced amplitudes index better visual processing efficiency (see Rypma, Berger, & D'Esposito, 2002; Wiegand et al., 2014). It follows then, that a loss of neural efficiency during mind-wandering may have induced more synchronised neural activity increasing the SSVEP amplitude. However, it is important to note that previous research into decoupling has focused on perceptual processing of target stimuli – and in this regard, our target-aligned results show a similar outcome via less target sensory evidence and more mind-wandering in younger adults. Furthermore, it might be that when sensory evidence is stable (i.e. unchanging in contrast) as is the case with the pre-probe states, an index of variability may better capture how efficiently the 25Hz flicker is sampled. Indeed using the CoV measure picked up greater variability prior to mind-wandering than focused states for younger adults.

Prominent work has similarly shown elevated posterior alpha activity prior to lapses in attention (O'Connell et al., 2009), and during subjective mind-wandering states (Compton et al., 2019), internally-oriented attention (Braboszcz & Delorme,

2011) or at rest (Laufs et al., 2003), suggesting the influence of top-down processes on sensory inhibition (Klimesch, 2012). This is further corroborated by studies reporting compromised sensorimotor processing of perceptual events via attenuated electrophysiological and pupillary responses to sensory input during or preceding mind-wandering (Baird et al., 2014; Barron et al., 2011; Braboszcz & Delorme, 2011; Kam et al., 2011; Macdonald et al., 2011; Smallwood et al., 2011; Walpola et al., 2020), as well as pupillary changes preceding explorative behaviours (Jepma & Nieuwenhuis, 2011).

Contrary to predictions, however, there was no clear evidence of momentary reductions in the magnitude or rate of the sensory signal during mind-wandering compared to focus for older adults. Older adults maintained similar levels of sensory representation and attentional engagement prior to both subjective focus and mind-wandering states, supporting a more conservative strategic approach with age. Moreover, the age-related reduction in pre-mind-wandering alpha CoV, which was not similarly evident pre-focus, highlights a less pronounced shift away from the exploit to the explore state by older adults when mind-wandering is reported. Given the temporally unpredictable nature of the target onset, older adults showed a tendency for more cautious and continual task monitoring to ensure adequate performance. However, given the low incidence of mind-wandering for older adults, and as a consequence, low trial counts, these non-significant results may have been subject to issues of statistical power. Future research may be necessary to clarify the extent of perceptual decoupling with age. Nonetheless, these findings demonstrate different age-related neurophysiological patterns associated with mind-wandering.

3.4.3 Earlier Evidence Accumulation and Greater Sensory Encoding by Older Adults

Dissociable stimulus-aligned neural indices of perceptual decision formation, sensory evidence encoding, and motor preparation demonstrated that both age groups reliably, and similarly, tracked the exogenous feature changes of the target contrast reductions as they evolved over time (see also McGovern et al., 2018; O'Connell et al., 2012). In contrast to previous studies demonstrating decreased P3 amplitudes and increased peak latencies (e.g. Fjell & Walhovd, 2001; Rossini et al., 2007), and stronger mu/beta desynchronization with age (e.g. Quandt et al., 2016; Sailer et al., 2000), we observed no differences in the ERP and spectral measures of CPP between groups. Additionally, we observed only a weak effect showing greater beta power desynchronization via a more pronounced slope for older adults around the time of mean RT consistent with older adults maintaining an exploitative approach; this was not further supported by the between-group analyses of mean amplitude measurements or the examination of LHB slopes during the broader target-locked time window. However, our results are broadly consistent with McGovern et al. (2018) who used a variant of the present task and observed similar target processing across groups with the exception of an age-related difference in the variability of the CPP build up rate.

In the present study, however, older adults exhibited earlier CPP onset and more faithfully tracked the downward trajectory of the contrast reduction throughout the target period, as indexed by reduced mean target-related SSVEP amplitude. These patterns of earlier initiation of evidence accumulation accompanied by enhanced sensory encoding of the target stimulus are consistent with older adults adopting a more cautious decision policy and engaging in more persistent perceptual monitoring to prevent missed targets. This may be considered an adaptive age-related compensatory strategy, particularly in light of their reduced executive resources. This is supported by drift diffusion models showing wider and more conservative decision boundaries with age (Ratcliff et al., 2006b, 2010; Starns & Ratcliff, 2010).

On the other hand, the delayed onset in younger adults was indicative of more reactive temporal integration of sensory evidence, which was postponed until the evidence was more salient; this may have occasioned more opportunity for younger adults to engage in mind-wandering without impacting overall performance. The delayed and reduced sensory evidence representation during the target trials provides additional support for perceptual decoupling in younger adults; namely, they integrated the target stimulus sensory evidence less efficiently due to their more frequent attentional disengagement.

3.4.4 Poorer Performance Accompanied Attentional Fluctuations, Independent of Group

Our exploratory partial correlations demonstrated the disruptive influence of fluctuating attentional states on neurocognitive processing and behavioural performance, independent of age group. In line with perceptual decoupling, top-down stimulus-independent (oscillatory alpha activity) neural activity and bottom-up task-evoked (attenuated decision formation and variable sensory evidence representation) neural activity were associated with greater withdrawal from the primary task. Specifically, enhanced performance accuracy and reduced mind-wandering were associated with steadier attentional engagement in the pre-target and pre-probe intervals, indexed by reduced pre-target alpha variability, pre-mind-wandering pupil dilation, and less pronounced strategic shifting between probe states (indexed by PD difference scores).

Previous research has similarly shown poorer and more variable task performance during mind-wandering states across a range of tasks (Cheyne et al., 2006; McVay & Kane, 2009; Mooneyham & Schooler, 2013; Smallwood, McSpadden, & Schooler, 2008). Moreover, performance decrements have been observed alongside attenuated and oscillatory pre-stimulus alpha activity (Dockree et al., 2017; Macdonald et al., 2011; Mazaheri et al., 2009; O'Connell et al., 2009; Thut et al., 2006; van Dijk et al., 2008), and with pupillary response changes (Smallwood et al., 2011).

Performance decrements were also associated with reduced efficiency of task-related processing, controlling for age group. Specifically, delayed decision formation and reduced motor preparation were associated with slower responding and increased false alarms, respectively. Greater RTV was linked with earlier decision formation and with greater post-target pupil dilation in the target interval. Taken together, fluctuating performance was accompanied by a less robust response to target evolution and earlier, impulsive perceptual decision formation (see also Dockree et al., 2017; Kelly & O'Connell, 2013; O'Connell et al., 2009). Additionally, greater performance variability was associated with probe-aligned variables including more variable sensory evidence encoding prior to focused states and with greater exploratory shifting during the pre-probe interval. Taken together, these findings suggest that oscillating attentional engagement and explorative states have implications for task-related processing and performance.

3.4.5 Methodological Strengths of the Current Paradigm

The principal contributions of the present study were derived from a multi-faceted methodological approach whereby subjective mind-wandering states were probed periodically during task conditions of low cognitive demand. We employed a triangulated approach to overcome previous methodological challenges for measuring spontaneous thought, owing to the ephemeral, covert, and stimulus-independent phenomenological properties appurtenant to mind-wandering. We converged behavioural, subjective, and neurophysiological evidence to elucidate the dynamics underlying different attentional states, with the capacity to differentiate younger and older adults. Specifically, the ES procedure enabled qualitative categorisation of mental states preceding probes, facilitating comparisons of neural activity accompanying periods of on- (Focused) and off-task (Mind-Wandering) thought. Moreover, the high temporal resolution of the physiological recordings permitted direct and real-time assessment of the dissociable neural signals arising during stimulus-evoked and goal-directed thinking, and self-generated, intrinsically oriented mind-wandering with millisecond precision. Extending traditional paradigms for investigating perceptual decoupling, the target contrast changes unfolded smoothly and gradually, thereby eliminating sensory-evoked deflections from the signal recordings, circumventing exogenous attention capture, and placing greater dependence on endogenous attentional control. Our novel paradigm thus enabled isolation and investigation of the complex and dynamic properties of mind-wandering in ageing.

3.4.6 Methodological Issues and Directions for Future Research

Notwithstanding, a number of methodological issues are discussed with recommendations for future research. Firstly, the present findings must be interpreted relative to the current context; that is, a non-demanding sustained attention lab task. The "context-regulation hypothesis" (Andrews-Hanna, Smallwood, & Spreng, 2014; Smallwood & Andrews-Hanna, 2013; Smallwood & Schooler, 2015) suggests that the ability to regulate mind-wandering is modulated according to the external context or primary task demands. It follows that mind-wandering propensity should increase in low-demanding situations where fewer executive resources are required for successful performance and are hence, are available for mind-wandering. Conversely, attenuated mind-wandering should occur in high-demanding tasks requiring continuous attention (Giambra, 1989; Jackson & Balota, 2012). The context-dependent manner in which an individual consigns mind-wandering or maintains goal focus may therefore determine the relative extent to which costs or benefits accompany mind-wandering. Indeed, studies have demonstrated increased working memory capacity (Kane et al., 2007; Levinson, Smallwood, & Davidson, 2012; McVay & Kane, 2009) and greater creativity (Baird et al., 2012) in individuals who more efficiently regulate their mind-wandering in accordance with task demands in non-demanding conditions. Conversely, consequent performance impairments have been observed from competing resources for mind-wandering and goal-maintenance processes (e.g. Cheyne et al., 2006; Levinson et al., 2012; McVay & Kane, 2009).

In the present study, the minimised task demands may have enabled younger adults to dual-task between competing task and off-task concerns, while maintaining adequate performance. The observed patterns of oscillating neural and performance activity in younger adults support such transient shifts from intrinsic to extrinsic attention modes. Older adults, on the other hand, consigned their more limited resources and constrained their mind-wandering to mitigate performance costs. Future research should therefore investigate age-related mind-wandering across a range of paradigms where task demand is manipulated, to better understand the complex relationship between executive function, cognitive load, and mind-wandering. Further adaptability in ageing might be observed if older adults show greater promotion of mind-wandering, when the context allows. It may be that the metacognitive ability to choose the appropriate moment to wander is affected by ageing, but this remains to be seen until such experiments are conducted.

Along the same line, naturalistic environments where tasks may be self-selected, other-imposed, include meaningful stimuli, or indeed have no focal task (Jordao et al., 2019; Murray et al., 2020), may expand the scope for investigating everyday mind-wandering propensity and strategic engagement within real-world scenarios. Open-ended and unstructured natural environments may foster more freedom to explore the mind-wandering space. Although preliminary research has replicated an age-related decrease in mind-wandering in natural settings (Jackson et al., 2013; Maillet et al., 2018), there is paucity of research examining the neural mechanisms accounting for such changes and its relative impact in daily life. Momentary lapsed, or maladaptive fluctuating, attention has been shown to increase incidences of traffic accidents and poor driving performance in younger adults (Lohani et al., 2019; Yanko & Spalek, 2013; 2014). Traffic reports also suggest that although older adults are among the safest drivers, accidents involving older adults tend to have a comparatively increased risk of serious injury and mortality compared to younger adults (Cunningham, Howard, Walsh, Coakley, & O'Neill, 2001; Lombardi, Horrey, & Courtney, 2017). Moreover, mind-wandering may potentiate risk of falls in older adults (Nagamatsu et al., 2013); as such, it is imperative for future studies to dissect the mechanisms, and consequences, of mind-wandering as it ebbs and flows across heterogeneous lab and natural real-world contexts given its importance for the adaptive functioning of many daily life activities.

Secondly, although the high temporal resolution of the neurophysiological recordings was valuable for covertly tracking moment-to-moment neural processing, we acknowledge some associated challenges. As demonstrated in *Chapter 2* of this thesis, mind-wandering types distinguished by intentionality have dissociable correlates and consequences. However, within the confines of older adult's reduced proclivity for mind-wandering generally, and intentional mind-wandering specifically, we did not have sufficient trial counts to conduct a more fine-grained analysis of the neural activity associated with different mind-wandering dynamics. Future research should examine unintentional and intentional mind-wandering at the neural level with a larger sample size and with ample trial counts for each sub-condition for a more comprehensive understanding of the mechanisms underlying different mind-wandering dimensions in ageing.

Additionally, the temporal windows for each measure indexed antecedent attentional activity prior to a target or probe, and task-evoked decision-related activity over target evolution. These windows were restricted by the ITI durations (3-, 5-, and 7-seconds) and may not fully capture the precise temporal properties reflecting the onset, offset, and flow of particular mind-wandering episodes. Therefore, another direction of research would be to record the full evolution of mind-wandering episodes as they unfold, unperturbed by task-related activity to track the timescale of, and neural signatures governing, the full temporal evolution of attentional fluctuations. Studies combining resting-state EEG and blood-oxygen-level-dependent imaging (BOLD) activity in the DMN (e.g. Gusnard & Raichle, 2001; Laufs et al., 2003; Mantini, Perrucci, Del Gratta, Romani, & Corbetta, 2007) may shed light on these issues.

Thirdly, despite the advantage of ES probes, we are cognizant that these reports are not arrived at objectively but formed from a first-person viewpoint. Subjective reports may be influenced by researcher-imposed or self-interpreted definitions of mind-wandering, probe-framing, and meta-awareness capabilities, factors which are influenced by ageing (Jordao et al., 2019). However, in *Chapter 2* (Moran et al., 2021) we showed that the probes were meaningfully related to behavioural concomitants (see also Cheyne et al., 2009; McVay & Kane, 2009; Mooneyham & Schooler, 2013; Smallwood, McSpadden, Luus, et al., 2008) and in the current chapter, we further demonstrated associations between self-reported mind-wandering frequency and neurophysiological signals in both the pre-target and pre-probe epochs (see also Frank et al., 2015; Golchert et al., 2017). This triangulation supports the validity of ES as a tool for gauging phenomenologically different mental states without introspection unduly disrupting the flow of mental experience it purports to measure, as proffered by

Schooler (2002). Nonetheless, investigative and analytical developments, including functional magnetic resonance imaging (fMRI) (e.g. Laufs et al., 2003; Mantini et al., 2007), and machine learning algorithms (e.g. Kragel, Knodt, Hariri, & LaBar, 2016; Tusche, Smallwood, Bernhardt, & Singer, 2014) may be used in future studies to covertly assess and predict mind-wandering, obviating over-reliance on self-report.

Beyond solely documenting mind-wandering and its impact, combining online and covert methodological approaches may enable researchers and clinicians to independently monitor, or alert individuals to, periods of lapsed attention. This may be especially useful when applied to clinical conditions that are associated with more explorative tendencies, and greater attention or sensory processing impairments such as attention-deficit/hyperactivity disorder (ADHD) (Hauser et al., 2016; Seli, Smallwood, et al., 2016), mild cognitive impairment (Niedźwieńska & Kvavilashvili, 2018), dementia syndromes including Alzheimer's disease and frontotemporal dementia (Gyurkovics et al., 2018; O'Callaghan et al., 2019), and Parkinson's disease (Geffen et al., 2017; Walpola et al., 2020). Identifying biomarkers for different attentional states and developing neurofeedback procedures may facilitate personalised training that aid an individual's meta-awareness of the contents of their consciousness and can be used to propagate the adaptive, and minimise the maladaptive, features of mind-wandering depending on the environmental and other circumstances.

Finally, the results of the present study were interpreted in line with the oscillation strategy and perceptual decoupling, but these results neither support causal claims, nor represent the sole factors or theories that may explain the documented observations. Other factors not explicitly examined in the present study may be worthy of future investigation, for example the roles of cognitive reserve or meta-awareness and their impact on dual-tasking capacity and optimal strategic modulation with age. Additionally, the fatigue strategy (e.g. Carruthers, 2015; Irving, 2016; Sripada, 2018) posits that goal-directed and mind-wandering processes exhibit different dynamic oscillations as a function of time and increasing cognitive fatigue. Traditional research paradigms (present study included) tend to examine global performance measures, averaging trials across the total task, which may miss the subtle changes occurring across distinct timescales. Future research is needed to measure the changes in mind-wandering, performance, and pupil dynamics to parse out the strategies and mechanisms involved in the manifestation of attentional fluctuations over time for younger and older adults.

3.4.7 Conclusions

In summary, our research provides a new perspective on the influence of the natural ageing process on mind-wandering, elucidating the distinct strategies employed by younger and older adults in line with the exploitation/exploration framework (Sripada, 2018). We proffer that older adults suspended the wandering mind and implemented a more exploitative oscillation strategy to allay potential costs and circumvent their reduced cognitive resources, when the context demands it. This may represent an adaptive quality of successful ageing, namely, older adults prioritise task-relevant information and choose their prime moment to explore. Conversely, younger adults exhibited greater exploration of the mind-wandering space and utilised their greater cognitive resources to flexibly oscillate between competing goal-directed and mind-wandering strategies without incurring relative performance costs. Despite delayed evidence accumulation and reduced amplitude for target sensory evidence, younger adults showed no corresponding decline in sustained attention performance, suggesting insulated mind-wandering through perceptual decoupling. These novel insights stem from a triangulated approach combining subjective, behavioural, and direct, real-time neurophysiological assessments during a non-demanding continuous monitoring task. Our research, therefore, provides critical insight into the complex features of age-related mind-wandering, highlighting its interaction with cognitive and perceptual processes and associated behavioural concomitants. Understanding the dynamics of spontaneous thought may help elucidate the dynamics supporting successful ageing.

3.5 Supplemental Material

3.5.1 Target-Aligned Signal Trial Counts

Following artifact rejection and pre-processing procedures, the number of trials included in the pre-target alpha analysis was different across groups, $t(52) = -2.11$, $p = .040$, 95% CI [-93.05, -2.33]. However, a random selection of cases representing 70% of all cases, wherein the groups were matched in trial numbers, was re-analysed and revealed a similarly significant between-groups alpha CoV difference as when the total sample was used. Hence, analyses with the total sample are reported in the § *Results*. Further, there were no significant between-groups differences in the number of trials included in the target-aligned PD, $t(62) = -.28$, $p = .782$, 95% CI [-32.10, 24.26], or decision-making (i.e. for CPP, SSVEP, and LHB), $t(53) = -1.50$, $p = .139$, 95% CI [-89.07, 12.75], analyses (see Table **S.3.1**).

Table S.3.1

Number of Trials Included in the Between-Group Analyses of Target-Aligned Neurophysiological Signals for Younger and Older Adult Participants

	Young			Old		
	n	*M* (*SD*)	Range	*n*	*M* (*SD*)	Range
			Target-Aligned Analyses			
Alpha*	25	181.48 (95.40)	[30- 346]	29	229.17 (70.28)	[101- 348]
PD	33	340.27 (60.04)	[132-384]	31	344.19 (52.16)	[184-384]
Decision-Making	25	147.84 (94.66)	[23-322]	30	186.00 (92.95)	[25-361]

Note. M, mean; n, Number of observations; PD, Pupil Diameter, SD, Standard deviation. Decision-Making variables included target-aligned CPP, SSVEP, and LHB variables.

**p* < .05

3.5.2 Probe-Aligned Signal Trial Counts

After artifact rejection and pre-processing, there was no significant difference in the number of PD trials in the Focus and Mind-Wandering comparison for younger adults**,** *t*(31) = 1.81, *p* = .079, 95% CI [-1.54, 26.29], although a significant difference in trial counts across conditions was observed for older adults, *t*(23) = 5.41, *p* < .0005, 95% CI [27.59, 61.75]. Additionally, the number of trials contributing to the probe-aligned SSVEP and alpha analyses were similarly matched across Focused and Mind-Wandering conditions for younger adults, *t*(22) = 1.48, *p* = .153, 95% CI [-3.85, 23.07], but were significantly different for the older group, *t*(19) = 3.18, *p* = .005, 95% CI [9.13, 44.37]. Trial counts were thus matched across conditions for younger adults but not for older adults, consistent with their decreased proclivity for mind-wandering (see Table **S.3.2**). For these analyses we especially note the BF values, supplementing the frequentist results, to further parse out if non-significant effects were under-powered or supported the null hypothesis of no difference.

Table S.3.2

Number of Trials Included in the Within-Group Analyses of Probe-Aligned Neurophysiological Signals for Younger and Older Adult Participants

Variable	Young				Old			
	Focus		Mind-Wandering		Focus		Mind-Wandering	
	n	*M* (*SD*) [range]	*n*	*M* (*SD*) [range]	*n*	*M* (*SD*) [range]	*n*	*M* (*SD*) [range]
SSVEP/Alpha	23	47.87 (23.34)	23	38.26 (17.93)	20	59.35 (24.58)[a]	20	32.60 (20.65)[a]
PD	33	68.42 (23.14)	32	54.31 (21.63)	31	84.77 (27.06)[b]	24	39.00 (20.03)[b]

Note. M, mean; n, Number of observations; PD, Pupil Diameter, SD, Standard deviation; Steady-state visually evoked potential, SSVEP.

[a] Significant within-groups difference at $p < 0.01$

[b] Significant within-groups difference at $p < 0.0005$

Chapter 4: Empirical Paper 3

Tracking the Temporal Dynamics of Mind-Wandering in Healthy Ageing: Converging Evidence from Experience Sampling, Behavioural, and Pupillometric Data

4.1 Introduction

4.1.1 Context for the Present Research

In our previous work (*Chapter 3*), we observed that fluctuating attentional states are accompanied by disrupted behavioural performance and reduced task-related neural processing, independent of Age Group. In light of the potential consequences of attentional withdrawal from a task, our finding of group parity in overall task performance (*Chapter 2*) suggests that younger and older adults employed different task strategies to mitigate performance costs, in line with the exploitation/exploration framework (Sripada, 2018). Indeed, we found younger adults displayed a greater tendency for exploration, flexibly shifting between goal-directed and mind-wandering processes without a corresponding decline in performance. Despite younger adults' increased propensity for unintentional and intentional mind-wandering and evidence of more variable responding, sensory evidence encoding, and attentional engagement, they appeared to utilise their greater cognitive resources to balance these serial modes more optimally. Conversely, older adults compensated for their reduced cognitive capacity by dedicating their resources to the task in a more exploitative manner, prioritising task-relevant information, and suspending mind-wandering.

