Age-Related Changes in Cognitive Processing

Submitted by

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List of Abbreviations in Text

AD	Alzheimer’s disease
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
ANS	Autonomic Nervous System
ANT	Attention Network Task
BDNF	Brain-Derived Neurotrophic Factor
CRUNCH	Compensation-Related Utilization of Neural Circuits Hypothesis
Cod	Coding
CSVD	Cerebral Small Blood Vessel Disease
DA	Dopamine
Gc	Crystallized Intelligence
Gf	Fluid Intelligence
HAROLD	Hemispheric Asymmetry Reduction in Older Age model
HPA	Hypothalamic-Pituitary-Adrenal axis
M	Magnocellular
MCI	Mild Cognitive Impairment
MMSE	Mini-Mental State Exam
P	Parvocellular
PET	Positron Emission Tomography
PFC	Prefrontal Cortex
PSI	Processing Speed Index
IT	Inspection Time
RAN	Rapid Automatic Naming
RAPM	Ravens Advanced Progressive Matrices
RAVLT	Rey Auditory Verbal Learning Test
SN	Substantia Nigra
SNS	Sympathetic Nervous System
SRT	Saccade Reaction Time
SS	Symbol Search
STAC	Scaffolding Theory of Aging and Cognition

TIA	Transient Ischemic Attack
TNF	Tumor Necrosis Factor
U3A	University of the Third Age
UHEC	University Human Ethics Committee
V1	Primary Visual Cortex
VCE	Victorian Certificate of Education
VPEST	Visual Parameter Estimation by Sequential Testing
VTA	Ventral Tegmental Area
WAIS	Wechsler Adult Intelligence Scale
WM	Working Memory
WCST	Wisconsin Card Sorting Test

Publications and Manuscripts Related to this Thesis

Chapter 2 (Manuscript)

Ebaid, D. & Crewther, S. G. (2019). Time for a Systems Biological Approach to Cognitive Aging? –A Critical Review, *Frontiers in Aging Neuroscience* **(Accepted for Publication).**

Chapter 4

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A. & Crewther, D. P. (2017) Cognitive processing speed across the lifespan: beyond the influence of motor speed. *Frontiers in Aging Neuroscience 9*(62) doi: 10.3389/fnagi.2017.00062

Chapter 5

Ebaid, D., & Crewther, S. G. (2019). Visual information processing in young and older adults, *Frontiers in Aging Neuroscience, 11*: 116. DOI: 10.3389/fnagi.2019.00116

Chapter 6 (Manuscript)

Ebaid, D., MacCalman, K., & Crewther, S.G. The contribution of oculomotor function to visual information processing in young and older adults*, Nature Scientific Reports* **(Accepted for Publication).**

Chapter 7

Ebaid, D., & Crewther, S. G. (2018). Temporal aspects of memory: a comparison of memory performance, processing speed and time estimation between young and older adults. *Frontiers in Aging Neuroscience*, 10; 352 DOI: 10.3389/fnagi.2018.00352

Presentations Related to this Thesis

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Ebaid D. (2019). Cognitive processing across the lifespan- The role of vascular anomalies in aging. *Clinical Neuroscience and Neuropsychology Undergraduate Lecture*, La Trobe University, Melbourne, Australia. **(Oral Presentation – University Lecture)**

Crewther, S. G. & Ebaid D. (2019, May). Oculomotor function during rapid automatised naming in young and older adults. *Vision Science Society (VSS) 19th Annual Meeting,* St Pete Beach, Florida, USA **(Poster Presentation)**

2018

Ebaid, D. & Crewther, S. G. (2018, August). Temporal aspects of working memory: A comparison of working memory performance and time estimation between young and older adults. *La Trobe University Research Showcase- John Scott Meeting House, La Trobe University,* Melbourne, Australia **(Poster Presentation)**

Ebaid, D. & Crewther, S. G. (2018, July). Temporal aspects of working memory: A comparison of working memory performance and time estimation between young and older adults. *Higher Degree by Research Seminar- La Trobe University,* Melbourne, Australia **(Oral Presentation)**

Ebaid, D. & Crewther, S. G. (2018, November). Oculomotor function during rapid automatised naming and its correlation to cognitive speed in young and older adults, 8th *Australasian Cognitive Neuroscience Society Conference (ACNS)*, Melbourne University**,** Melbourne, Victoria **(Poster Presentation).**

Ebaid, D. & Crewther, S. G. (2018, December). Oculomotor function during rapid automatised naming and its correlation to cognitive speed in young and older adults, *School of Psychology and Public Health Research Festival, La Trobe University,* Melbourne, Victoria **(Oral Presentation).**

2017

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A. & Crewther, D. P. (2017, November). Speed of information processing for simple visual perceptual and more complex salient cognitive tasks in young and older adults, *7th Australasian*

Cognitive Neuroscience Society Conference (ACNS), Adelaide, South Australia **(Poster Presentation)**

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A. & Crewther, D. P. (2017, October). Cognitive processing speed across the lifespan: Beyond the influence of motor speed, *23rd International Conference on Psychology & Language Research (ICPLR),* Dubai, United Arab Emirates **(Oral Presentation)** **Awarded Best Overall Presentation*

Ebaid, D. & Crewther, S. G. (2017, July). Cognitive processing across the lifespan, *Post Graduate Presentation Seminar*- La Trobe University, Melbourne, Australia **(Oral Presentation)**

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A. & Crewther, D. P. (2017, April). Cognitive processing across the lifespan, *La Trobe University Hallmark Program*, Melbourne, Australia **(Oral Presentation)**

2016

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A. & Crewther, D. P. (2016, November). Cognitive processing speed across the lifespan: Beyond the confounds of motor speed, *Students of Brain Research Symposium*, RMIT University, Melbourne, Australia (Poster Presentation)

Ebaid, D., Crewther, S. G., & Peters, J. (2016, October). The contribution of rate of visual processing to cognition in healthy aging. *Western Hospital Research Showcase* – Footscray Hospital, Melbourne, Australia, **(Poster Presentation)**

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A. & Crewther, D. P. (2016, October). Cognitive processing speed across the lifespan: Beyond the influence of motor speed, *Western Hospital Research Showcase – Footscray Hospital,* Melbourne, Australia, **(Poster Presentation)**

Ebaid, D., Crewther, S. G., & MacCalman, K., Brown, A., Crewther, D. P, & Peters, J. (2016, July). The contribution of rate of visual processing to cognition across the lifespan. *Asia Pacific Conference on Vision (APCV)* – Fremantle, Western Australia **(Oral Presentation)**

Ebaid, D., Crewther, S. G., & MacCalman, K., Brown, A. & Crewther, D. P. (2016, March). The contribution of rate of visual processing to cognition across the lifespan.

Experimental Psychology Conference (EPC) – Melbourne University, Australia **(Poster Presentation) ***Awarded Best Student Presentation

Ebaid, D., Crewther, S. G., & MacCalman, K., Brown, A. & Crewther, D. P. (2015, January). Processing speed across the lifespan. *Healthy Aging Research Showcase*, La Trobe University, Melbourne, Australia **(Oral Presentation)**

Thesis Abstract

Cognitive processing is consistently reported to decline in accuracy and speed with aging. However, there is no current theory that accounts for such decline from the viewpoint of both biological and psychological age-related changes. Accordingly, the present thesis has critically reviewed prominent theories of aging and highlighted the need for a newer more extensive systems approach to cognitive aging. Indeed, the experimental studies in this thesis have assessed information processing in a sample of young and older adults with similar educational profiles, and demonstrated that motor speed makes a significant contribution to performance on