These advancements pertained to group level trends and global performance metrics averaged over the total task. By their nature, they precluded more fine-grained interpretation of the subtle changes in attentional states for younger and older adults as they evolved over time. Therefore, the purpose of the present chapter was to examine the temporal properties of mind-wandering and behavioural performance as a function of time to parse out the strategies and dynamics involved in the manifestation of attentional fluctuations as they unfold over distinct timescales for younger and older adults.

4.1.2 Advances in Mind-Wandering Research

Mind-wandering is generally understood as a core mental state, falling under the umbrella of spontaneous thought phenomena (Christoff et al., 2016), wherein attentive resources are temporarily withdrawn from an ongoing task or the external environment, and redistributed towards self-generated mental content (Smallwood & Schooler, 2015). Accordingly, mind-wandering reflects momentary fluctuations in the allocation of attentional resources from extrinsic to intrinsic sources. Though its conceptual boundaries are reasonably demarcated, there is a lack of unanimity as to the best way to characterise and measure the mind-wandering experience (see Christoff et al., 2016; Christoff et al., 2018; Seli, Kane, et al., 2018; Smallwood & Schooler, 2015). Recent research has embraced an operational definition of mind-wandering distinguished by its intentionality; namely, dissociating attentional fluctuations that occur spontaneously (i.e. unintentional mind-wandering) from those that occur with volition (i.e. intentional mind-wandering) (Seli, Risko, Smilek, et al., 2016).

Previous studies have demonstrated an age-accompanied attenuation in unintentional and intentional mind-wandering specifically (Grodsky & Giambra, 1990; Moran et al., 2021; Seli, Maillet, et al., 2017) and in mind-wandering more generally (Jordao et al., 2019; Maillet & Schacter, 2016). Despite some purported benefits, such as for creativity and relief from boredom (e.g. Mooneyham & Schooler, 2013), mind-wandering at critical moments has been predominantly associated with behavioural and functional consequences, including impaired and more variable task performance (Bastian & Sackur, 2013; Cheyne et al., 2006; McVay & Kane, 2009; Mooneyham & Schooler, 2013; Smallwood, McSpadden, & Schooler, 2008), as well as with clinical and subclinical symptomologies and pathologies (Elua, Laws, & Kvavilashvili, 2012; Killingsworth & Gilbert, 2010; Seli, Risko, et al., 2017; Seli, Smallwood, et al., 2016; Smallwood, O'Connor, et al., 2007). The experience of subjective mind-wandering is a common concomitant of lapses in sustained attention (Smallwood & Schooler, 2006) as indexed by behavioural fluctuations and errors on a range of sustained attention tasks (Bastian & Sackur, 2013; McVay & Kane, 2009; Stawarczyk et al., 2011).

Declining or more variable sustained attention with age has also been linked with an increased incidence of falls in older adults (Nagamatsu et al., 2013; O'Halloran et al., 2011), a factor that may contribute to loss of independence and reduced quality of life. Indeed, the ability to sustain attention and maintain alertness is an integral component of healthy cognitive ageing (Robertson, 2014), is critical for cortical plasticity (Polley, Steinberg, & Merzenich, 2006), underlies many higher order cognitive processes, and is required for efficient task performance and goal fulfilment (Fortenbaugh, DeGutis, & Esterman, 2017; Smilek, Carriere, & Cheyne, 2010). Considering global population ageing and the potential maladaptive consequences of mind-wandering, it is important to characterise the nature of momentary changes in attentional states occurring with and without intention over the lifespan.

4.1.3 Temporal Dynamics of Fluctuating Attentional States

4.1.3.1 The Influence of Time-On-Task on Mind-Wandering and Performance. The phenomenon of sustained attention involves complex and dynamic moment-to-moment alternations between periods of focus and inattention, or mind-wandering (Fortenbaugh et al., 2017). Maintaining attention and continuous task engagement over prolonged durations is effortful, challenging, and prone to fluctuations over time (Smallwood & Schooler, 2006; Thomson et al., 2015; Warm, Parasuraman, & Matthews, 2008). Indeed, previous studies using tasks that require continual attention have demonstrated increased mind-wandering with commensurate deteriorating performance over protracted periods; for example, across task (Brosowsky, Degutis, Esterman, Smilek, & Seli, 2020; Cunningham, Scerbo, & Freeman, 2000; Hopstaken et al., 2015; McVay & Kane, 2012), across within-session quartiles (Massar, Poh, Lim, & Chee, 2020), with increasing block length (J. Smallwood, Obonsawin, & Reid, 2003), and during the second half of a task relative to the first (Robertson et al., 1997; Smallwood et al., 2004; Teasdale et al., 1995). Additionally, fluctuating attentional states and greater performance variability (which is itself a marker of mind-wandering, Seli, Cheyne, et al., 2013) have been observed over shorter timescales in the manner of seconds and multiple trials (Bastian & Sackur, 2013; Esterman et al., 2013; Kucyi & Davis, 2014). This effect is further qualified by a proportional coupling showing incremental increases in mind-wandering corresponding with steeper performance decrements over time (Thomson, Seli, Besner, & Smilek, 2014).

Research on time-on-task and mind-wandering intentionality, however, is under-developed; though a recent study observed that increased mind-wandering with time-on-task was predominantly driven by changes in unintentional relative to intentional mind-wandering (Massar et al., 2020). Despite growing recognition of the intentionality distinction, the potential shared and distinct temporal dynamics of these specific mind-wandering types remain unclear. Additionally, although there is some limited research examining the effect of age on time-on-task behavioural performance in attentional task paradigms, these studies have yielded conflicting results, partly owing to the different tasks and measures used (Staub, Doignon-Camus, Bacon, & Bonnefond, 2014; Staub, Doignon-Camus, Despres, & Bonnefond, 2013; Staub, Doignon-Camus, Marques-Carneiro, Bacon, & Bonnefond, 2015). The inconsistency in the literature is compounded by a scarcity in research examining age-related changes in subjectively reported mind-wandering states as a function of time.

4.1.3.2 Prominent Theories on Time-On-Task Effects. Why is maintaining attentional engagement over prolonged periods of time so challenging? Different theoretical frameworks have been proposed to account for the consistently observed decline in attentional performance over extended durations. The most predominantly debated frameworks include "*Overload*" and "*Underload*" theories of sustained attention (see Fortenbaugh et al., 2017; Pattyn, Neyt, Henderickx, & Soetens, 2008). More recently, "Resource Control" (Thomson et al., 2015) and "Exploitation/Exploration" (Sripada, 2018) frameworks have been tendered to account for changes in subjective mind-wandering states over time. These theories are henceforth discussed.

4.1.3.2.1 The "Overload" Resource Depletion Model of Sustained Attention. The overload, or resource depletion model, proposes that the temporary and systematic depletion of attentional resources that comes with protracted task performance or more exigent task demands leaves fewer resources available for sustained focus and optimal performance (Grier et al., 2003; Helton et al., 2005; Helton & Warm, 2008; Parasuraman, 1979; Parasuraman & Mouloua, 1987; Smit, Eling, & Coenen, 2004; Warm et al., 2008). This model attributes declining performance over time to the cumulative cost of extended attentional engagement and lapsing attention at critical task moments. Although this theory is more directly concerned with sustained attention and vigilance decrements, it follows that mind-wandering may increase when resources become depleted over time.

In contrast with the above, the "context-regulation hypothesis" in the mind-wandering literature suggests that tasks requiring more significant information processing should see a corresponding decrease in mind-wandering propensity as more attentional resources are consigned towards the task leaving fewer free for engaging in off-task thought (Smallwood & Schooler, 2015). As such, the finding that self-reported mind-wandering increases with time-on-task is in line with the resource depletion account but at odds with the context-regulation hypothesis. This may speak to the broader debate on the role of executive resources in either facilitating or inhibiting mind-wandering, as proffered by the "Executive Control hypothesis" (Smallwood & Schooler, 2006) and the "Control Failures X Current Concerns" account (McVay & Kane, 2010), respectively (see *Chapter 2* for a discussion).

Additionally, incongruent with the overload model is the finding that by increasing or incentivising task-related motivation, vigilance performance decrements are negated (Esterman et al., 2016; Pop, Stearman, Kazi, & al., 2012), and overall mind-wandering rates are attenuated in both younger (Seli et al., 2019; Seli, Wammes, et al., 2016; Unsworth & McMillan, 2013) and older adults (Krawietz et al., 2012; Seli et al., 2020; Shake et al., 2016).

4.1.3.2.2 The "Underload" Mindlessness Model of Sustained Attention. The underload or mindlessness model posits that boredom, under-stimulation, and low arousal may arise due to the monotony and tedium of traditional sustained attention tasks and contribute to task withdrawal in the form of lapsed or fluctuating attentional engagement (Robertson & Garavan, 2004; Smallwood et al., 2004). The length and repetitive nature of such tasks may encourage mindless or automated responding leading to consequent performance decrements over time (Manly, Robertson, Galloway, & Hawkins, 1999; Robertson et al., 1997). By extension, mind-wandering propensity should increase as a task unfolds as participants become less motivated, less interested, or increasingly familiar with the task. Although the aforementioned accounts have been useful for propagating understanding of attentional performance and vigilance decrements, these theories do not relate directly to mind-wandering but rather foster predictions through conceptual extrapolation and speculation.

4.1.3.2.3 The Resource-Control Framework of Mind-Wandering. The related "resource-control" framework synthesises previous accounts to specifically address changes in mind-wandering over time (Thomson et al., 2015). This framework predicts increased mind-wandering over time as the draw of current personal concerns supersedes the subjective value of maintaining task focus over time, particularly during monotonous tasks (for similar arguments see Klinger, 1971; McVay & Kane, 2010). This theory further posits a steeper increase in intentional mind-wandering over time, as individuals deliberately disengage when they are under-stimulated. This account, however, has not been assessed with regard to its interaction with ageing, which is especially pertinent given known age-related differences in motivation and task interest

(Jackson & Balota, 2012; Krawietz et al., 2012; Maillet & Rajah, 2013; Moran et al., 2021; Shake et al., 2016).

4.1.3.2.4 The Exploitation/Exploration Model of Oscillatory Attention. The exploitation/exploration framework (Sripada, 2018) offers an alternate lens through which the oscillatory dynamics of fluctuating attention over time may be characterised. According to this framework, goal-directed thinking is understood as an exploitative process where available resources and known informational stores are utilised in the pursuit of a goal. Conversely, mind-wandering is considered an explorative state involving an open-ended search for unknown but potentially more advantageous opportunities. Optimal performance is supported by an adaptive balance of these serial modes of thought through dynamic switching between competing task and personal goals to maximise rewards and minimise costs (Sripada, 2018). The apparent reciprocal duality of the exploit/explore trade-off may be better understood as a continuum, whereby states can be comparatively more exploitative or explorative, and more or less adaptive, relative to the context.

Oscillation strategies are regulated on a trial-by-trial basis in response to changing task demands or temporal uncertainties. Reaction time variability (RTV) has been proposed as a marker of such temporal oscillatory attention cycles (Esterman et al., 2013) and has been shown to fluctuate over time with periods of high variability, accompanied by mind-wandering and more erroneous performance (Cheyne et al., 2009; Esterman et al., 2013; Seli, Cheyne, et al., 2013; Smallwood, McSpadden, Luus, et al., 2008).

The locus-coeruleus noradrenaline (LC-NA) neuromodulatory system, implicated in arousal, vigilance, and attentional control (e.g. Berridge & Waterhouse, 2003; Coull et al., 2004; Sara & Bouret, 2012; Smith & Nutt, 1996), may represent one mechanism through which temporal oscillatory attentional cycles are regulated over time (O'Callaghan et al., 2021; Sripada, 2018). Specifically, the LC-NA system may influence top-down endogenous attentional mechanisms to gate sensory processing for successful goal-fulfilment and to coordinate the balance between exploitative and explorative modes relative to task demands (Aston-Jones & Cohen, 2005; Hauser et al., 2016; Jepma & Nieuwenhuis, 2011).

Empirical consensus supports pupil diameter (PD) as an indirect measure of attentional allocation, cognitive load, the intensity of task processing (Alnaes et al., 2014; Beatty, 1982; Kahneman, 1973; Kahneman & Beatty, 1966, 1967). PD has also been proposed as an indirect measure of the psychophysiological activity in the LC-NA system tracking fluctuating endogenous attention (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Joshi et al., 2016; Murphy et al., 2014; Murphy et al., 2011). In line with the 'adaptive gain theory' (Aston-Jones & Cohen, 2005), distinct LC firing patterns between phasic and tonic modes correspond to strategic shifts between exploitative and explorative states. These transitions follow a Yerkes-Dodson inverted u-shape relationship with task performance, mirroring optimal patterns observed for PD (van den Brink et al., 2016). Specifically, comparatively low or high tonic NA levels are associated with lower arousal/alertness and greater explorative tendencies, respectively. Intermediate tonic NA levels (with corresponding phasic activity) promote an adaptive level of exploitative task focus and optimal performance.

The observation that PD reflects LC-mediated co-ordination of neuronal activity is supported by a direct relationship between single-unit LC firing rates and pupil diameter in non-human primates (Joshi, Kalwani, & Gold, 2016). The co-variation of LC activity and pupil dilation, and the associated release of NA throughout the brain, reflects underlying changes in arousal over set timescales in macaque monkeys. These authors did not replicate the tonic and phasic firing modes previously reported by Aston-Jones and Cohen (2005), but instead showed a linear association between LC and the size of the pupil, suggesting that PD and LC activity fluctuate in line with underlying changes in arousal and attentional engagement.Therefore, PD is a promising covert and non-invasive candidate proxy measure tracking changing arousal and oscillatory attention over time.

With regard to ageing, research has proposed the roles of executive function and neuromodulatory influence in the navigation between competing exploit/explore strategies (Cohen, McClure, & Yu, 2007; Hills, Todd, & Goldstone, 2010; O'Callaghan et al., 2021). Age-related decline in executive resources and age-accompanied catecholaminergic deficits (Backman et al., 2000) may limit the capacity of older adults to pursue exploration and dynamically switch between task strategies, especially within the context of intentional mind-wandering. Indeed age-related differences in explorative tendencies have been previously documented (Hills, Wilke, & Samanez-Larkin, 2011; Mata et al., 2013; Moran et al., 2021). Moreover, greater neuronal density in the LC, indicative of more availability of NA, was observed in older adults who maintained better cognitive status with advancing age and showed attenuated age-related cognitive decline before death (Wilson et al., 2013). The exploit/explore framework, as indexed by LC-NA activity, therefore holds promise for delineating the patterns of changing performance and fluctuating subjective attentional states in younger and older adults over time.

4.1.3.3 The Influence of Other Task-Relevant Temporal Properties. Aside from time-on-task, other temporal influences such as target timing and task structure may also impact mind-wandering and performance. For instance, in tasks with predictable target onsets, participants reduced their mind-wandering in anticipation of the target stimulus and increased their mind-wandering during inter-trial intervals (ITI) when target expectancy was low (Massar et al., 2020; Seli, Carriere, et al., 2018). Explicit temporal expectations enabled participants to flexibly regulate their mind-wandering on a moment-to-moment basis according to the time available without incurring performance costs, showing that mind-wandering may be open to a degree of top-down modulation.

Alternatively, in tasks featuring unpredictable target onsets and no explicit target timing cues, participants must actively monitor and continually attend to the task to perform well. Despite absent alerting cues, participants may form implicit expectations of targets based on the conditional likelihood of their occurrence after a period of time passing without a task event (Nobre, Correa, & Coull, 2007). Attentional resources may be strategically modulated based on predicted target probabilities (Alegria & Delhaye-Rembaux, 1975) or informed learning experiences (Los, Knol, & Boers, 2001). It follows that when the expectation of a target is low, participants may be unprepared to respond and consequently demonstrate poorer performance. Conversely, with longer target lead in times, participants may anticipate a target and show greater attentional readiness. Accordingly, studies have demonstrated faster RTs and greater accuracy during longer target lead-in times, or foreperiods, compared to shorter intervals (Thomaschke, Wagener, Kiesel, & Hoffmann, 2011; Unsworth, Spillers, Brewer, & McMillan, 2011; Vangkilde, Coull, & Bundesen, 2012). Less is known, however, about how attention fluctuates between on- and off-task states, or between exploitative and explorative modes, during variable ITIs. If the patterns of implicit temporal expectations hold, participants may show more attentional readiness in the form of more exploitative behaviour during longer pre-trial durations. However, in a recent study, no effect of foreperiod duration on unintentional or intentional mind-wandering frequency was observed, despite a significant effect on behavioural performance (Massar et al., 2020).

Inconsistent with the aforementioned account, previous studies have shown that periods with less frequent targets and slower task pacing may be more conducive to mind-wandering and goal neglect than faster-paced periods (De Jong, Berendsen, & Cools, 1999; J. Smallwood, McSpadden, et al., 2007). In support, a task featuring unpredictable target onsets (alternating between 2- and 8-second fixed ITIs on a trial-by-trial basis) observed increased mind-wandering, particularly of the unintentional type, and slower responding during the longer relative to shorter intervals (Unsworth & Robison, 2018). Additionally, participants reported more focused (with correspondingly greater pre-trial PDs) than mind-wandering states during the shorter “faster-paced” interval. No differences were observed between attentional states, and associated PD measures, in the longer “slower-paced” interval (Unsworth & Robison, 2018). Collectively, these studies broadly suggest that the propensity for mind-wandering may be modulated according to the temporal structure of the task and the time available for engaging in off-task thoughts. Given the highlighted inconsistencies in the literature, this prediction needs to be further evaluated. In particular, further research is required to examine the degree to which younger and older adults strategically modulate their attentional focus according to different ITIs and to investigate if explorative mind-wandering follows implicit temporal expectation patterns.

4.1.4 The Present Study

Although there is a growing body of research examining mind-wandering and its impact on performance, the temporal dynamics of shifting attentional engagement, particularly as they pertain to cognitive ageing, have been largely neglected from empirical evaluation. The majority of mind-wandering studies have analysed global performance metrics, averaging trials across the task and treating temporal fluctuations as noise. These studies may, therefore, forego the more subtle changes in mind-wandering as it unfolds over more fine-grained timescales. Moreover, there is a paucity of research decomposing the temporal trajectory of separate unintentional and intentional mind-wandering experiences over time. This is especially worthy of consideration in light of the known associations between intentionality dimensions and motivation/fatigue, factors jointly moderated by time-on-task and ageing (Jordao et al., 2019).

Against this backdrop, the purpose of the present study was to investigate time-on-task changes in momentary attentional fluctuations and deteriorations by examining the temporal evolution of behavioural sustained attention performance and subjective mind-wandering serially over different longer-term (across blocks) and short-term (within-block) timescales for younger and older adults. We explored whether unintentional and intentional mind-wandering display different temporal oscillations with time-on-task. Given the repetitive nature of the primary task and a youth-oriented bias for exploration and reduced motivation (*Chapter 2*), we predicted that increases in mind-wandering over time, particularly intentional mind-wandering, would be especially pronounced for younger adults. As a secondary aim, we investigated whether the ability to maintain continuous attentional engagement over the task was influenced by younger and older adults implementing different task strategies during variable pre-trial durations. Specifically, we examined whether pre-trial PD, as a proxy measure of exploit/explore shifts and LC-NA activity, was influenced by different fixed but unpredictable ITIs (i.e. 3-, 5-, and 7-seconds).

To examine these aims, we capitalised on data collected during performance of the Gradual Contrast Change Detection Task with Experience Sampling (GradCCD-ES) with simultaneous pupillometry recording (see *Chapters 2* and *3*). The simplified perceptual requirements of the task meant that performance was relatively non-demanding over shorter timescales (i.e. the targets were easily identifiable in isolation); still, vigilance became increasingly effortful and challenging to maintain over an extended duration. Compared to traditional sustained attention tasks, there was relative unpredictability of target onset, variable ITIs, and gradually transitioning perceptual feature changes. These features meant that greater emphasis was placed on maintaining endogenous attentional control for successful performance and as such, the task operated as a purer measure of sustained attention. Given the tedium and monotony of these low demand task requirements, our novel paradigm was, therefore, well suited for tracking attentional fluctuations and performance decrements with increased time-on-task. Further, given the group parity in overall behavioural performance (*Chapter 2)*, the present temporal analysis may be sensitive to age-related differences in strategic task approach, with minimised confounding by any baseline differences.

4.2 Methodology

Experience sampling (ES), behavioural, and pupillometry data were collected for the parallel purposes of exploring phenomenological properties (*Chapter 2*) and neurophysiological signatures (*Chapter 3*) of age-related differences in mind-wandering. These data were further analysed in the current chapter to address more fine-grained and temporally sensitive time-on-task changes. No new data were collected; for brevity, the reader is directed to previous chapters of this thesis, where appropriate, for supplemental detail on the methodological and data management procedures. Any detail pertinent to the interpretation of the present analyses are provided herein.

4.2.1 Participants

Data from 68 participants, who completed the study per-protocol, were included in the behavioural time-course analyses and comprised 34 cognitively normal, healthy older adults (mean age 71 years, standard deviation (*SD*) = 3.54, 20 female) and 34 healthy younger adults (mean age 22 years, *SD* = 4.59, 16 female). The groups did not significantly differ regarding gender, $x^2(1, N = 68) = .94$, $p = .331$, or years of education, $t(60.99) = 1.47$, $p = .148$ (two-tailed). From this sample, one younger and three older adult participants were excluded from the pupillometry analysis owing to insufficient trials from excessive artifacts and/or missing pupillometric data. The full recruitment and participant selection pipeline and broader participant sociodemographic characteristics are detailed in *Chapter 2* (§§ *2.2.1*, *2.5*).

4.2.2 Materials and Procedures

4.2.2.1 Gradual Contrast Change Detection with Experience Sampling (GradCCD-ES) Task. The unabridged details on data collection procedures are outlined in *Chapters 2* and *3* of this thesis (§§ *2.2.2*, *3.2.2*). In brief, healthy younger and older adult participants performed a computerised sustained attention task, namely the GradCCD-ES task (McGovern et al., 2018; Moran et al., 2021; O'Connell et al., 2012) in a dark, sound-attenuated lab room. Participants monitored a continuously presented flickering checkerboard annulus stimulus (25Hz) to detect intermittent, smooth, and gradually evolving targets, defined as linear stimulus contrast reductions from 65% to 35% saliency over 1.6 seconds. Targets were presented pseudo-randomly with ITIs of 3-, 5-, or 7-seconds, selected randomly on a trial-by-trial basis. Participants responded to targets with a button press as soon as they noticed the contrast fading. Periodic online ES probes asked participants to characterise their metal state immediately prior to the probe as being either focused, or unintentionally or intentionally mind-wandering. Participants completed eight blocks of the main experimental task. Each block comprised 48 target trials and 16 probes with an approximate duration of 8 minutes. Participants availed of brief breaks between blocks; During these breaks participants rested for approximately 1-2 minutes, and then eye-tracker calibration commenced signalling the onset of the next block.

Behavioural performance indices included Hit Rate, Reaction Time (RT) for correct hits, RT Coefficient of Variance (CoV) for correct hits, and the number of False Alarms. Additionally, subjective ES probe responses comprised the frequency of Focused, Unintentional, and Intentional Mind-Wandering reports. In the broader study (Moran et al., 2021; see also § Results in Chapters 2 and 3), groups were compared on the global performance metrics averaged over the total task. The analyses in the present study complement and extend those previously described by exploring trends in these performance metrics as a function of time across distinct longer (between-block) and shorter (within-block) timescales.

4.2.2.2 Pupillometry Acquisition and Pre-Processing. An EyeLink 1000 eye-tracking system (SR Research Ltd, Canada) continuously tracked and recorded monocular pupil measurements from the left eye during each task block. Prior to each block recording, the eye-tracking system was calibrated and validated. Pupillometric data were collected, extracted, and pre-processed in accordance with the procedures detailed in *Chapter 3* (§ 3.2.4). The resulting pupil time series were *z*-score normalised (within-individual). Normalised PD was measured prior to target onset as a psychophysiological index of attentional engagement and proxy measure for exploit/explore shifts (Aston-Jones & Cohen, 2005; van den Brink et al., 2016). Pre-target PDs were calculated over temporal windows separated according to ITI length, namely 3-, 5-, and 7-seconds, and were baseline corrected on a trial-by-trial basis relative to the -200ms to 0ms pre-target window. For each participant, the mean PD amplitude for each ITI was extracted over a temporal window of -2000ms to -200ms, relative to target onset. Further, the rate of the pupil changes prior to each target ITI was quantified by the pre-trial slope computed using a linear least squares fit on the individual epoched signals [from -2000ms to -200ms relative to target onset] and subsequently mean averaged for each participant.

4.2.3 Data Management

For *between-block* analyses, all individual behavioural and subjective trials were averaged over each block for each participant (Blocks 1-8). For *within-block* analyses, a condition of Quartile was created by grouping trials into four equally sized bins per block such that each quartile contained 12 target and 4 probe trials. All equivalent quartiles were averaged across the total task to create mean measures for Quartiles 1 to 4 for each participant. Finally, to explore the effect of *Task Break* on performance, outcomes were averaged across all fourth quartiles occurring before a break (i.e. calculated across blocks 1 to 7, "pre-break") and across all first quartiles that followed a break (i.e. computed across blocks 2 to 8, "post-break").

4.2.4 Statistical Analysis

A three-pronged statistical analytical approach (following the procedures used in Brosnan et al., 2020) was employed to investigate age-related differences in the temporal evolution of sustained attention performance (behavioural outcomes) and subjective attentional states (ES probe outcomes) during the GradCCD-ES task. A series of two-way mixed repeated measures analyses of variance (ANOVAs) were conducted to evaluate behavioural performance and subjective attentional states with respect to a between-subjects factor of "Age Group" (younger and older adults) and separate within-subjects factors of:

1) "Block" (longer-term changes across the 8 task blocks),
2) "Quartile" (shorter-term changes within-block across four quartiles),
3) "Task Break" (changes from pre- to post-breaks).

The dependent variables including the behavioural performance (RT, RT CoV, and Hit Rate) and subjective (Focused, and Unintentional and Intentional mind-wandering) indices were evaluated across all timescales. The number of False Alarms, however, was only analysed across blocks as these datapoints could not be binned into quartiles given the spurious nature of this variable. An additional 2 x 3 mixed repeated measures ANOVA was conducted to explore the difference in mean PD amplitude and slope measures across the different pre-trial intervals (3-, 5-, and 7-seconds) across groups.

For each mixed repeated-measures ANOVA, data were screened for suitability for parametric analysis. Firstly, major violations to normality were investigated and outliers, characterised here as studentised residuals exceeding absolute three standard deviations for each group, were removed from the analysis. Outliers represented .72%

and 2.12 % of all performance datapoints for younger and older adults, respectively. In instances where the assumption of sphericity was violated, denoted by a significant Mauchly's test, the Greenhouse Geisser correction (epsilon, ε) was applied and the adjusted degrees of freedom and associated p-values were reported.

Where the omnibus F test for an interaction term was significant, simple effects analyses were performed to determine the direction of the differences. Additionally, where appropriate, within-subjects polynomial contrasts were analysed to further examine the trends in performance across blocks separately for younger and older adults. For ANOVAs that revealed a non-significant interaction, the main effects for the between- and within-subjects factors were interpreted. Significant main effects were followed with post-hoc pairwise comparisons (paired samples t-tests) to locate the source of the differences; Bonferroni-corrected p-values were reported to correct for these multiple comparisons. SPSS Version 24 (IBM; Chicago, IL, United States) was used to perform the mixed ANOVA analyses and Prism 8 (GraphPad) was used to visually represent the behavioural findings.

4.3 Results

4.3.1 Time-on-Task Effects Across Blocks (Longer-Term Intervals)

A series of 2x8 mixed repeated measures ANOVAs were performed to explore time-on-task changes across the 8 task blocks (Figure **4.1**). Significant interactions and main effects are discussed in the text; however, the statistics for all effects are provided in Table **4.1**. For significant main effects, follow-up Bonferroni-corrected paired samples *t*-tests were conducted. The resulting significant pairwise comparisons are summarised in the main text and the relevant statistics are detailed in Table **S.4.1**, (§*4.5 Supplemental Material*).

4.3.1.1 Behavioural Performance. Significant time-on-task deteriorations in behavioural performance, collapsed across group, were observed. Specifically, RT increased, $F_{4.14, 264.71} = 4.47, p = .001, \eta p^2 = .07, \varepsilon = .59$, and Hit Rate decreased, $F_{5.12, 312.20} = 3.85, p = .002, \eta p^2 = .06, \varepsilon = .73$, over the blocks, indicating slower and more erroneous responding. Follow-up Bonferroni pairwise comparisons demonstrated significantly lower RT for Block 1 relative to Block 7 ($p = .011$). None of the Hit Rate pairwise comparisons reached significance after Bonferroni corrections.

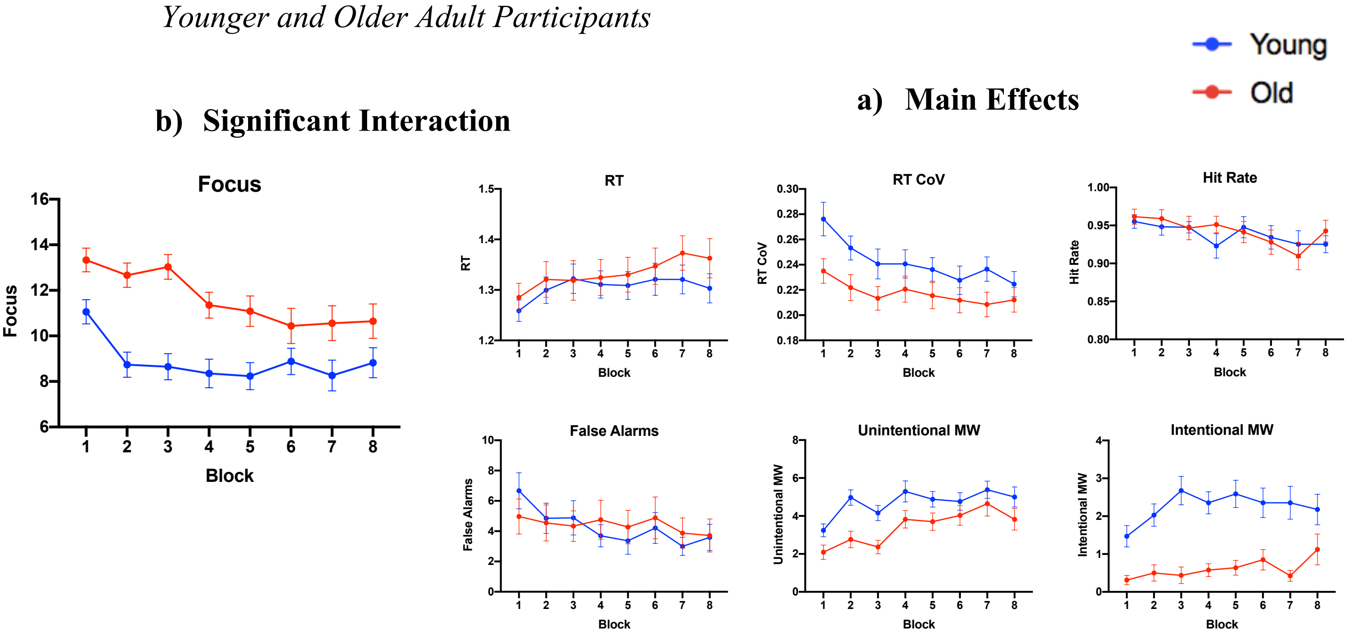
RT CoV, $F_{5.79, 365.12} = 5.83, p < .0005, \eta p^2 = .09, \varepsilon = .83$, and the number of False Alarms, $F_{4.02, 244.96} = 4.10, p = .003, \eta p^2 = .06, \varepsilon = .57$, decreased over the blocks independent of Group. Bonferroni pairwise comparisons revealed significantly greater RT CoV for Block 1 compared to Blocks 3 to 8 (all $p < .05$). Further, the number of False Alarms was higher for Block 1 relative to Blocks 5 to 8 (all $p < .05$). These patterns indicate steadier performance and less impulsivity over the course of the task, with the changes occurring predominantly after the first block. Additionally, a main effect of Group indicated that regardless of timepoint, younger and older adults differed with respect to RT CoV performance, $F_{1, 63} = 5.97, p = .017, \eta p^2 = .09, \varepsilon = .83$. This aligns with our previous finding of steadier task engagement for older adults compared to their younger counterparts (see § 2.3.3).

4.3.1.2 Subjective Attentional States. Consistent with the prediction that subjective attentional engagement would fluctuate over time, a significant Group x Block interaction was observed for self-reported Focus, $F_{4.63, 296.54} = 3.70, p = .004, \eta p^2 = .06$. Separate within-subjects polynomial contrasts were conducted to determine the direction of temporal patterns in Focus over the task for each group. A large linear effect was observed for the older group showing that their Focus attenuated proportionately over time, $F_{1,\,32} = 22.80, p < .005, \eta p^2 = .42$. By contrast, for younger adults a quadratic relationship better captured the observed drop in Focus occurring from Blocks 1 to 2 and the subsequent stabilisation in Focus over remaining blocks, $F_{1,\,33} = 15.58, p < .0005, \eta p^2 = .32$. This was qualified by a shift in Focus from Blocks 1 to 2, $t(33) = 6.45, p < .0005$, and then an absence of change from Blocks 2 to 8, as further characterised by a non-significant linear contrast, $F_{1,\,33} = .000, p = .991, \eta p^2 = .00$. Furthermore, simple main effects for Group demonstrated statistically significant differences in the level of Focus between younger and older adults during Blocks 1 to 5 (all $p < .01$) and Block 7 ($p < .05$).

Additionally, the propensity for mind-wandering increased across blocks irrespective of group as observed by the higher rates of Unintentional, $F_{4,\,282.04} = 9.33, p < .0005, \eta p^2 = .13, \varepsilon = .65$, and Intentional, $F_{4.57,\,283.37} = 2.36, p = .045, \eta p^2 = .04, \varepsilon = .65$, Mind-Wandering over the task. Follow-up pairwise comparisons demonstrated significant differences in Unintentional Mind-Wandering, regardless of Group, between Block 1 and Blocks 2 to 8 (all $p < .01$), and between Block 3 and Blocks 4, 5, and 7 (all $p < .05$). Intentional Mind-Wandering was lower for Block 1 compared to Block 5 ($p = .049$). Furthermore, irrespective of time point, there were significant differences between younger and older adults with respect to Unintentional, $F_{1,\,62} = 6.72$, $\text{p} = .012$, $\eta p^2 = .09, \varepsilon = .65$, and Intentional, $F_{1,\,62} = 32.17, p < .0005, \eta p^2 = .34, \varepsilon = .65$, Mind-Wandering; in line with our previously documented findings (see § 2.3.4).

Figure 4.1

Behavioural Performance and Subjective Attentional States Across Task Blocks for Younger and Older Adult Participants



b) Significant Interaction

a) Main Effects

Note. Graphs display mean and standard error of the mean (SEM) for all performance indices on each block of the GradCCD-ES task for younger and older adults. CoV; Coefficient of Variance; MW, Mind-Wandering; RT, Reaction Time

4.3.2 Time-on-Task Effects Within Blocks (Shorter-Term Intervals)

To examine performance decrements over shorter-term intervals, namely within-block quartiles, a series of 2x4 mixed repeated measures ANOVAs were conducted (see Table **4.1**, Figure **4.2**).

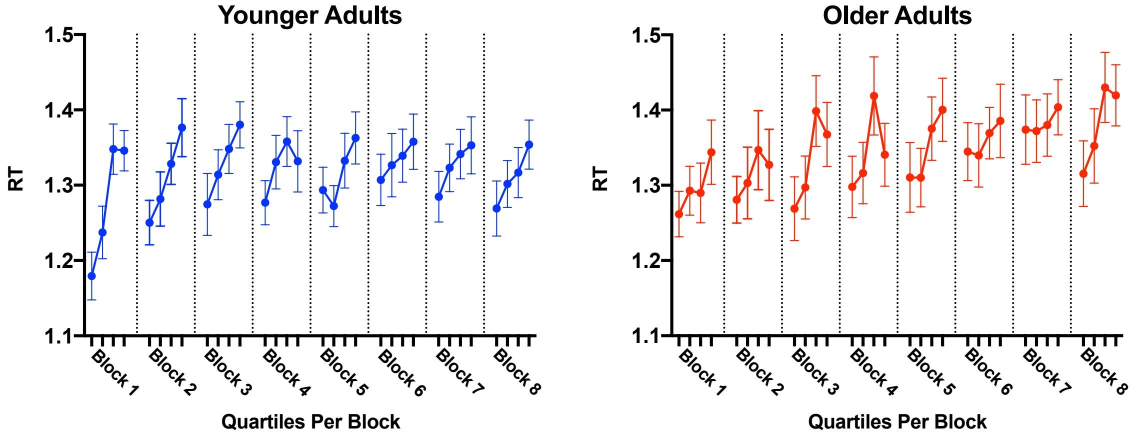
4.3.2.1 Behavioural Performance. A main effect of Quartile demonstrated that performance deteriorated over the duration of a block, irrespective of Group, as evidenced by a progressive slowing of RT, $F_{2.43,\ 158.27} = 47.67$, $p < .0005$, $\eta p^2 = .42$, $\varepsilon = .81$, and less accurate responding, $F_{1.81,\ 114} = 15.61$, $p < .0005$, $\eta p^2 = .20$, $\varepsilon = .603$, over the quartiles. Specifically, RT was significantly lower for Quartile 1 than the other three quartiles, and further, RT was lower for Quartile 2 in comparison to Quartiles 3 and 4 (all $p < .0005$), regardless of Group. Additionally, Hit Rate decreased from Quartiles 1 to Quartiles 3 and 4, and from Quartile 2 to Quartiles 3 and 4 (all $p < .01$) (see Table **S.4.1** in §*4.5 Supplemental Material* for significant pairwise comparisons). As before, a main effect of Group was also observed for RT CoV, $F_{1,\ 65} = 4.27$, $p = .043$, $\eta p^2 = .06$, independent of time-point.

4.3.2.2 Subjective Attentional States. Regarding the subjective attentional states, the level of Focus decreased over the quartiles, $F_{2.58,\ 170.32} = 32.36$, $p < .0005$, $\eta p^2 = .33$, $\varepsilon = .86$, specifically from Quartile 1 to the remaining quartiles (all $p < .0005$). Moreover, regardless of group, Unintentional, $F_{3,\ 195} = 16.55$, $p < .0005$, $\eta p^2 = .20$, and Intentional, $\mathrm{F}_{3,\ 195} = 8.71$, $p < .0005$, $\eta p^2 = .12$, Mind-Wandering increased over these shorter-term intervals. For both mind-wandering types, the source of the differences was between Quartile 1 in comparison with Quartiles 2 to 4 (all $p < .01$). Significant main effects of Group were also observed for Focus, $F_{1,\ 66} = 11.69$, $p = .001$, $\eta p^2 = .15$, $\varepsilon = .86$, Unintentional, $F_{1,\ 65} = 4.78$, $p = .032$, $\eta p^2 = .07$, and Intentional, $F_{1,\ 65} = 21.66$, $p < .0005$, $\eta p^2 = .25$, Mind-Wandering indices, independent of time-point.

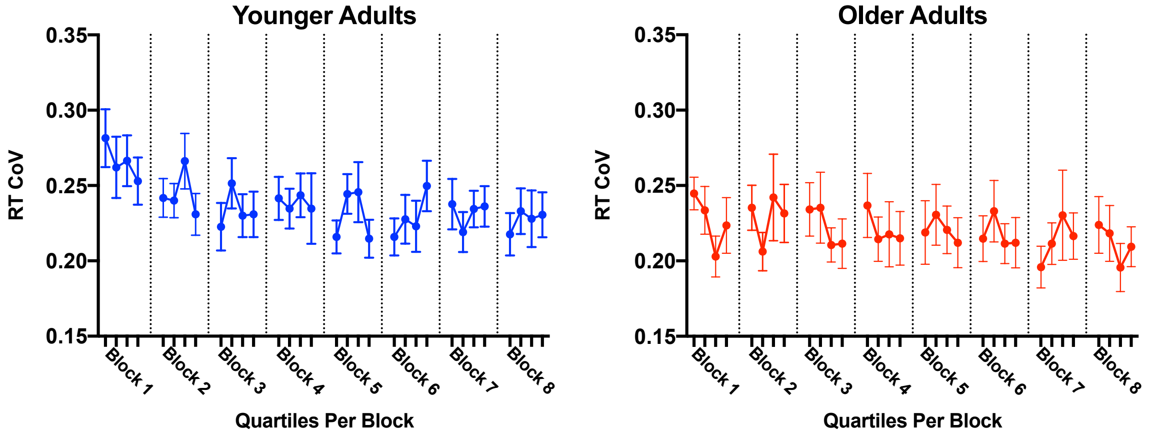
Figure 4.2

Behavioural Performance and Subjective Attentional States over Four Quartiles Within-Block for Younger (Left) And Older (Right) Adult Participants

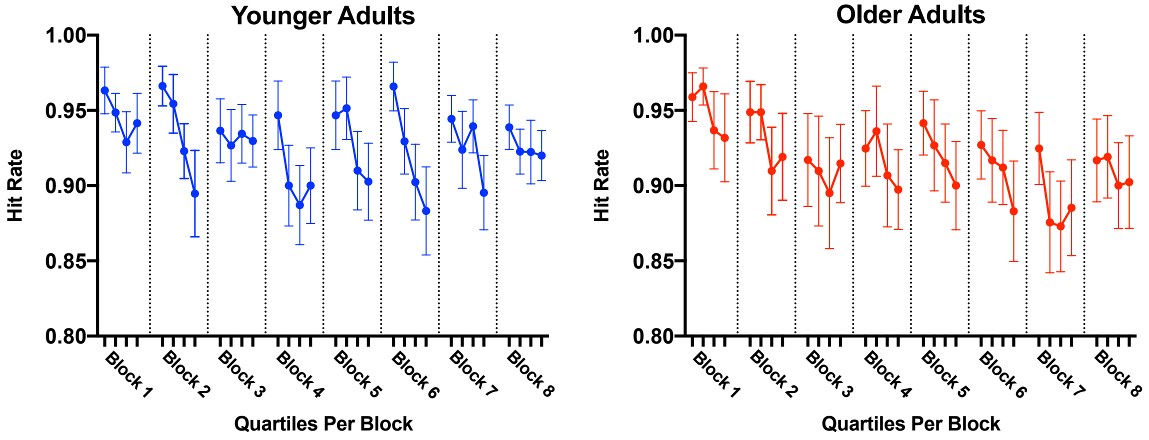
a) RT



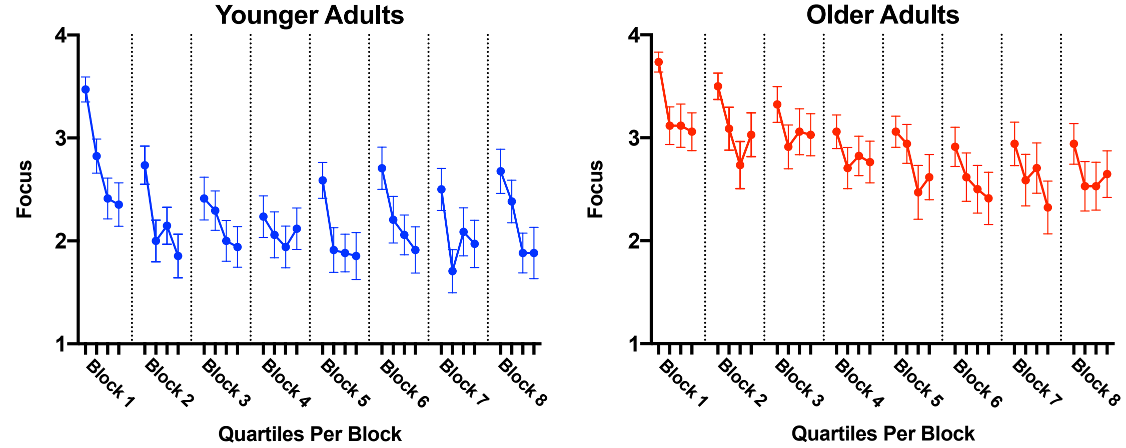
b) RT CoV



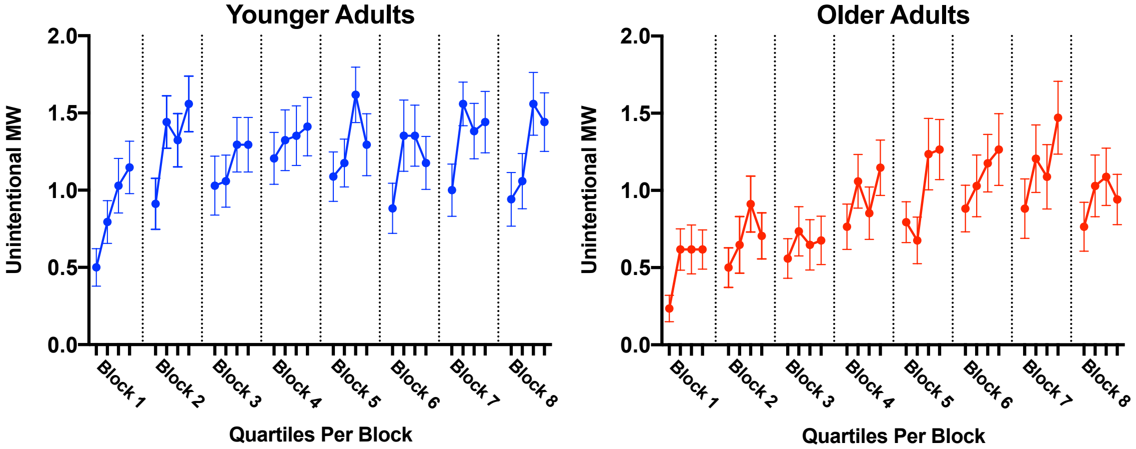
c) Hit Rate



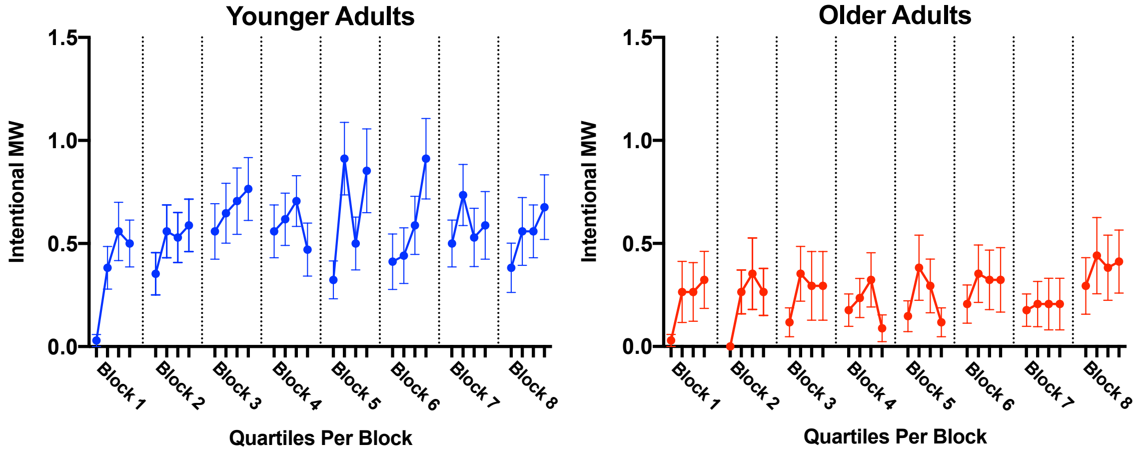
d) Focus



e) Unintentional MW



f) Intentional MW



Note. Graphs show mean and SEM for all performance indices for each quartile per block of the GradCCD-ES task. Given that no significant Group x Quartile interactions were observed, the graphs are displayed separately for younger and older adults for ease of interpretation. The dotted vertical lines represent the start of each task block. CoV; Coefficient of Variance; MW, Mind-Wandering; RT, Reaction Time

4.3.3 Effect of Task Break

To examine if the brief rest breaks between blocks had a beneficial restorative impact on performance, metrics from the fourth quartiles (averaged across Blocks 1 to 7, i.e. all blocks that preceded a break) were compared against the first quartiles (averaged across Blocks 2 to 8, i.e. all blocks that followed a break) using a mixed 2x2 repeated-measures ANOVA with Group as the between subjects factor, and Break (pre/post) as the within subjects factor (see Table **4.1**, Figure **4.3**).

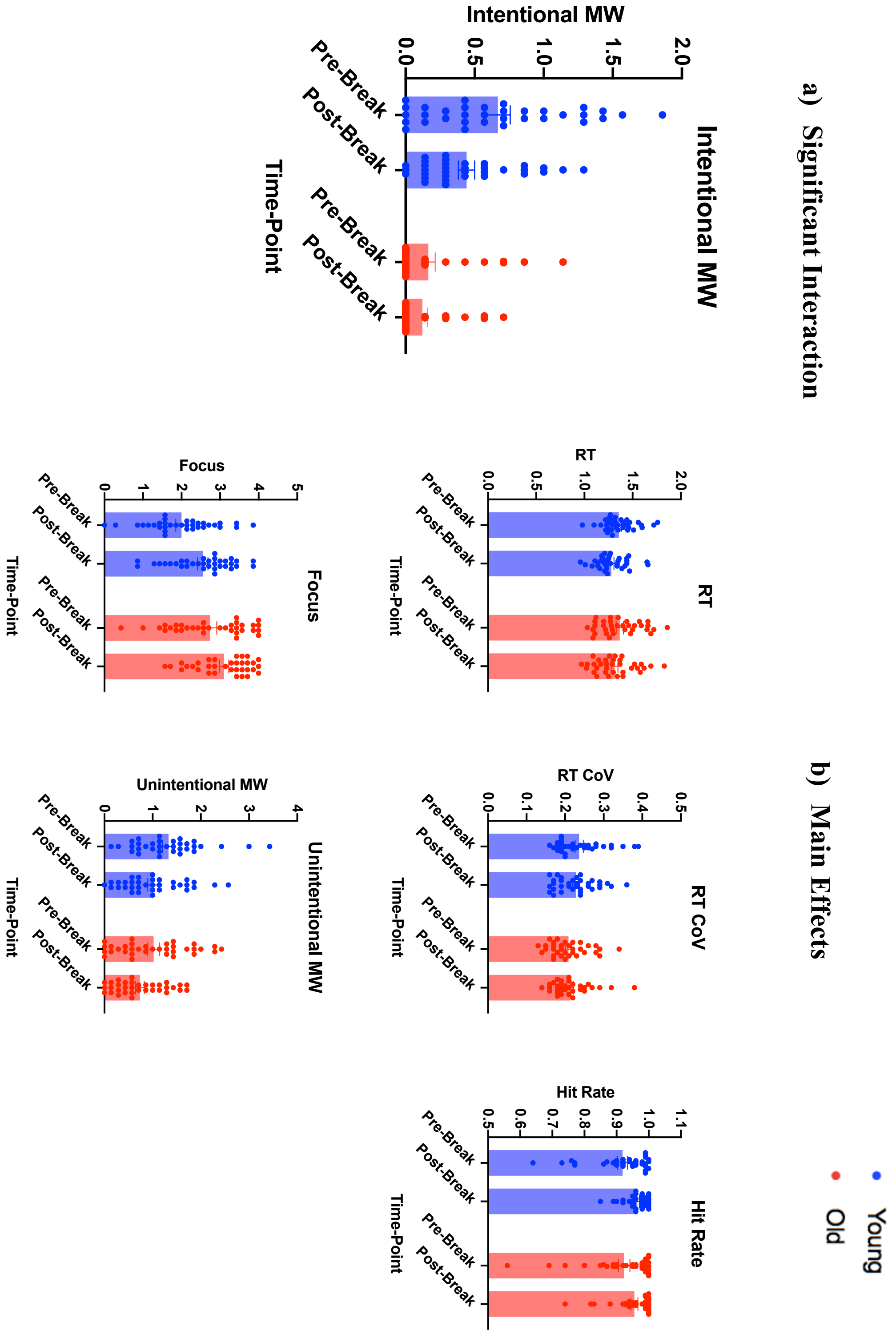
4.3.3.1 Behavioural Performance. A significant main effect of Task Break was observed indicating that regardless of Group, performance was enhanced following a break, through faster RTs, $F_{1, 66} = 61.74$, $p < .0005$, $\eta p^2 = .48$, and greater Hit Rate accuracy, $F_{1, 63} = 16.67$, $p < .0005$, $\eta p^2 = .21$. Given the previous findings documenting time-on-task performance decrements in RT and Hit Rate across- and within-blocks, irrespective of Group, the brief break interruptions appeared to revive performance and temporarily compensate for these deteriorations.

4.3.3.2 Subjective Attentional States. Further, Focus increased, $F_{1, 66} = 35.03$, $p < .0005$, $\eta p^2 = .35$, and Unintentional Mind-Wandering decreased, $F_{1, 66} = 23.39$, $p < .0005$, $\eta p^2 = .26$, from pre- to post-break. A main effect of Group supported significant differences between younger and older adults in the frequency of Focus, $F_{1, 66} = 12.18$, $p = .001$, $\eta p^2 = .16$, and Unintentional Mind-Wandering, $F_{1, 66} = 4.02$, $p = .049$, $\eta p^2 = .06$, irrespective of timepoint.

Additionally, a significant Group x Task Break interaction was observed for Intentional Mind-Wandering, $F_{1, 65} = 4.35$, $p = .041$, $\eta p^2 = .06$. Follow-up simple main effects of Task Break demonstrated that younger adults intentionally mind-wandered less after a break, $F_{1, 33} = 9.01$, $p = .005$, whereas there was no such effect observed for older adults, $F_{1, 32} = .98$, $p = .330$. The simple Group main effect showed that younger and older adults differed with respect to Intentional Mind-Wandering both before, $F_{1, 65} = 22.83$, $p < .0005$, $\eta p^2 = .27$, and after, $F_{1, 65} = 20.76$, $p < .0005$, $\eta p^2 = .24$, the break. The short rest breaks, therefore, enhanced attentional engagement to the task through greater Focus and less Unintentional Mind-Wandering for both groups, and through less Intentional Mind-Wandering for younger adults specifically.

Figure 4.3

Effect of Task Break on Behavioural Performance and Subjective Attentional States for Younger and Older Adults Participants

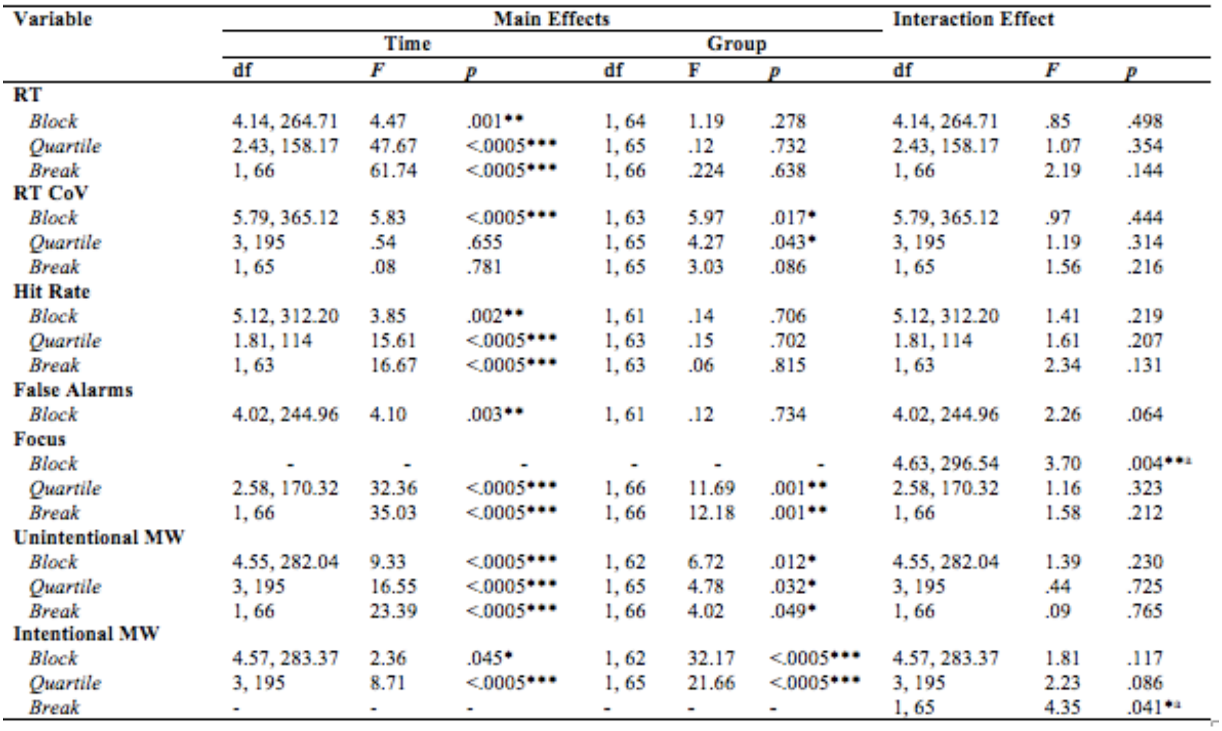


Note. Graphs display mean and SEM for all performance indices averaged before and after between-block breaks during the GradCCD-ES task.

CoV; Coefficient of Variance; MW, Mind-Wandering; RT, Reaction Time

Table 4.1

Summary Data for the Mixed Repeated Measures ANOVAs Comparing Behavioural Performance and Subjective Attentional States Over Time



Variable	Main Effects						Interaction Effect		
	Time			Group					
	df	*F*	*p*	df	F	*p*	df	*F*	*p*
RT									
Block	4.14, 264.71	4.47	.001**	1, 64	1.19	.278	4.14, 264.71	.85	.498
Quartile	2.43, 158.17	47.67	<.0005***	1, 65	.12	.732	2.43, 158.17	1.07	.354
Break	1, 66	61.74	<.0005***	1, 66	.224	.638	1, 66	2.19	.144
RT CoV									
Block	5.79, 365.12	5.83	<.0005***	1, 63	5.97	.017*	5.79, 365.12	.97	.444
Quartile	3, 195	.54	.655	1, 65	4.27	.043*	3, 195	1.19	.314
Break	1, 65	.08	.781	1, 65	3.03	.086	1, 65	1.56	.216
Hit Rate									
Block	5.12, 312.20	3.85	.002**	1, 61	.14	.706	5.12, 312.20	1.41	.219
Quartile	1.81, 114	15.61	<.0005***	1, 63	.15	.702	1.81, 114	1.61	.207
Break	1, 63	16.67	<.0005***	1, 63	.06	.815	1, 63	2.34	.131
False Alarms									
Block	4.02, 244.96	4.10	.003**	1, 61	.12	.734	4.02, 244.96	2.26	.064
Focus									
Block	-	-	-	-	-	-	4.63, 296.54	3.70	.004**[a]
Quartile	2.58, 170.32	32.36	<.0005***	1, 66	11.69	.001**	2.58, 170.32	1.16	.323
Break	1, 66	35.03	<.0005***	1, 66	12.18	.001**	1, 66	1.58	.212
Unintentional MW									
Block	4.55, 282.04	9.33	<.0005***	1, 62	6.72	.012*	4.55, 282.04	1.39	.230
Quartile	3, 195	16.55	<.0005***	1, 65	4.78	.032*	3, 195	.44	.725
Break	1, 66	23.39	<.0005***	1, 66	4.02	.049*	1, 66	.09	.765
Intentional MW									
Block	4.57, 283.37	2.36	.045*	1, 62	32.17	<.0005***	4.57, 283.37	1.81	.117
Quartile	3, 195	8.71	<.0005***	1, 65	21.66	<.0005***	3, 195	2.23	.086
Break	-	-	-	-	-	-	1, 65	4.35	.041*[a]

Note. CoV, Coefficient of Variance; df, degrees of freedom; F, *f*-test statistic; MW, Mind-Wandering, RT, Reaction time.

[a] Significant interactions were followed up with tests of simple effects and discussed in the main text. *$p < .05$; ** $p < .01$; *** $p < .001$

4.3.4 Effect of Variable Inter-Trial Interval Durations

A 2x3 mixed repeated measures ANOVA was conducted to examine if there were differences in PD amplitudes prior to the different 3-, 5-, and 7-second ITIs for younger and older adults, see Table **4.2** for descriptive statistics and Figure **4.4** for grand-averaged PD waveforms.

For mean PD amplitude, there was a significant main effect of ITI observed, $F_{1.56, 96.59} = 39.21$, $p <.0005$, $\eta p^2 = .39$, $\varepsilon = .78$. Bonferroni pairwise comparisons demonstrated that the pre-trial PDs were smaller in amplitude during the 3-second ITI in comparison to the longer 5- and 7-second ITIs (all $p < .0005$), independent of Group (see Table **S.4.1** in §*4.5 Supplemental Material*). A significant main effect of Group was also observed, $F_{1, 62} = 21.11$, $p <.0005$, $\eta p^2 = .25$, $\varepsilon = .78$ such that irrespective of timepoint, younger adults showed greater PD amplitudes compared to their older counterparts prior to target onset (mean difference = .06, $p < .0005$, 95% CI [.03, .08]). The Group x ITI interaction was not, however, statistically significant, $F_{1.56, 96.59} = 3.08$, $p =.063$, $\eta p^2 = .05$, $\varepsilon = .78$.

A significant Group x ITI interaction was observed for pre-trial PD slopes, $F_{1.51, 93.47} = 4.53$, $p = .022$, $\eta p^2 = .07$, $\varepsilon = .75$. Separate within-subjects repeated measures ANOVAs demonstrated a significant effect of ITI for both younger, $F_{1.48, 47.40} = 13.08$, $p < .0005$, $\eta p^2 = .29$, and older adults, $F_{1.50, 45.03} = 38.79$, $p < .0005$, $\eta p^2 = .56$. For both age groups, the significant differences in PD slopes were located between the 3-second ITI compared with the longer 5- and 7-second ITIs (all $p < .01$).

Furthermore, follow up simple main effects for Group showed significant differences between younger and older adults with respect to pretrial PD slope during each of the 3-, 5-, and 7-second ITIs (all $p < .01$). Collectively, these findings show that with longer pre-trial durations (5- and 7-seconds), younger adults, especially, dropped out of a greater exploratory state and shifted back into an exploitative state just in time for target onset. This was indexed by steeper negative slopes relative to the shorter 3-second interval and relative to older adults. In comparison, older adults maintained steadier PD than their younger counterparts during these longer intervals as shown by relatively shallow negative slopes during the 5- and 7- second ITIs. The pre-trial slopes during the 3-second ITI are consistent with phasic responses from attending to a previous target, an effect which was more pronounced for older adults.

Table 4.2

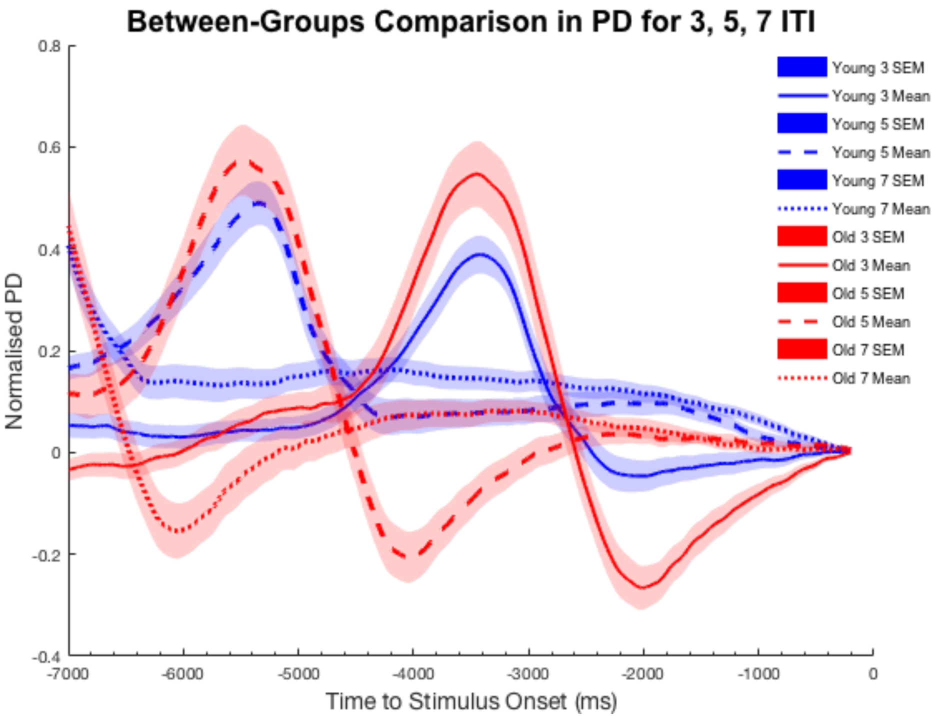
Within-Group Descriptive Statistics for the Pre-Trial Pupil Diameters According to the Inter-Trial Intervals for Younger and Older Adult Participants

Variable	Young (*n* = 33)			Old (*n* = 31)		
	3 ITI	5 ITI	7 ITI	3 ITI	5 ITI	7 ITI
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
PD Mean Amp	-.02 (.09)	.05 (.07)	.07 (.06)	-.11 (.12)	.02 (.04)	.02 (.05)
PD Slope	.00002 (.00009)	-.00006 (.00007)	-.00007 (.00005)	.00014 (.00014)	-.00002 (.00005)	-.00002 (.00006)

Note. Amp, Amplitude; ITI, Inter-Trial Interval; M, mean; n, Number of observations; PD, Pupil Diameter; SD, Standard deviation. “3”, “5”, and “7” represent the ITI durations in seconds. Pre-trial PD amplitude and slope measures [window: -2000ms to -200ms].

Figure 4.4

Target-Aligned Grand-Averaged Pupil Diameter Waveforms According to the Different Inter-Trial Intervals for Younger and Older Adult Participants



Note. Grand-averaged waveforms of normalised and baseline-corrected pupil diameter (PD) comparing pre-trial PD across 3-, 5-, and 7-second inter-trial-intervals (ITIs) for younger and older adults. Shaded areas indicate the SEM of data points. Mean amplitude and slope measures were extracted from a target-locked measurement window of -2000ms to -200ms.

4.4 Discussion

The present study examined the time-on-task changes in subjective attentional states, sustained attention performance, and pupillary dynamics during the GradCCD-ES task. The overarching purpose of the present investigation was to delineate the temporal nature of moment-to-moment attentional fluctuations over distinct longer and shorter timescales with the capacity to distinguish the different task strategies implemented by younger and older adults.

4.4.1 Time-On-Task Effects Across Longer and Shorter Timescales

We observed time-on-task performance decrements independent of Group through prolonged response latencies and reduced hit accuracy over shorter (within-block) and longer (across-blocks) timescales. These temporally-induced performance decrements were broadly similar for younger and older adults across the task and reflect traditionally observed time-on-task effects. Curiously, despite increased attentional lapses over time, RTV and the number of False Alarms decreased over the task, driven primarily by changes relative to the first block. The more modulatory activity at the beginning of the task may represent initial familiarisation and adaptation to novel task demands. Accordingly, with cumulative practice over subsequent blocks and greater adjustment to the task requirements, participants’ responding became less variable and impulsive.

Furthermore, the frequency of Unintentional and Intentional Mind-Wandering steadily increased for both groups over the task, increasing within- and across-block durations. In particular, older adults exhibited a linear decrease in self-reported Focus across the task blocks, suggesting a steady decline in their exploit mode and capacity to maintain focal task attention over time. In contrast, younger adults demonstrated a sudden drop in Focus after Block One but an absence of subsequent change over the remaining blocks. This finding challenges the resource-control model of sustained attention (Thomson et al., 2015); namely, in younger adults, Focus did not decline in a linear fashion giving way to increased mind-wandering, but rather there was more efficient calibration of exploit/explore modes in line with the demands of the task.

The forgoing observations contribute to the growing body of evidence recognising the time-on-task phenomenon, substantiating changes in momentary attentional fluctuations for younger and older adults over time. Maintaining steady attentional engagement is effortful and challenging, and accordingly, we observed deteriorating performance and more frequent mind-wandering as a function of time-on-task, in line with previous studies (Brosowsky et al., 2020; Cunningham et al., 2000; Hopstaken et al., 2015; Massar et al., 2020; McVay & Kane, 2012; Thomson et al., 2014). Although it is widely recognised that attention fluctuates over protracted performance periods, less is known about the exact temporal dynamics of different mind-wandering dimensions and how they change with age. Indeed, typical vigilance paradigms predominantly explore performance changes over the course of a task (e.g. 8-10 minutes) with a younger population. Our findings show that fluctuations in subjective attentional Focus and performance also occur over the course of shorter intervals, namely, over several trials for both age groups (see also Esterman et al., 2013; Kucyi & Davis, 2014). As such, our findings add to the vigilance literature while propounding specific time effects in subjective mind-wandering and focal task attention over longer and short timescales for younger and older adults.

Performance decrements and more frequent mind-wandering have been suggested to reflect systematically depleting resources due to fatigue or task demands (Grier et al., 2003; Helton et al., 2005; Helton & Warm, 2008; Parasuraman, 1979; Parasuraman & Mouloua, 1987; Smit et al., 2004; Warm et al., 2008), diminishing utility of task goals and reallocation of resources to mind-wandering (Thomson et al., 2015), or decreased motivation due to under-stimulation (Robertson & Garavan, 2004; Smallwood et al., 2004). Despite the reduced executive capacity of older adults, both age groups demonstrated similar trends of performance decrements and disengagement of sustained attention at critical moments over time. However, the age-related differences in subjective attentional states suggests that the groups implemented different strategies over the course of the task. Younger adults exhibited greater capacity to oscillate between competing exploit and explore modes in accordance with task demands whereas older adults maintained an exploitative task strategy which waned over the extended duration of the task.

4.4.2 Restorative Effect of Task Breaks

Both age groups received a boost in performance and attentional engagement after brief rest breaks in between blocks, demonstrating faster and more accurate responding, enhanced Focus, and attenuated Unintentional Mind-Wandering. Given the time-on-task performance decrements in RT and Hit Rate, the rest breaks appeared to revive these performance metrics and temporarily alleviate such deteriorations. Additionally, younger adults exhibited a lower propensity to Intentionally Mind-Wander following the break, suggesting that they intentionally explored the mind-wandering space when their task motivation waned by the end of each block. By contrast, there was no difference in Intentional Mind-Wandering rates from before to after the break for older adults, consistent with their reduced tendency to deliberately disengage from the task to explore. Considering that there was no such dissociation with Unintentional Mind-Wandering, this supports the idea that the main effects represent more classic time-on-task involuntary changes. Given these reset effects, the time-on-task effects reported in the present study may thus be underreported and may be subject to further deterioration with extended and uninterrupted performance.

The restorative effect of rest breaks for behavioural performance and subjective alertness demonstrates the inherent value in rest breaks for sustained attention for both younger and older adults, supporting previous research showing that rest can temporarily mitigate performance decrements (Ariga & Lleras, 2011; Ralph, Onderwater, Thomson, & Smilek, 2017). These effects may occur through multiple routes including combatting cumulative fatigue, replenishing depleted resources, or alleviating task-related boredom with prolonged performance durations. The break effect on Intentional Mind-Wandering suggests that rest provided a particular attentional refresh for the younger group by disrupting the monotony and tedium of the task. This effect was not similarly demonstrated for older adults and is in accordance with our previous findings that older adults exhibit a lower propensity to intentionally mind-wander generally and display greater task-related interest and engagement (*Chapter 2* or Moran et al., 2021).

It should be noted, however, that the rest breaks in the present study were not standardised; that is, there were no specific time limits imposed or deliberate consistency in whether the break consisted of silent rest or chatting with the experimenter (which may be cognitively stimulating, or possibly demanding). As such, there may be a degree of between-subject variation unaccounted for in the present study that future research should consider when developing paradigms to measure the effects of breaks for younger and older adults.

4.4.3 Differential Age-Related Strategies According to Inter-Trial Intervals

Endogenous baseline PD was analysed as a proxy psychophysiological measure of LC-NA neuromodulatory activity to examine the capacity of younger and older adults to flexibly shift between different serial exploit/explore modes throughout the task relative to different ITIs. In *Chapter 3* we observed that greater PDs pre-target and pre-probe were indicative of greater explorative off-task processing. In the present study, younger adults gradually reduced their PD as time unfolded before the target, dropping out of a relatively exploratory state prior to the longer 5- and 7-second ITIs. With longer ITIs, younger adults shifted between exploratory and exploitative states, shifting back to the latter just in time for target onset, as indexed by steep negative slopes. Implicit temporal expectations of target occurrence enabled younger adults to dynamically switch between focused and mind-wandering states. In the absence of explicit visual cues, younger adults implicitly learned when they could mind-wander more without cost, tuning their explorative mode to the amount of time available. Given that younger adults mind-wandered more without a commensurate negative impact to performance accuracy, it follows that they employed a balanced and optimal oscillation ratio between exploitative and explorative strategies (Sripada, 2018).

By contrast, older adults continually attended to the task and maintained their PD relatively steady before target onset, demonstrating more consistent attentional readiness and less oscillatory switching between exploit/explore modes. This is indexed by the more shallow negative slopes as the targets approached the 5- and 7-second ITIs for older adults in comparison to their younger counterparts. Older adults prioritised task-relevant information and implemented a more restrictive exploitative approach, allocating their attentional focus toward the task during shorter and longer intervals. They reaped the benefit of this conservative strategy by minimising the potential consequences of exploration on their performance. Further, the patterns for the shorter 3-second ITIs are comparatively different to the longer durations as they show the end of target processing and phasic response from the previous trial for both younger and older adults.

In summary, our research demonstrated broadly comparable time-on-task effects between younger and older adults with decreased performance and increased mind-wandering over shorter and longer timescales. Older adults alone, however, demonstrated a shift in strategy, maintaining an exploitative oscillatory approach to avoid risking any consequences from exploration. This is in line with previous research demonstrating more conservative strategies with age (Fortenbaugh et al., 2015).

4.4.4 Methodological Considerations and Avenues for Future Research

The present paradigm incorporated a continuous sustained attention task with embedded online ES and concurrent pupillometry recording to assess the nature of time-on-task effects in ageing. Classic sustained attention and vigilance tasks typically feature abrupt stimulus onsets that serve as exogenous cues to initiate responding and may therefore mask the full nature of time-on-task decrements. Building upon such paradigms, the GradCCD-ES in the present study utilised gradually-evolving stimuli transitions in a single perceptual feature, and hence, successful task performance was reliant on top-down endogenous attentional control mechanisms, serving as a purer measure of sustained attention. The repetitive and non-demanding performance requirements sufficiently taxed sustained attention, produced time-on-task effects, and was conducive to mind-wandering incidences. Intermittent probe sampling enabled subjective reporting on current attentional states at distinct moments in time and proved to be sensitive to changing temporal dynamics throughout the task. Coupled with the structured task block design and short rest breaks, these elements facilitated the isolation of the temporal dynamics of fluctuating attentional states occurring over longer and shorter temporal windows with the further ability to assess potential restorative effects of brief rest breaks.

Despite the advantages of the present approach, four limitations are discussed with suggestions for future research. Firstly, the present study does not provide an exhaustive account of all conditional factors that may contribute to, or moderate, the degree of time-on-task impairment reported. Sustained attention and the extent of explorative thinking may be partly contingent upon intrinsic factors such as sleep, arousal, and perceived locus of control, or extrinsic factors like motivation incentivisation. Indeed, several attention-relevant variables are sensitive to changes in sleep state and fatigue. For example, time-on-task decrements in performance and fluctuations in arousal are more pronounced with sleep deprivation (Lim & Dinges, 2008; Massar, Lim, Sasmita, & Chee, 2019), and are partially attenuated by caffeine and sleep medication (Wesensten, Belenky, Thorne, Kautz, & Balkin, 2004).

Additionally, the inclination to explore may be further constrained by one's perceived locus of control and belief in their agency and self-efficacy during situations of relative uncertainty (Kayser, Mitchell, Weinstein, & Frank, 2015).

Regarding potential external moderating factors, research has shown that performance fluctuations (Esterman, Poole, Liu, & DeGutis, 2017; Esterman, Reagan, Liu, Turner, & DeGutis, 2014), time-on-task decrements (Esterman et al., 2016; Massar et al., 2019; Steyvers & Gaillard, 1993), and mind-wandering propensity (Seli et al., 2020; Seli et al., 2019) may be minimised by enhancing motivation through incentivisation and rewards. This suggests that a degree of top-down modulation of attention allocation may bolster performance. However, it remains to be established whether such incentivisation is equally effective for younger and older adults who demonstrate different levels of task-related interest and motivation from the offset (Jackson & Balota, 2012; Krawietz et al., 2012; Maillet & Rajah, 2013; Shake et al., 2016). The complex nature of fluctuating attention and multiple putative moderators thus requires further study to examine the various factors that underlie changes in attentional engagement over time.

Secondly, attention is not a static or unitary process, as so far demonstrated. Our inner mental life involves a constant, discursive stream of thoughts that dynamically shift between periods of focus and inattention (Christoff et al., 2016). In the present study we operationalised mind-wandering as occurring due to the unintentional (automatic) or intentional (strategic) reallocation of attentive resources from extrinsic to intrinsic sources. This dissociation was grounded in research showing distinct associations with behavioural, functional, and clinical correlates and outcomes (see Seli, Risko, Smilek, et al., 2016).

Although the ES probes were sensitive to changes in subjective attentional states over shorter and longer timescales, there may be other relevant mental experiences not captured by the response options employed in the present study that fall under the broad spectrum of attentional lapses and mind-wandering. Indeed, the lack of a universal consensus on mind-wandering terminology remains a matter of ongoing debate in the field (see Christoff et al., 2016; Christoff et al., 2018; Seli, Kane, et al., 2018; Smallwood & Schooler, 2015). For example, external distraction (e.g. Stawarczyk, Majerus, Catale, & D'Argembeau, 2014; Unsworth & Robison, 2016) or further characterisations by the content, affective valency, temporal orientation, and meta-awareness of task-unrelated thoughts (Irish et al., 2019; Miles, Karpinska, Lumsden, &

Macrae, 2010; Schooler et al., 2011) have been shown to alter engagement with the external environment. These alternate mind-wandering dimensions have yet to be investigated with respect to time-on-task effects. These dynamics are not inherently at odds with the present classification of mind-wandering as occurring with and without intention (see Family Resemblances framework, Seli, Kane, et al., 2018), but their examination may provide further nuance to the processes and content of our inner mentations as they unfold over time. Future research should incorporate open-ended methods (see Irish et al., 2019) which may offer a further opportunity to gauge the richness of different mental experiences as they evolve.

Thirdly, the present study focused primarily on mapping the temporal patterns in oscillatory attention for younger and older adults during a non-demanding, continuous sustained attention task. However, maintaining attentional engagement plays an integral role in functions of daily life, with trivial to potentially far-reaching consequences of lapsed attention in real-world settings. Choosing the appropriate moment to explore needs to be weighed against the demands of the context and this trade-off may be less clear-cut in unstructured and constantly evolving naturalistic scenarios compared to more constrained task-specific environments (Cohen et al., 2007). Fluctuating attention at critical moments in everyday settings may be a threat to safety, particularly in situations where actions become more automated or mental states become subject to fatigue or distraction with time. Indeed, mind-wandering and suboptimal attention during driving is a leading cause of traffic accidents in younger adults (Lohani et al., 2019; Schmidt et al., 2017; Yanko & Spalek, 2013), impacts educational and employment outcomes (e.g. Kalechstein et al., 2003; Pachai et al., 2016; Seli, Wammes, et al., 2016), and potentiates the risk of falls in older adults (Nagamatsu et al., 2013; O'Halloran et al., 2011). Therefore, it is important for future research to examine the factors that impede or perturbate sustained attention at critical moments or exploration at opportune moments within real-world scenarios particularly for younger adults who may be more predisposed toward mind-wandering.

Additionally, although the present study demonstrated relatively monotonic increases in mind-wandering with shorter and longer time-on-task durations, such temporal patterns are likely more complex in daily life. For example, a recent study using ES in the field demonstrated dynamic diurnal fluctuations in mind-wandering (Smith, Mills, Paxton, & Christoff, 2018). As such, future research incorporating lifelogging technology (e.g. Gurrin et al., 2014) should examine the temporal patterns and relative impact of fluctuating and deteriorating attentional states in an ecologically valid, real-world environment over extended timeframes. Such research will help researchers to better understand the ebb and flow of various mental experiences in daily life and identify the factors governing exploitative and explorative processes as they unfold within natural time-courses.

Fourthly, the older adults in the present study were aged between 65 and 78 years old ("young-old") and were highly educated. Hence, the reported temporal patterns of mind-wandering and performance may be different from those that might be observed in adults in later life, those with lower educational attainment, or those with more pronounced cognitive decline (Borella et al., 2008; Stern et al., 1992). Longitudinal designs with large sample sizes might be better positioned to monitor changing attentional dynamics over the lifespan and provide more cognitively varied samples (e.g. Fortenbaugh et al., 2015). Research of this kind may help monitor the putative contribution of cognitive reserve variables to identify the changes and underlying mechanisms that represent indications of successful ageing from those maladaptive patterns that may pre-empt cognitive impairment.

4.4.5 Conclusions

Maintaining attentional engagement over longer durations requires effort and is subject to fluctuations and deteriorations with time. The deleterious impact of lapsing attention has been shown on performance, with wider real-world consequences for the safety and well-being of individuals, particularly in cognitive ageing. In light of the reported costs of fluctuating attention during mind-wandering, research on different attentional states is vital for shaping our understanding of the brain and the natural ageing process. Our findings provide new insight into temporal dynamics of attentional fluctuations and deteriorations in healthy younger and older adults during a continuous sustained attention task. Specifically we showed deteriorating performance and increased unintentional and intentional mind-wandering as a function of time-on-task. The capacity to maintain attentional engagement was impacted by prolonged task exposure for both age groups. We further demonstrated the restorative effect of rest breaks for enhancing performance for younger and older adults, and for minimising intentional mind-wandering specifically for younger adults.

In line with the exploit/explore trade-off (Sripada, 2018), younger adults strategically and implicitly modulated their attention on a trial-by-trial basis in response to task demands and temporal uncertainties. This modulation was done by dynamically switching between exploitative and explorative serial modes of thought in an optimal manner without incurring performance costs. Conversely, older adults prioritised task performance showing a reduced inclination for exploration to offset their reduced cognitive resources and avoid risking performance costs from exploration. Temporary oscillatory attentional cycles were thus regulated over time as demonstrated by the differential pre-trial PD patterns for younger and older adults. Our research therefore contributes to the growing research base exploring time-on-task changes by demonstrating attentional fluctuations and deteriorations over shorter and longer timescales and elucidating different strategic approaches to task performance between younger and older adults. Understanding the temporal nature of attentional changes in healthy ageing may inform future interventions targeted at preserving sustained attention as a gateway to enhancing successful ageing.

4.5 Supplemental Material

Table S.4.1

Significant Results for the Bonferroni-Corrected Paired Samples t-Tests Pertaining to Significant Main Effects of Time (Block, Quartile, and ITI)

Dependent Variable	Comparison		Mean Difference	*p*	95% CI
	Condition 1	Condition 2			
Significant Main Effects of Block					
RT	Block 1	Block 7	-0.07	.011*	[-.13, -.01]
RT CoV	Block 1	Block 3	2.64	.019*	[.23, 5.04]
	Block 1	Block 4	2.25	.028*	[.12, 4.39]
	Block 1	Block 5	2.71	.022*	[.21, 5.20]
	Block 1	Block 6	3.51	<.0005***	[1.15, 5.87]
	Block 1	Block 7	3.02	<.0005***	[1.01, 5.04]
	Block 1	Block 8	3.54	<.0005***	[1.17, 5.91]
False Alarms	Block 1	Block 5	2.02	.008**	[.30, 3.75]
	Block 1	Block 6	1.68	.019*	[.15, 3.21]
	Block 1	Block 7	2.31	.002**	[.52, 4.09]
	Block 1	Block 8	2.20	.004**	[.43, 3.98]
Unintentional MW	Block 1	Block 2	-1.13	<.0005***	[-1.87, -.38]
	Block 1	Block 4	-1.64	<.0005***	[-2.53, -.75]
	Block 1	Block 5	-1.59	<.0005***	[-2.45, -.74]
	Block 1	Block 6	-1.63	<.0005***	[-2.65, -.61]
	Block 1	Block 7	-2.14	<.0005***	[-3.44, -.84]
	Block 1	Block 8	-1.69	.008**	[-3.13, -.25]
	Block 3	Block 4	-.98	.010*	[-1.84, -.13]
	Block 3	Block 5	-.94	.014*	[-1.77, -.11]
	Block 3	Block 7	-1.48	.001**	[-2.59, -.38]
Intentional MW	Block 1	Block 5	-.73	.049*	[-1.45, -.00]
Significant Main Effects of Quartile					
RT	Quartile 1	Quartile 2	-.02	.004*	[-.04, -.01]
	Quartile 1	Quartile 3	-.07	<.0005***	[-.09, -.05]
	Quartile 1	Quartile 4	-.08	<.0005***	[-.10, -.06]
	Quartile 2	Quartile 3	-.05	<.0005***	[-.07, -.03]
	Quartile 2	Quartile 4	-.06	<.0005***	[-.08, -.04]
Hit Rate	Quartile 1	Quartile 3	.03	<.0005***	[.01, .05]
	Quartile 1	Quartile 4	.03	<.0005***	[.01, .05]
	Quartile 2	Quartile 3	.02	.001**	[.01, .03]
	Quartile 2	Quartile 4	.02	<.0005***	[.01, .04]
Focus	Quartile 1	Quartile 2	.43	<.0005***	[.24, .62]
	Quartile 1	Quartile 3	.53	<.0005***	[.33, .73]
	Quartile 1	Quartile 4	.56	<.0005***	[.37, .76]
Unintentional MW	Quartile 1	Quartile 2	-.24	.001**	[-.41, -.07]
	Quartile 1	Quartile 3	-.34	<.0005***	[-.51, -.18]
	Quartile 1	Quartile 4	-.36	<.0005***	[-.51, -.21]

Intentional MW	Quartile 1	Quartile 2	-.18	<.0005***	[-.29, -.06]
	Quartile 1	Quartile 3	-.15	.004**	[-.26, -.03]
	Quartile 1	Quartile 4	-.18	<.0005***	[-.29, -.07]
		Significant Main Effects of ITI			
PD Mean	3sec ITI	5sec ITI	-.09	<.0005***	[-.14, -.06]
	3sec ITI	7sec ITI	-.11	<.0005***	[-.14, -.07]

Note. CI, confidence interval; CoV, Coefficient of Variance; ITI, Inter-trial Interval; MW, Mind-Wandering; PD, Pupil Diameter; RT, Reaction time.

p* < .05; ** *p* < .01; * *p* < .001

Chapter 5: General Discussion

5.1 Thesis Overview

Mind-wandering is a dynamic, discursive, and ubiquitous mental state usually included within the portmanteau of spontaneous thought phenomena (Christoff et al., 2016). In its broadest sense, mind-wandering involves the transition -or decoupling- of attentional resources from task-related or perceptually-guided thoughts, to unrelated, endogenously-generated mental content (Smallwood & Schooler, 2015). More specifically, theorists have proffered an important and clinically-relevant distinction of mind-wandering as occurring due to the unintentional or intentional redirection of attentional resources from extrinsic to intrinsic sources (Seli, Risko, Smilek, et al., 2016), although this remains a topic of debate (see Christoff et al., 2016; Christoff et al., 2018; Seli, Kane, et al., 2018; Smallwood & Schooler, 2015). In any case, there perhaps exists no other mental phenomenon that is so universal, so foundational to the lived experience, and so familiar to us in a natural sense, yet remains so poorly empirically understood as mind-wandering.

Burgeoning scientific interest in mind-wandering over the last two decades, heralded as the “era of the wandering mind” (Callard et al., 2013), has seen a corresponding upsurge in research aiming to characterise the nature of this mental phenomenon within healthy ageing populations (usually defined as over 65 years of age). An emerging and seemingly robust finding is that mind-wandering, both the unintentional and intentional forms, decreases as a function of age in healthy individuals (Jordao et al., 2019; Maillet & Schacter, 2016). This somewhat paradoxical finding raises the question as to whether common-sense notions or conventional stereotypes about ageing, such as the view of older adults as being “absent-minded”, are well-founded.

Indeed, the capacity to sustain attention is a core cognitive operation at the heart of the cognitive ageing discussion. Failure to maintain steady attentional engagement at critical moments, or to strategically and adaptively transition between serial modes of thought at opportune moments, has ramifications ranging from the benign (e.g. throwing away a spoon instead of an empty yoghurt pot), or trivial (e.g. task performance decrements), to more far-ranging deleterious consequences (e.g.

disorientation, road or workplace accidents and risk of falls). Sustained attention is a fundamental facet of healthy cognitive ageing in that it supports the cortical plasticity integral for cognitive reserve, optimises performance and goal-directed behaviours, and influences many other vital higher-order cognitive processes (Fortenbaugh et al., 2017; McAvinue et al., 2012; Polley et al., 2006; Robertson, 2014; Smilek et al., 2010).

To date, however, studies have not sufficiently examined the exact nature and core underpinning facets of mind-wandering in healthy ageing populations. This is a timely issue given the well-recognised phenomenon of global population ageing and the fine boundary separating age-associated changes that represent normal ageing, from those that predict a pathological decline. Indeed, cognitive processes do not uniformly or monotonically deteriorate over one’s lifespan (Fortenbaugh et al., 2015), and adopting a “decrement perspective” on ageing is generally discouraged (Salthouse, 2010). As such, research is warranted to assess the complexity and richness of adaptive and maladaptive mind-wandering as it changes with advancing age to ultimately better understand the natural ageing process.

Motivated by this backdrop, the present thesis began with two general research questions. Firstly, does the frequency and phenomenology of unintentional and intentional mind-wandering change with age? Secondly, what are the neuropsychological and neurophysiological signatures of different attentional states in healthy younger and older adults? Therefore, the over-arching purpose of the present study is to characterise the nature of different mind-wandering qualia (i.e. qualitative experiential states) as they manifest across age groups. To address this goal, this thesis is composed of three separate but closely related empirical studies, and focuses chiefly on the following objectives:

- **Chapter 2 (*Empirical Paper 1*)** investigates age-related differences in the frequency and phenomenology of unintentional and intentional mind-wandering experiences, and examines the neuropsychological factors mediating their advent to dissociate between prominent theories in the field of mind-wandering and ageing.
- **Chapter 3 (*Empirical Paper 2*)** traces the neurophysiological signals of oscillatory endogenous attention and task-related processing to a) ascertain the mechanistic basis of transient strategic shifts in brain states between competing

task focus and mind-wandering, and b) explore how they are differentially affected by the ageing process. Furthermore, *Chapter 3* examines whether neurophysiological measures preceding subjective probe attentional states provided support for the perceptual decoupling hypothesis: which proposes the redirection of attentive resources away from sensory input toward self-generated mental content during mind-wandering.

- **Chapter 4 (*Empirical Paper 3*)** investigates time-on-task changes in moment-to-moment attentional fluctuations by delineating the temporal trajectory of behavioural sustained attention performance and subjective mind-wandering states over longer- and shorter-term timescales for both younger and older adults. Additionally, *Chapter 4* investigates pupil dilation changes, as a proxy measure of oscillatory attentional shifts, during variable pre-trial intervals to distinguish the different task strategies implemented by younger and older adults to maintain attentional engagement throughout the task.

5.2 Novel Contributions: Advantages of the Current Methodological Approach

Mind-wandering reflects an inner, first-personal, and reasonably ephemeral qualitative experience, that, so defined, poses a significant challenge to direct experimental investigation. Traditional paradigms for measuring attentional states (e.g. the Sustained Attention to Response Task, SART, Robertson et al., 1997) are afflicted by a number of limitations owing to their use of salient, punctuated, sudden-onset, and often predictably occurring target changes. These target transitions exogenously capture attention and serve as alerting cues for target occurrence, which may aid performance responding. The resultant complications of such discrete visual stimuli are that they evoke spatially and temporally overlapping signals in physiological recordings that are difficult to disentangle and interfere with the examination of endogenously maintained attentional engagement over time. Moreover, typical tasks usually necessitate speeded responses which raises the question as to whether age-associated deficits in performance should be attributed to attentional lapses or age-related motor-speed slowing (McAvinue et al., 2012). Allied with these traditional task limitations, introspection through online probe-caught experience sampling (ES) may be subject to issues of subjective biases, meta-cognitive judgments, and being tied to specific probe time-courses (Nisbett & Wilson, 1977; Smallwood & Schooler, 2015; Weinstein, 2018).

Considering the aforementioned challenges, the present study capitalised on evolving methodologies for measuring and classifying mind-wandering using an innovative, multi-faceted approach that incorporated a comprehensive neuropsychological test battery and complementary use of subjective, behavioural, and neurophysiological measures. The Gradual Contrast Change Detection task, modified to include built-in online ES (GradCCD-ES, McGovern et al., 2018; O'Connell et al., 2012), captured self-reported mind-wandering experiences during sustained attention performance with concurrent electroencephalography (EEG) and pupillometry recordings. The advantages of these convergent methodological components for the examination of the wandering mind are henceforth discussed.

In the present study, intermittent probe sampling enabled qualitative categorisation of subjectively reported mental states at discrete moments in time to facilitate comparisons of behavioural patterns and neural activity between on- and off-task states. We observed that the probes were meaningfully related to behavioural and neuropsychological concomitants (*Chapter 2*), decoded the neural mechanisms of perceptual decoupling (*Chapter 3*), and were sensitive to changing temporal dynamics throughout the task (*Chapter 4*). This triangulation supports the validity of ES as a tool for classifying phenomenologically dissociable mental states without undue disruption to the natural dynamics of the conscious flow of experience (Schooler & Schreiber, 2004; Schooler, 2002). Further, these relationships support the enduring appeal and inherent value of first-personal and embodied subjective judgments. Such subjectivity is not necessarily at odds with the objectivity often espoused by the natural sciences but rather serves as a necessary first step for achieving objectivity. ES can thus be usefully applied in tandem with complementary direct measures, as demonstrated by the present study, to provide new insight into the inner workings, complexity, and richness of the mind-wandering constitution.

Extending previous paradigms, the GradCCD-ES task presented smooth and gradually unfolding stimulus changes in a single perceptual feature (stimulus contrast). These subtle target transitions removed momentary sensory-evoked deflections from the signal recordings. They, therefore, enabled isolation and monitoring of the individual dynamics of transient attentional states as they evolved in real-time. The minimised perceptual requirements further circumvented issues of exogenous attention capture and minimised the degree to which bottom-up processes guided responding, thereby placing greater reliance on endogenous attentional control mechanisms for successful performance. Further, the rapid, synchronous flicker of the critical stimulus feature generated a steady-state visually evoked potential (SSVEP) that tracked the representation of the stimulus contrast against which the integrity of sensory evidence encoding could be measured during subjective focused and mind-wandering states. The temporal unpredictability of the target stimuli over long, repetitive, and tedious blocks effectively occasioned opportunities for mind-wandering and enabled investigation of time-on-task effects. Additionally, the broad and variable inter-trial intervals (ITI) provided a wider berth for response than previous paradigms (e.g. the SART), facilitating changes in fluctuating attention with age to be documented with minimized confounding from age-accompanied motor-slowing. Moreover, to surmount the issue of trial summation and the assessment of global performance measures traditionally observed in the extant mind-wandering literature, the block structure and quartile trial binning in the present study enabled attentional engagement to be tracked as it fluctuated over longer and shorter within-task temporal windows.

The high temporal resolution of the electrophysiological recordings provided a direct and real-time continuous index of mind-wandering with the capacity to decompose the dissociable signals involved in perceptual decoupling with millisecond precision. Analysis of exogenously and endogenously driven brain signals offered a means to examine perceptual information processing alongside neural oscillations that occurred independent of sensory stimuli to elucidate the oscillating quality of the wandering mind, that has so far been poorly understood with respect to ageing.

Pupil dilation indices also offered a useful, objective, non-intrusive, and temporally precise proxy measure of the intensity of attentional allocation and strategic oscillatory exploit/explore shifts during the task (Alnaes et al., 2014; Aston-Jones & Cohen, 2005; Joshi et al., 2016; van den Brink et al., 2016). Incorporating pupillometry in the present paradigm provided insight into the attentional mechanisms underlying the complex and dynamic strategic shifts between attentional states within set temporal parameters in younger and older adults. Collectively, the value of this triangulated approach is that it obviated sole dependence on a single measure, delineated differential processes involved in the manifestation of mind-wandering in ageing, and augmented our understanding of how these processes evolve in a momentary manner.

The forthcoming sections summarise the global findings and theoretical advances of the present empirical work. We posit potential limitations that should be heeded when interpreting the present results, suggest possible avenues for future research, and conclude with a discussion of potential practical implications of the research as a whole.

5.3 Key Research Findings and Theoretical Advances

5.3.1 Research Question 1: Does the Frequency and Phenomenology of Unintentional and Intentional Mind-Wandering Change with Age?

In *Chapter 2*, we observed that younger and older adults exhibited a natural tendency to engage in mind-wandering during the GradCCD-ES task, suggesting that mind-wandering represents an integrative constituent feature of our everyday cognition. Older adults, however, displayed a reduced proclivity for unintentional and intentional mind-wandering than their younger counterparts. What factors influenced the inclination to mind-wander in younger but not older adults? Understanding this effect is not straightforward, as shown by the lack of theoretical unanimity in the field. Disputes exist regarding the factors driving age-related differences in mind-wandering with different theoretical expressions propounding the roles of (a) executive resources (i.e. Executive Control Hypothesis, Smallwood & Schooler, 2006), (b) the interaction of executive resources with current concerns (i.e. Control Failure X Concerns theory, McVay & Kane, 2010), (c) strategic oscillatory dynamics (i.e. the Exploitation/Exploration framework, Sripada, 2018), (d) dispositional variation through affective (Frank et al., 2015) and motivational (Jackson & Balota, 2012) factors.

In *Chapter 2*, we demonstrated that unintentional mind-wandering was mediated by affective and motivational factors. In other words, older adults reduced their unintentional mind-wandering driven, at least in part, by their reduced anxiety and greater task-related engagement compared to younger adults. Although an age-related difference in intentional mind-wandering frequency was also reported, this effect was not similarly mediated by dispositional variables. Despite age-related cognitive decline on standardised measures of executive function, neither cognitive resource nor task demand variables further contributed to the relationships between age group and mind-wandering propensity.

A significant novelty of the present study is that it is the first (to our knowledge) to directly contrast the roles of multiple putative theoretically driven factors in an integrated model in order to compare their relative contributions for explaining the age and mind-wandering effect. Our findings underscore the roles of dispositional accounts, namely affective and motivational factors, as driving the age-related difference in unintentional mind-wandering, with reasons to be less persuaded by cognitive resource accounts. Together our findings suggest that older adults curbed their unintentional mind-wandering throughout the task due to their lower anxiety and heightened motivation. Moreover, the differential influence of these mediating factors on unintentional and intentional mind-wandering substantiates a functional divergence in mind-wandering intentionality. It supports the practice of distinguishing heterogeneous mind-wandering experiences with proprietary phenomenological characters to avoid conflation of separable dimensions of experience.

5.3.2 Research Question 2: What are the Neuropsychological and Neurophysiological Signatures of Different Attentional States in Healthy Younger and Older Adults?

5.3.2.1 Ageing Influences the Strategic Trade-Off Between Focus and Mind-Wandering. In line with the exploitation/exploration framework (Sripada, 2018), the present results indicate strategic differences in how younger and older adults approached the task. The basis of these strategic shifts in momentary attentional experiences, from exploitative to explorative states, and the extent to which they were guided by bottom-up or top-down processes were revealed during our investigation employing the novel paradigm. The GradCCD-ES enabled the evolution of continuous, gradually unfolding perceptual information to be tracked alongside the wandering mind. We advance the role of different oscillatory dynamics in age-related mind-wandering patterns for younger and older adults and suggest that ageing influences the capacity for optimal strategic regulation.

5.3.2.1.1 Age-Related Differences in Subjective and Behavioural Markers of Attentional Engagement (Chapter 2). Although both groups exhibited frequent mind-wandering during the GradCCD-ES, the large effect size observed for the age-related reduction in intentional mind-wandering suggests a particular inclination for younger adults to deliberately disengage from the task. Despite reduced cognitive resources with age, there was relative group parity in behavioural task performance. However, we observed an age-related difference in reaction time variability (RTV), a marker of oscillatory attention cycles, which suggests that older adults perform the task with steadier attentional engagement. Our exploratory partial correlations, after controlling for age group and IQ, demonstrated a pernicious effect of mind-wandering on concurrent task performance. Unintentional mind-wandering was associated with reduced performance accuracy, whereas intentional mind-wandering was related to increased false alarms, further mediated by RTV.

Considering the trade-off in competing resources for mind-wandering and task performance, we advance that older adults adopted a more restrictive oscillatory approach to mitigate potential performance costs. Older adults consigned their more limited cognitive resources toward the primary task in a more exploitative manner, decreasing their tendency to intentionally disengage, and in doing so, procured a relative behavioural advantage via reduced performance variability. Younger adults, conversely, implemented a more optimal and balanced oscillation strategy relative to the context. The latter exhibited greater explorative tendencies indexed by more frequent mind-wandering and more variable performance without incurring commensurate performance decrements. Intentional mind-wandering may thus reflect an adaptive exploratory state that younger adults engaged in more frequently without cost.

***5.3.2.1.2* Age-Related Differences in Neurophysiological Markers of Oscillatory Attention and Perceptual Decoupling (Chapter 3).** Age-related differences in endogenous attention states (alpha oscillations), strategic oscillatory shifts (pupil changes), and task-related processing (sensory representation, evidence accumulation, motor action) were examined in relation to the target and probe trials. Steadier attentional engagement antecedent to target onset was observed for older compared to younger adults as evidenced by attenuated alpha band variability, reduced mean pupil diameter (PD), and increasing pupil dilation in anticipation of the target. Additionally, older adults displayed higher PD after target presentation, suggesting that they more faithfully tracked the target contrast changes.

Signal analysis in the pre-probe interval showed that younger, but not older, adults exhibited perceptual decoupling. Younger adults also demonstrated more intermittent sensory encoding, as indexed by greater variability in the sensory (SSVEP) and attentional (alpha) signals, and higher PD amplitudes prior to self-reported mind-wandering relative to focused states. The observed patterns of oscillatory activity in attentional and perceptual event processing is in line with the greater explorative tendencies of younger adults. On the other hand, older adults demonstrated reduced attentional variability compared to younger adults prior to mind-wandering and, crucially, not prior to focus; this substantiates a reduced bias and less marked shift toward exploration by older adults even when mind-wandering is reported.

Both groups reliably tracked the evolution of the target stimulus contrasts; however, another significant finding is that older adults displayed earlier onset of evidence accumulation and better sensory representation of the target stimulus compared to younger adults. Older adults therefore demonstrated greater integration of the changes in goal-relevant stimuli. Conversely, younger adults tracked the target sensory evidence less efficiently as indexed by delayed and reduced sensory evidence integration for target trials. Given that younger adults did not exhibit a corresponding decline in sustained attention performance, this suggests insulated mind-wandering through perceptual decoupling.

Exploratory correlations, independent of group, demonstrated that greater withdrawal from the task via oscillatory attentional engagement and attenuated neurocognitive processing were associated with poorer performance. In light of the potential consequences of transitional shifting between serial modes of thought, the aforementioned age-related patterns in neurophysiological activity support different performance strategies implemented by younger and older adults. Against the backdrop of their reduced cognitive resources, older adults adopted a more cautious exploitative approach, prioritising task-relevant information and suspending mind-wandering to avoid performance costs; this reflects an adaptive age-related compensatory strategy. In contrast, despite increased attentional variability and attenuated task-related processing, younger adults maintained adequate performance. This suggests that younger adults utilised their greater cognitive capacity to optimise a more balanced exploit/explore ratio.

***5.3.2.1.3* Age-Related Differences in the Temporal Dynamics of Fluctuating Attentional States (Chapter 4).** We analysed the dynamic temporal properties of the manifestation of mind-wandering across more fine-grained timescales to further delineate the capacity for strategic modulation on a moment-to-moment basis. We observed broadly similar time-on-task effects for younger and older adults; both groups exhibited deteriorating sustained attention performance and fluctuations in attentional engagement with protracted time. Younger and older adults displayed similarly prolonged response latencies and reduced accuracy and increased unintentional and intentional mind-wandering over both shorter (within-block) and longer (across-block) timescales. These fluctuations in subjective attentional states extend previous research, showing that changes in engagement may occur over shorter timescales than are typically examined. Additionally, older adults displayed a linear reduction in task focus over the blocks, suggesting a gradual decline in their exploit mode and focal task engagement with time. Conversely, younger adults exhibited a pronounced drop in their focus after the first block with subsequent stabilisation, indicating a more balanced strategic oscillation between competing thought modes. This challenges the resource-control model of sustained attention (Thomson et al., 2015) as focus did not decline in a linear fashion giving way to mind-wandering for younger adults; but rather, they calibrated their exploit/explore ratio more efficiently in line with the demands of the task.

The between-block brief rest breaks provided a restorative effect, temporarily reviving performance and attentional engagement for both groups. Younger adults, however, demonstrated reduced intentional mind-wandering after a break, suggesting that they deliberately disengaged from the task when their motivation waned over the course of the block. By contrast, no difference in intentional mind-wandering propensity was observed for older adults after the break, consistent with their reduced proclivity for intentionally mind-wandering.

Differential PD patterns between younger and older adults were observed prior to variable pre-target durations (across 3-, 5-, and 7-second ITIs). Younger adults gradually reduced their PD and shifted back to an exploitative state, from an exploratory state, just in time before a target. Implicit temporal expectations of target occurrences aided younger adults to strategically regulate their explore modes and occasion mind-wandering when the task allowed it. This can be seen by younger adults exhibiting greater PD shifts particularly over the longer intervals between targets at 5 and 7 seconds. By contrast, older adults demonstrated steadier PD than their younger counterparts, consistent with more cautiously maintained attentional readiness with age.

Collectively the present work demonstrates that age-related dispositional variation influenced the propensity for unintentional mind-wandering. Additionally, different strategic oscillatory dynamics implemented by younger and older adults influenced their relative capacity and motivation to alternate between competing exploitative and explorative modes, particularly within the context of intentional mind-wandering. The present study, therefore, provides new insight into the dynamics of attentional fluctuations, propounding a more restricted oscillatory approach with advancing age. We suggest that future investigations of mind-wandering consider these strategic and dispositional factors to augment our understanding of the natural ageing process.

5.4 Methodological Considerations and Suggestions for Future Research

Notwithstanding current advances, several methodological issues merit consideration and further research. Specific limitations were addressed in the preceding chapters (§§ *2.4, 3.4.6, 4.4.4*). In the current section, several general methodological issues relating to the present work as a whole are hitherto discussed.

5.4.1 The Heterogeneity and Context-Dependency of the Mind-Wandering Experience

Perhaps the most pressing methodological consideration for research on mind-wandering owes to its inherent phenomenology as a dynamic, oscillatory, and embodied conscious experience. Ongoing mental experience is governed by features of the individual, their present context, and how they interact with said context. The heterogeneity of mental experience means that findings seeking to characterise mind-wandering are intimately linked to the choice of paradigm and environmental setting (Smallwood et al., 2021). The context-dependency of the mind-wandering experience is a central facet of the context-regulation hypothesis (Andrews-Hanna et al., 2014; Smallwood & Andrews-Hanna, 2013; Smallwood & Schooler, 2015), and indeed the exploitation/exploration framework (Sripada, 2018). It follows that the capacity to optimally oscillate between attentional states may be modulated according to changing environmental demands and uncertainties.

The experiential context interweaves dynamically with meaning content in ways that are individual but that may also be generalised to a degree if systematically tracked across different situations and with a variety of populations. The present contributions are contextualised by the specific non-demanding, continuous sustained attention lab task paradigm. Mind-wandering propensity should be further investigated across a range of task paradigms where task demands and cognitive load are manipulated to assess the degree to which an individual prioritises task-related information versus self-generated thought during differentially demanding tasks (Seli, Konishi, et al., 2018; Turnbull et al., 2019). Additionally, the present task presented little semantic variability, and therefore the amount of subjective input prompting mind-wandering may differ within richer, more semantically meaningful and vivid, real-world scenarios (Jordao et al., 2019). The impetus and freedom to explore the mind-wandering space may unfold differently for younger and older adults in open-ended, less circumscribed, natural environments (Jackson et al., 2013; Maillet et al., 2018).

Future field research should incorporate ES (Ho et al., 2020; Kane et al., 2017; Maillet et al., 2018; McVay et al., 2009) and non-invasive lifelogging technology (e.g. Gurrin et al., 2014) to enhance our understanding of the landscape of attentional experiences, and their complex temporal patterns and functional consequences within daily life. This is a potentially valuable direction for research in light of the far reaching consequences of lapsing attention in everyday life for events such as traffic accidents for younger adults (Lohani et al., 2019; Schmidt et al., 2017; Yanko & Spalek, 2013), educational and employment outcomes (e.g. Kalechstein et al., 2003; Pachai et al., 2016; Seli, Wammes, et al., 2016), and the frequency of falls in older age (Nagamatsu et al., 2013; O'Halloran et al., 2011). Research of this kind is especially valuable for younger adults given their increased proclivity toward mind-wandering at critical moments. Building on the present results, future research should investigate the phenomenological, neural, and temporal architecture of mind-wandering across different task paradigms and more naturalistic settings to isolate the task-specific patterns from more generalisable cognitive processes for younger and older adults.

5.4.2 Challenges of Cross-Sectional Research on Cognitive Ageing

5.4.2.1 Inter-Individual Variability. Stringent recruitment procedures (e.g. physical health and cognitive status screening, and age limit criteria) and convenience sampling may have favoured the selection of older adult participants who were potentially more high functioning and had fewer comorbidities (including health conditions with known links to cognitive functioning) than the wider ageing population. Indeed, our older adult participants were well-educated, and the majority had previously participated in scientific research. The recourse of such sampling is that the older adults may have been more interested in cognitive research and, possibly by extension, their own cognitive health. Similarly, the younger participant group were mostly recruited from the university in which the research was conducted and therefore, their participation may have been motivated by different factors compared to older adults. This is an especially pertinent consideration given known age-related differences in task interest and engagement and their interaction with mind-wandering frequency (Jackson & Balota, 2012; Krawietz et al., 2012; Maillet & Rajah, 2013; Shake et al., 2016). However, in the present study the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 1999) was administered before and after the task to measure specific task-induced motivation depreciation and, as such, our observed age-related discrepancy in task interest and engagement (*Chapter 2* or Moran et al., 2021) reflects a purer task-specific motivation difference.

Moreover, our older adults represented a specific "young-old" age-range (65 to 78 years). Previous research has demonstrated that cognitive deficits become more pronounced with greater age progression and with poorer education (Borella et al., 2008; Stern et al., 1992). Therefore, the narrow age range and specific demographics of the older sample may limit the generalisability of the present findings or may mask the contribution of executive resources in driving age-related mind-wandering differences (Gyurkovics et al., 2018; Jordao et al., 2019; Zavagnin et al., 2014). Indeed, mind-wandering rates have been shown to be further attenuated in conditions marked by executive deficits, including mild cognitive impairment (Niedźwieńska & Kvavilashvili, 2018), Alzheimer's disease (Gyurkovics et al., 2018; although see O'Callaghan et al., 2019), frontotemporal dementia (O'Callaghan et al., 2019), and Parkinson's disease (Geffen et al., 2017), relative to healthy older controls. The capacity to optimally oscillate between serial modes of thought may be more difficult and result in a more detrimental trade-off for individuals with more depleted cognitive resources. Therefore, grouping age distributions at either dipole may provide an incomplete picture of mind-wandering propensity over the lifespan. This speaks to the broader discussion on the relative value of age-comparative versus age change designs (Schaie, 2001).

Other inter-individual factors may moderate age trends in mind-wandering such as socio-economic status, ethnicity, cultural norms, and age-compromised sensory abilities such as visual acuity (Pitts, 1982) and visual processing speed (Owsley, 2011; Salthouse, 1996). Regarding the latter point, future research should examine whether age-related sensory deficits impact the putative saliency of bottom-up processes versus top-down modulation guiding attentional engagement. However, in the present study, within-subject baseline correction procedures for the physiological measures were conducted to facilitate group comparisons and further, we demonstrated better and more stable sensory evidence encoding, driven by an exogenous measure of visual stimulus representation (SSVEP), by older adults in comparison to their younger counterparts. Relatedly, our age differences in electrophysiological signals do not appear to reflect potential age-related structural differences but rather pertain to resource or strategic differences between younger and older adults. For instance, our findings demonstrated that some signals showed the same amplitude between groups, whereas other specific signals such as the timing of evidence accumulation onset were different. Furthermore, some signals (like the phasic pupil diameter response to target) were more robust in older than younger adults. Together, it seems unlikely that structural decline was the common denominator for these findings.

5.4.2.2 Intra-Individual Variability. The aforementioned potential limitations are, by design, embedded within cross-sectional research of this kind. Longitudinal approaches with larger and more diverse samples may thus be better suited for capturing attentional changes with age (e.g. Fortenbaugh et al., 2015). Longitudinal age trends may capture within-subject variability to determine developmental influences on the progression of mind-wandering tendencies at different stages across the lifespan. Given the oscillatory nature of attentional engagement, multiple assessments over time may help to dissociate shorter- from longer-term fluctuations in mind-wandering and evaluate the predictive abilities of the previously documented mediators for longer-term outcomes. A longitudinal approach would obviate age group clustering and limit the potential misattribution of results to age effects versus other qualitative group differences or artefactual differences arising from the research design. Moreover, larger and more cognitively diverse samples may increase the number of usable trial counts enabling more fine-grained neurophysiological examinations to be conducted to delineate the patterns of different mind-wandering experiences.

On the other hand, no design is without its challenges, for example, longitudinal investigations are also subject to attrition, learning effects, and other biases. Cross-sectional research is, therefore, valuable to pinpoint mechanisms worthy of further empirical scrutiny and may inform the development of novel investigative or remedial strategies for attentional deficits. Nonetheless, future research should move beyond chronological age characterisations that view ageing as a linear and homogenous construct and instead look at the relative contribution of cognitive reserve variables that welcome the wider context and lived experience of the individual. It is vital that such studies evaluate the changes and underlying mechanisms that represent adaptive compensatory strategies underpinning successful ageing, from maladaptive patterns that may indicate or pre-empt cognitive impairment.

5.5 Practical Implications of the Present Research

The next frontier of research should utilise the knowledge advanced by basic research and examine the translational applicability and validity of various techniques for ameliorating attentional deficits in certain populations (e.g. those with neuropsychiatric disorders and widespread cognitive impairment or depleted executive resources) in the short and long-term. Given the association between mind-wandering and dispositional factors, interventions may offer dual benefits for curbing cognitive decline as well as enhancing emotional well-being.

Mind-wandering may confer benefits or consequences depending on how it is applied relative to the demands of the ongoing context. Affordance of an opportunity to mind-wander when the context allows promotes meaning-making, generative modes of creativity and problem-solving, and underpins reflective recollection and anticipatory prospective modes of thinking. From the present study, mind-wandering has also been shown to be associated with performance decrements and reduced sensory evidence tracking and delayed decision-making. Against the backdrop of reduced cognitive resources in older adults, translational research may seek to: a) develop methods that propagate an adaptive and balanced oscillation of mind-wandering for older adults to confer the benefits of spontaneous thought without unduly affecting performance, and b) minimize the detrimental trade-off of mind-wandering at critical moments which may be especially pertinent for younger adults who demonstrate a greater proclivity for off-task thought. Four potential techniques that may be useful in this regard are discussed.

Number One: The cultivation of mindfulness meditation practices, which promote a moment-to-moment awareness, openness, and compassion toward one's ongoing thoughts, may produce translational benefits for the wandering mind (for a review see Brandmeyer & Delorme, 2021). Such contemplative practice may increase meta-awareness of mental states, enhance top-down cognitive control, decrease the level of oscillatory shifts between focused and mind-wandering states, and offset time-on-task performance decrements (Brefczynski-Lewis, Lutz, Schaefer, Levinson, & Davidson, 2007; Brewer et al., 2011; Melnychuk et al., 2018; Mrazek et al., 2013; Tang et al., 2009). Moreover, meditation may enhance equanimity and emotional regulation (Brandmeyer & Delorme, 2021; Tang et al., 2007), which is of particular relevance given the intimate link between affect and mind-wandering propensity (*Chapter 2*). Additionally, supporting neural evidence has demonstrated structural changes in brain regions implicated in attention, monitoring, and sensory processing (i.e. the prefrontal cortex and right anterior insula) in experienced meditators relative to matched controls, a finding which was particularly pronounced in older aged practitioners (Lazar et al., 2005). This suggests that regular meditation may offer a specialized protective effect against age-accompanied cognitive decline and enhance cortical plasticity, important for older adult groups vulnerable to depleting cognitive resources (see also Gard, Holzel, & Lazar, 2014). Given the particularly oscillatory nature of attentional experiences in younger adults, and their predisposition toward negatively valent affect, meditation may offer particular translational cognitive and affective benefits for this age group.

Number Two: Transcranial direct current stimulation (tDCS) over targeted areas, such as the right dorsolateral prefrontal cortex, may represent another promising non-invasive approach for enhancing sustained attention abilities, mitigating performance decrements over time, and providing a potential neurocognitive buffer against cognitive decline (Nelson, McKinley, Golob, Warm, & Parasuraman, 2014; Nitsche & Paulus, 2000). In support, there have been some preliminary improvements observed in various cognitive domains in older adults (e.g. Berryhill & Jones, 2012; Boggio et al., 2010; Meinzer, Lindenberg, Antonenko, Flaisch, & Floel, 2013). This technique may be useful for younger adults who demonstrate a greater proclivity toward variable attentional engagement during sustained attention tasks, as well as within daily life settings. Further, older adults who experience greater cognitive decline than in the present study may benefit from a tool which aids their capacity for optimal strategic regulation of attentional resources according to external demands, particularly when this exploration may offer translational benefits with respect to problem-solving, creativity, etc. However, its potential efficacy as a device for modulating cognitive function has also been disputed (see Horvath, Forte, & Carter, 2015; Steenbergen et al., 2016). Hence, before this technique can be implemented in commercial or clinical contexts, further work is needed to assess the feasibility and utility of tDCS for ameliorating attentional deficits in the shorter- and longer-term, and to examine how these benefits translate from the lab to everyday settings.

Number Three: Research on oscillatory mental states and their behavioural and physiological correlates may be leveraged to inform the development of covert and automated investigative approaches and remedial strategies. With regard to the former, functional magnetic resonance imaging (fMRI) (e.g. Laufs et al., 2003; Mantini et al., 2007) and supervised machine learning algorithms (e.g. Faber, Bixler, & D'Mello, 2018; Kragel et al., 2016; Rosenberg et al., 2020; Tusche et al., 2014) may be used to complement, or eventually succeed, self-report as a means of measuring and predicting momentary changes in attentional state. Furthermore, pupillometry in the field may also offer a useful online and unobtrusive physiological measure to chart arousal and attention allocation changes in real-time. For example, fluctuations in PD have been used to index alertness and drowsiness during driving (Maccora, Manousakis, & Anderson, 2019; Schmidt et al., 2017), although its feasibility in the field needs to be further examined, particularly in ageing. Finding reliable psychophysiological markers of different attentional states (as the present research has made strides towards doing) may ultimately circumvent the need to use ES. Indices of mind-wandering may instead be detected covertly from the physiology without the need for experience interruption.

Number Four: These methods may also have potential rehabilitative applications for clinical or neurodegenerative disorders of attention or those characterised by greater explorative tendencies (e.g. attention deficit hyperactivity disorder, obsessive compulsive disorder, dementia syndromes, and Parkinson’s disease). For example, training through closed-loop neurofeedback or biofeedback paradigms using fMRI, brain computer interfaces, or machine learning may aid an individual to detect, appraise, and strategically regulate their mental states. Additionally, aside from acting as a biomarker to predict or notify attention lapses, PD may be used as an indicator of response to treatment; for example, to assess the benefit of pharmaceutical treatments that target the noradrenergic system (e.g. Dockree et al., 2017; Loughnane et al., 2019).

5.6 Concluding Remarks

The mind-wandering experience is a core mental state, foundational to our personhood and inner mental life, and influential in how we interact with the “life-world” (to borrow a concept from Husserlian phenomenology, Schutz & Luckmann, 1973). Despite its ubiquity and potential functional impact, the crucial dynamics underlying mind-wandering in healthy ageing remain poorly understood. This is a timely issue given the documented trend of global population ageing. The puzzling finding of age-accompanied diminution in mind-wandering stands seemingly opposed to conventional wisdom and poses a direct challenge to theoretical accounts that present mind-wandering as an executive control failure. Moreover, the important mind-wandering intentionality distinction has been relatively precluded from consideration in the extant cognitive ageing literature. Therefore, the primary focus of this thesis was to elucidate the nature of dissociable and dynamically evolving attentional states within healthy younger and older adults.

Extending the state-of-the-art on mind-wandering research, this thesis provides deeper insights into some of the essential phenomenal properties, neuropsychological and neurophysiological signatures, and temporal features appurtenant to age-related mind-wandering. We propel distinct dispositional and strategic factors that individuate unintentional and intentional mind-wandering experiences, and their transitions over time, for younger and older adults. Beyond solely documenting these effects, the current research presents a number of outstanding avenues for further investigation that may inform future translational applied research aimed at preserving cognitive function in ageing. Collectively, the current research demonstrates that our inner mental life is a worthy topic for empirical evaluation and provides incremental theoretical advances that may contribute to the burgeoning “era of the wandering mind”.

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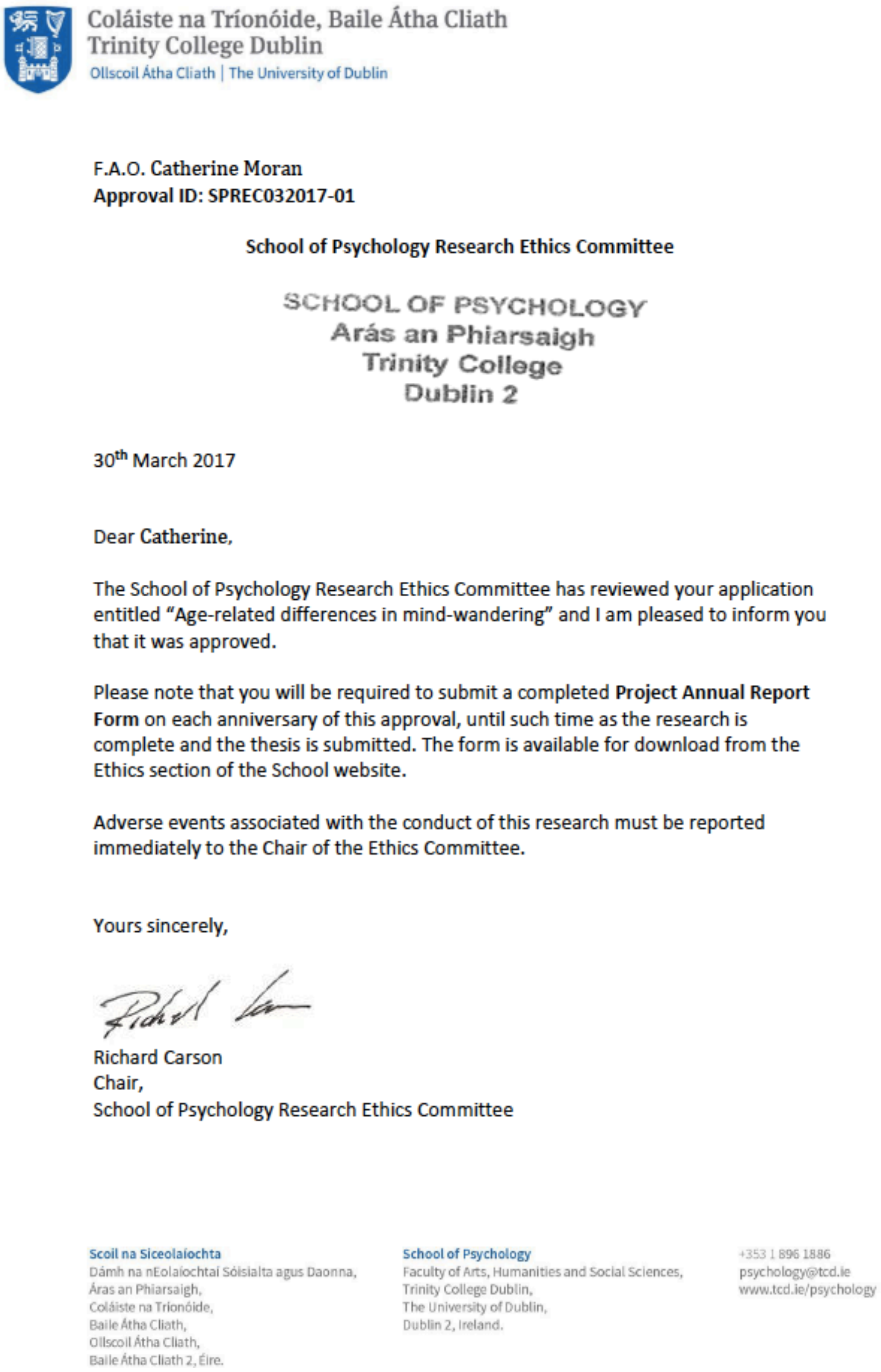
Appendices

Appendix A: Ethical Approval



Coláiste na Tríonóide, Baile Átha Cliath
Trinity College Dublin
Ollscoil Átha Cliath | The University of Dublin

F.A.O. Catherine Moran
Approval ID: SPREC032017-01

School of Psychology Research Ethics Committee

SCHOOL OF PSYCHOLOGY
Arás an Phiarsaigh
Trinity College
Dublin 2

30th March 2017

Dear Catherine,

The School of Psychology Research Ethics Committee has reviewed your application entitled "Age-related differences in mind-wandering" and I am pleased to inform you that it was approved.

Please note that you will be required to submit a completed **Project Annual Report Form** on each anniversary of this approval, until such time as the research is complete and the thesis is submitted. The form is available for download from the Ethics section of the School website.

Adverse events associated with the conduct of this research must be reported immediately to the Chair of the Ethics Committee.

Yours sincerely,

Richard Carson
Chair,
School of Psychology Research Ethics Committee

Scoil na Siceolaíochta
Dámh na nEolaíochtaí Sóisialta agus Daonna,
Áras an Phiarsaigh,
Coláiste na Tríonóide,
Baile Átha Cliath,
Ollscoil Átha Cliath,
Baile Átha Cliath 2, Éire.

School of Psychology
Faculty of Arts, Humanities and Social Sciences,
Trinity College Dublin,
The University of Dublin,
Dublin 2, Ireland.

+353 1 896 1886
psychology@tcd.ie
www.tcd.ie/psychology

Appendix B: Participant Information Leaflet and Consent Form

PARTICIPANT INFORMATION LEAFLET

PROJECT TITLE: Investigating age-related differences in mind-wandering

Investigators: PhD Candidate Catherine Moran, Research Assistants Rónán Ó Grálaigh

& Greta Warren, & Dr Paul Dockree

You are invited to participate in a research study exploring the impact of ageing on mind-wandering. Please read through this Participant Information Leaflet so that you understand the purpose and nature of the research and what your involvement will entail. If you would like to proceed with the study, we will ask you to sign two copies of a consent form – one for our research team and one for you to retain. If you would like clarification about any of the details within, please ask and we will be happy to provide further explanation. Please take as much time as you need to read this form. Thank you for your interest in this study.

Purpose of the Study:

When the mind wanders, attention changes its focus from external sources (e.g. task demands) to internal mental content. Although there is a large tradition of exploring attention, less is known about what happens in the brain when the mind wanders. At present, we know very little about how ageing influences our propensity to mind-wander. Given the constant growth of the elderly population worldwide, it has become important to investigate different spontaneous and intentional cognitive processes and explore how they change with age.

Who can take part in this study?

Participants must be aged:
- Between 18 and 35 years
- OR Between 65 and 80 years.

All participants must fulfil the following **inclusion criteria**:
- No personal or family history of epilepsy
- No personal or family history of unexplained fainting
- No sensitivity to flickering light
- No personal neurological or psychiatric illness or brain injury
- Normal or corrected-to-normal vision.

Do I have to take part?

Participation in this study is entirely voluntary and you are free to withdraw from the study at any time, without giving a reason and without penalty or consequence. If you choose to withdraw during testing, all data relating to you will be destroyed immediately. If having completed testing, you wish to withdraw your data retrospectively from the study, you will be free to do so up until the point that the data are grouped for analysis. A decision to withdraw, or a decision not to take part, will not affect your legal rights in any way.

What will happen to me if I take part?

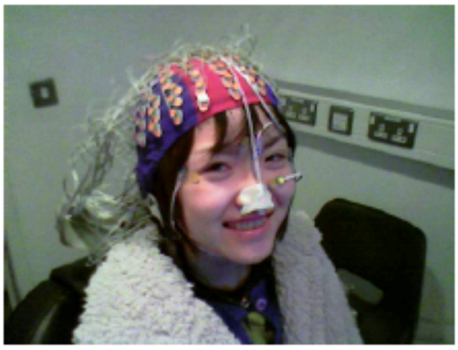
If you are eligible to take part and provide informed consent, you will be invited to complete **two testing sessions** in the Trinity College Institute of Neuroscience, Lloyd Building.

The first session should last approximately **1 hour**, and your final session will not exceed **3 hours**.

At the first session, we will ask you to fill out a short questionnaire providing basic demographic information and ask you to undertake brief assessments measuring aspects of your cognitive functioning, including attention and memory tasks, and mood questionnaires.

At the second session, you will then be guided to a laboratory where you will perform a computerised sustained attention task. This task requires you to monitor a persistent flickering stimulus on a desktop screen and to press a button to indicate when you are certain that the contrast of the image is fading. The task will be interrupted intermittently to ask you questions about whether your thoughts at that moment are focused or mind-wandering. Adequate training and practice, as well as regular brief breaks will be provided.

While you are performing the computerised attention task, electrical changes in your brain will be recorded using electroencephalography (EEG). In addition, the position of your eye and pupil dilation will be monitored using a remote eye-tracker. The recording of EEG involves a special cap (as below):



Conductive gel is used to form a link between small electrodes and your scalp. The experience is very comfortable, but it does mean that you will have water soluble gel in your hair at the end of the experiment. This gel washes out easily and you can wash it out quickly in a specially fitted sink in the Institute of Neuroscience.
(Shampoo, towels, and hairdryer are provided)

Safety and Risk:

There are no risks associated with any of the procedures in neurologically healthy individuals; however, if you meet any of the following criteria you should not participate in this experiment:

- Personal or family history of epilepsy
- Personal history of unexplained fainting
- Sensitivity to flickering light
- Personal history of neurological or psychiatric illness or brain injury

EEG and eye-tracking are safe, non-invasive procedures commonly used in this field. Researchers are well-trained on these techniques and standard procedure for EEG recording and participant safety will be followed. All equipment will meet Irish safety standards. If you are uncomfortable during the testing session, you may terminate your participation with immediate effect and without consequence.

Regular rest breaks will be provided to minimise any potential experimental fatigue. In the unlikely event that you experience any psychological distress from your participation in this study, please contact principle investigator Dr Paul Dockree, Trinity College Dublin Student Counselling Service or the Samaritans (contact details are provided below). Finally, if there is a possibility we show concern over your test scores, we may advise you to contact your G.P. Upon request, and with your prior consent, we may provide him/her with your raw data.

Confidentiality:

All information you supply to us in hard copy (i.e., completed questionnaires and the present form) will be held in confidence, and stored in secure facilities. The documents will be destroyed after a period of twelve months. All digital files (i.e. data collected during the study) will be stored in an anonymized format. Only research staff directly associated with the project will have access to this material. Your data will only be used for scientific purposes. Your data will not be subject to further processing that is incompatible with the purpose of the present study. You can have access to any identifiable information we store about you, if requested.

Confidentiality may be breached in circumstances in which:

a) The Investigator has a strong belief or evidence exists that there is a serious risk of harm or danger to either the participant or another individual. This may relate to issues surrounding physical, emotional or sexual abuse, concerns for child protection, rape, self-harm, suicidal intent or criminal activity.

b) Disclosure is required as part of a legal process or Garda investigation. In such instances information may be disclosed to significant others or appropriate third parties without permission being sought. Where possible a full explanation will be given to the participant regarding the necessary procedures and intended actions that may need to be taken.

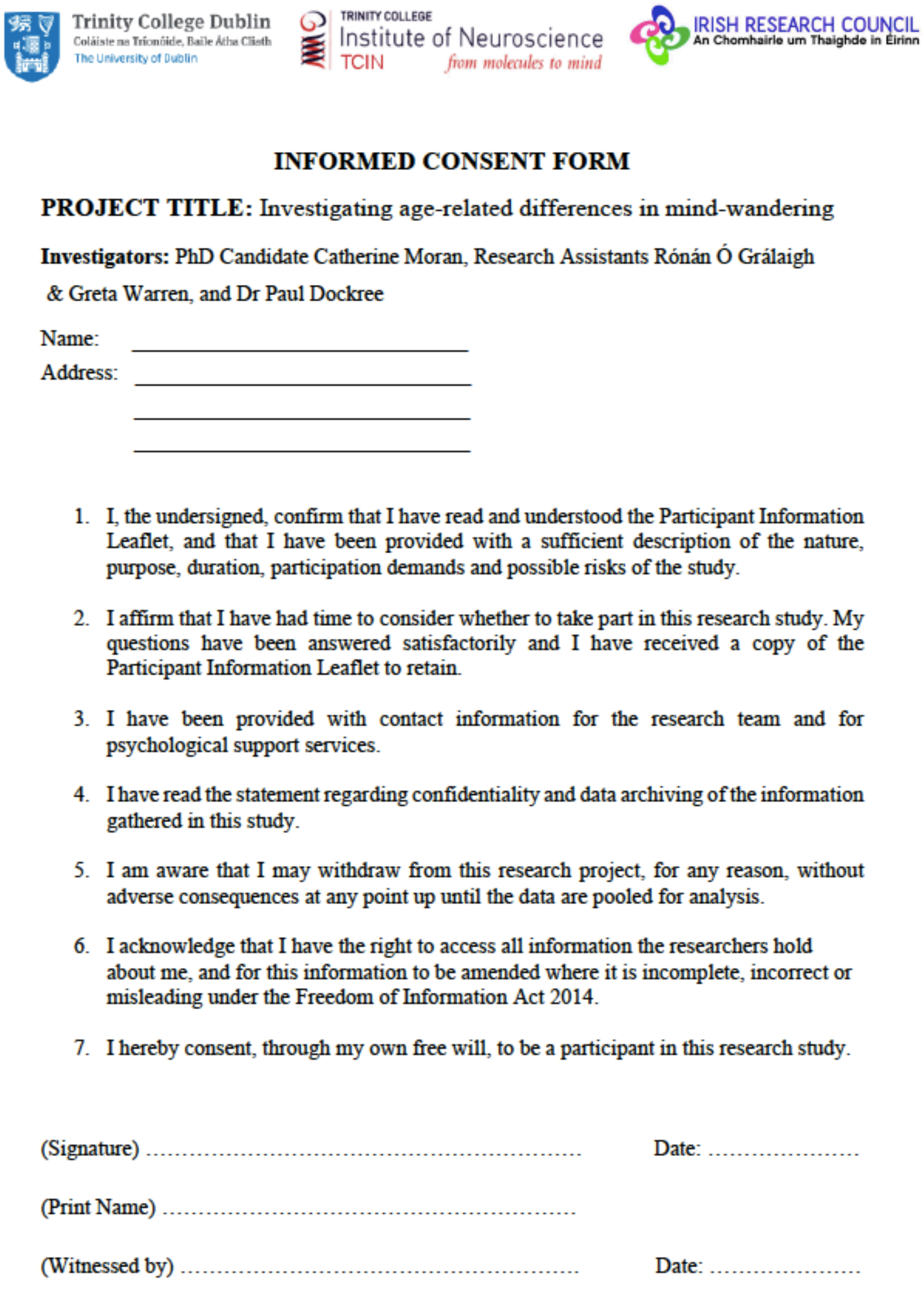
Data Management, Storage and Archiving:

1. Participant consent forms will be stored in a locked filing cabinet in a secure office in Trinity College Institute of Neuroscience, Lloyd building.
2. The master sheet containing the key linking participant names and their corresponding code numbers will be encrypted and stored on a password protected computer.
3. All physical documents will be kept in a locked filing cabinet, distinct from that used to store the consent forms. The data files will be stored on a secure password protected computer and backed up on an encrypted USB drive. Only the named investigators (the researcher and supervisor) will have access to these documents.
4. Under the Freedom of Information Act 2014, you have the right to access all information we hold about you, and for this information to be amended where it is incomplete, incorrect or misleading.

Ethical Approval:

This study has been approved by the School of Psychology Research Ethics Committee, Trinity College Dublin, in accordance with the Meta-Code of Ethics of the European Federation of Professional Psychologists' Associations (1995).

Research Team	**Catherine Moran** PhD Candidate, IRC Postgraduate Scholar School of Psychology Áras an Phiarsaigh, Trinity College, Dublin 2 Phone: 01-8968403 Email: cmoran5@tcd.ie **Rónán Ó Grálaigh** Research Assistant School of Psychology Áras an Phiarsaigh, Trinity College, Dublin 2 Email: ogralair@tcd.ie	**Greta Warren** Research Assistant School of Psychology Áras an Phiarsaigh, Trinity College, Dublin 2 Email: warrengr@tcd.ie **Dr Paul Dockree** Lecturer in Psychology School of Psychology Áras an Phiarsaigh, Trinity College, Dublin 2 Phone: 01-8963910 Email: dockreep@tcd.ie
Support Services	**Student Counselling Service** 3rd floor, 7 – 9 South Leinster Street Phone: 01-8961407 Email: student-counselling@tcd.ie	**The Samaritans** 151 Marlborough Street, Dublin 1 Phone: 01-8727700 Email: jo@samaritans.org



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TRINITY COLLEGE
Institute of Neuroscience
TCIN *from molecules to mind*

IRISH RESEARCH COUNCIL
An Chomhairle um Thaighde in Éirinn

INFORMED CONSENT FORM

PROJECT TITLE: Investigating age-related differences in mind-wandering

Investigators: PhD Candidate Catherine Moran, Research Assistants Rónán Ó Grálaigh & Greta Warren, and Dr Paul Dockree

Name: ______________________________
Address: ______________________________
____
____

1. I, the undersigned, confirm that I have read and understood the Participant Information Leaflet, and that I have been provided with a sufficient description of the nature, purpose, duration, participation demands and possible risks of the study.
2. I affirm that I have had time to consider whether to take part in this research study. My questions have been answered satisfactorily and I have received a copy of the Participant Information Leaflet to retain.
3. I have been provided with contact information for the research team and for psychological support services.
4. I have read the statement regarding confidentiality and data archiving of the information gathered in this study.
5. I am aware that I may withdraw from this research project, for any reason, without adverse consequences at any point up until the data are pooled for analysis.
6. I acknowledge that I have the right to access all information the researchers hold about me, and for this information to be amended where it is incomplete, incorrect or misleading under the Freedom of Information Act 2014.
7. I hereby consent, through my own free will, to be a participant in this research study.

(Signature) .... Date: ....

(Print Name) ....

(Witnessed by) .... Date: ....

Appendix C: Participant Debriefing Document

DEBRIEFING DOCUMENT

PROJECT TITLE: Investigating age-related differences in mind-wandering

Investigators: PhD Candidate Catherine Moran, Research Assistants Rónán Ó Grálaigh & Greta Warren, & Dr Paul Dockree

Dear Participant,

Thank you for taking part in this study investigating age-related differences in mind-wandering. This is an important area to investigate as it will provide insight into how the brain changes with age.

Study Background

It is widely accepted that cognition declines with advanced age. Older adults may experience predictable age-associated compromises in their memory, attention and executive functioning that may significantly impair their capacity to cope with daily demands. The population growth of elderly people worldwide is increasing. Indeed, it is expected that over 22% of the Irish population will be aged 65 or older by 2041. As such, it is imperative to investigate different spontaneous and intentional cognitive processes and explore how they change with age. This information will be vital for our understanding of the brain, and will help inform future interventions for healthy ageing. However, at present, very little is known about how ageing influences our propensity to mind-wander or what happens in the brain when mind-wandering occurs.

Research Aims

This study aimed to look at differences in the frequency and type of mind-wandering occurring for young and older adult participants. In addition, we were interested in exploring what cognitive, neuropsychological and electrophysiological (electrical brain recordings and pupil dilation) variables were associated with more or less mind-wandering.

Mind-Wandering Research

In the last decade, there has been a growth in research attention focusing on consciousness and mind-wandering. Recent studies suggest that individuals spend between 25% and 50% of their waking hours involved in mind-wandering or self-generated thought. When mind-wandering occurs, attention shifts from focusing on information cued from the environment towards inward mental content. People are not always aware of when they mind-wander and this can have implications for individual safety, for example during driving.

Given that the process of mind-wandering is not outwardly observable, this has made measurement of the occurrence and frequency of mind-wandering more challenging. In order to assess mind-wandering, we use multiple methods (triangulation) to gain a more comprehensive picture of the process. In this study, we investigated mind-wandering through:

1. Experience sampling – self-report questions during the computerised attention task that asked you about the content of your thought at that moment.
2. Behavioural measures – your reaction time on the computerised attention task.
3. Indirect measures – electrical brain signals, eye movements and pupil dilation to measure your alertness and attention.

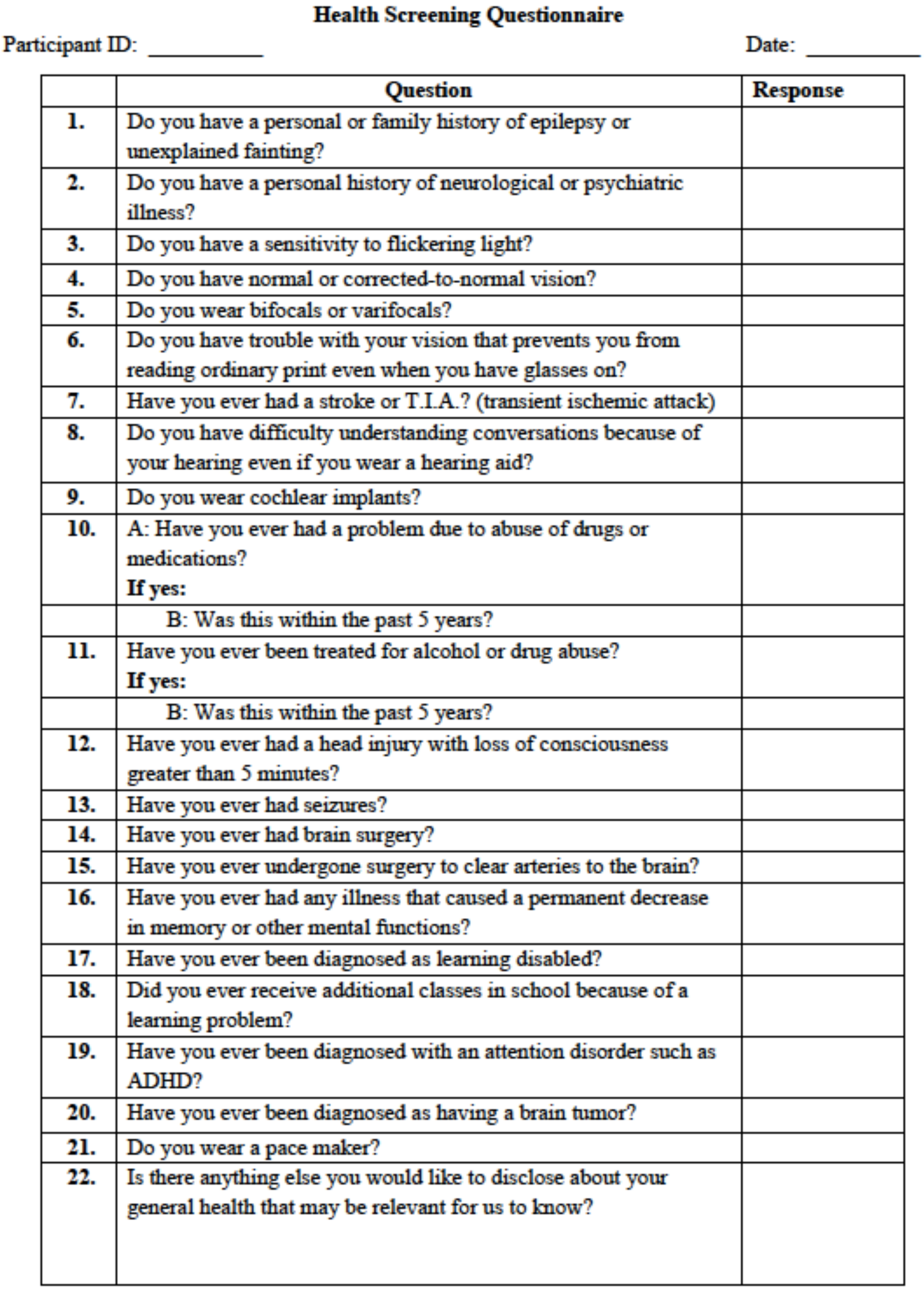
This paradigm has made it possible to explore the impact of ageing on the separable components of mind-wandering (when attention lapses and turns inward). By comparing younger and older adults, we hope to gain insight into how mind-wandering changes with age.

Contact:

If you have any questions about the study, please do not hesitate to contact a member of the research team. We would like to remind you that your data will remain confidential and that you are free to withdraw your data from the study at any point until data are grouped for analysis. If you have experienced any distress from taking part in this study, please contact the support services listed below.

Research Team	**Catherine Moran** PhD Candidate, IRC Postgraduate Scholar School of Psychology Áras an Phiarsaigh, Trinity College, Dublin 2 Phone: 01-8968403 Email: cmoran5@tcd.ie **Rónán Ó Grálaigh** Research Assistant School of Psychology Áras an Phiarsaigh, Trinity College, Dublin 2 Email: ogralair@tcd.ie	**Greta Warren** Research Assistant School of Psychology Áras an Phiarsaigh, Trinity College, Dublin 2 Email: warrengr@tcd.ie **Dr Paul Dockree** Lecturer in Psychology School of Psychology Áras an Phiarsaigh, Trinity College, Dublin 2 Phone: 01-8963910 Email: dockreep@tcd.ie
Support Services	**Student Counselling Service** 3rd floor, 7 – 9 South Leinster Street Phone: 01-8961407 Email: student-counselling@tcd.ie	**The Samaritans** 151 Marlborough Street, Dublin 1 Phone: 01-8727700 Email: jo@samaritans.org

Appendix D: Participant Recruitment Health Screening Questionnaire



Health Screening Questionnaire

Participant ID: __________ Date: __________

	Question	Response
1.	Do you have a personal or family history of epilepsy or unexplained fainting?	
2.	Do you have a personal history of neurological or psychiatric illness?	
3.	Do you have a sensitivity to flickering light?	
4.	Do you have normal or corrected-to-normal vision?	
5.	Do you wear bifocals or varifocals?	
6.	Do you have trouble with your vision that prevents you from reading ordinary print even when you have glasses on?	
7.	Have you ever had a stroke or T.I.A.? (transient ischemic attack)	
8.	Do you have difficulty understanding conversations because of your hearing even if you wear a hearing aid?	
9.	Do you wear cochlear implants?	
10.	A: Have you ever had a problem due to abuse of drugs or medications? **If yes:**	
	B: Was this within the past 5 years?	
11.	Have you ever been treated for alcohol or drug abuse? **If yes:**	
	B: Was this within the past 5 years?	
12.	Have you ever had a head injury with loss of consciousness greater than 5 minutes?	
13.	Have you ever had seizures?	
14.	Have you ever had brain surgery?	
15.	Have you ever undergone surgery to clear arteries to the brain?	
16.	Have you ever had any illness that caused a permanent decrease in memory or other mental functions?	
17.	Have you ever been diagnosed as learning disabled?	
18.	Did you ever receive additional classes in school because of a learning problem?	
19.	Have you ever been diagnosed with an attention disorder such as ADHD?	
20.	Have you ever been diagnosed as having a brain tumor?	
21.	Do you wear a pace maker?	
22.	Is there anything else you would like to disclose about your general health that may be relevant for us to know?	

Appendix E: Mind-Wandering Probe Instructions Sheet

Mind-Wandering Probe Instructions

In everyday life, you may find yourself mind-wandering or thinking about things that are either loosely bound, or entirely removed from, the here-and-now. Even during lab tasks, people may think about things that are unrelated to the task at hand; this type of thought is known as **“task-unrelated thought”**. Task-unrelated thoughts are a normal and frequent feature of every day cognition, especially during long and tedious tasks.

In this study, we are interested in seeing how frequently people’s thoughts stray away from the task they are completing. To explore this, we are asking you to complete a task. Every so often this task will momentarily stop, and you will be presented with a question screen that asks you to take note of where your thoughts were immediately before the question appeared. You will then be required to indicate if your thoughts at that time were focused on the task, or were ‘task-unrelated thoughts’.

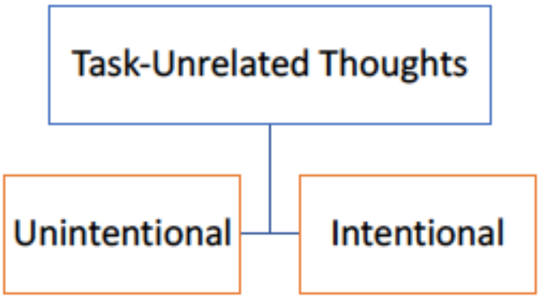
If you are **focused on the task**, this means that just before the question screen appeared, you were paying attention to some aspect related to the task. For example, you may have been looking for a target, thinking about making a button press, wondering about your performance, or how long the task will last, and so on. These types of thoughts are: ‘focused on the task’.

Focused on the task

You may also experience **task-unrelated thoughts**. This means that just before the question screen appeared, you were thinking about something other than the task. For example, you might be thinking about your grocery list, or about your transport home, an upcoming holiday, or you might be recounting a conversation you had with a friend that morning, and so on. Any thoughts like these that are entirely unrelated to the task are known as 'task-unrelated thoughts'.

Task-unrelated thoughts

Another important distinction is that these task-unrelated thoughts can occur because you unintentionally or intentionally thought about things other than the task.



Your mind may have **unintentionally** drifted away despite your best efforts to engage with the task. For example, have you ever had the experience of reaching the end of a paragraph and realizing that you did not take in anything you were reading? Despite you trying, your mind was elsewhere, unintentionally. Another example of unintentional mind-wandering would be the experience of 'mind-blanking', or 'zoning out'.

Alternatively, on other occasions you may have made the decision to **intentionally** disengage from the task in order to think about something else. This is more guided thought. For example, you might disengage from the task at hand to plan your to do list for that evening.

Mind-wandering Probe

In this study, the task will be intermittently interrupted with a question screen (otherwise known as a mind-wandering probe). We want you to check in with your thoughts that occurred immediately prior to the question screen, and to indicate if you were focused on the task, or if you were experiencing task-unrelated thoughts. If you had task-unrelated thoughts – were unintentional or intentional? The question screen, or mind-wandering probe, will look like this:

"Choose the response that best describes your mental state right before this screen appeared:

1) **Focused on the task**
2) **Unintentionally lost focus on the task**
3) **Intentionally disengaged from the task"**

You will then press a button on the right of your keyboard from 1-3 to indicate where your thoughts were prior to the presentation of the screen. The task will then resume.

Appendix F: Published Abstract

Moran, C., McGovern, D., Warren, G., Ó Grálaigh, R., Kenney, J., Smeaton, A., & Dockree, P. (2021). Young and restless, old and focused: Age-related differences in mind-wandering. *Psychology and Aging*. https://psycnet.apa.org/doi/10.1037/pag0000526

Abstract

The consistently observed age-accompanied diminution in mind-wandering stands seemingly opposed to accounts that present mind-wandering as a failure of executive control. This study examined the impact of aging on the frequency and phenomenology of mind-wandering and investigated distinct variables mediating age-related differences in unintentional and intentional mind-wandering. Thirty-four younger and 34 healthy older adults completed a neuropsychological test battery and contrast change detection task embedded with experience sampling probes asking participants to discriminate the nature of their thoughts. Results revealed age-related decreases in unintentional and intentional mind-wandering, but equivalent task accuracy. Parallel mediations demonstrated that older adults reduced their unintentional mind-wandering through having less anxiety and greater task engagement than younger adults. Despite evidence of age-related decline on cognitive function tests, neither executive function nor task demand variables further contributed to the model. Our results adjudicate between competing theories, highlighting the roles of affective and motivational factors in unintentional mind-wandering. Intentional mind-wandering showed no significant associations with the neuropsychological measures; however, intentional mind-wandering was associated with more false alarms, which was mediated by greater reaction time variability (RTV). In the context of the exploitation/exploration framework, we suggest that younger adults were more inclined to intentionally mind-wander, indexed by increased RTV, while preserving comparable performance accuracy to older adults. Conversely, older adults exploited greater task focus, marked by reduced RTV, with less bias toward, or resources for, exploration of the mind-wandering space. Therefore, dispositional and strategic factors should be considered in future investigations of mind-wandering across the lifespan.

Keywords: cognitive aging, mind-wandering, intentionality, negative affect, motivation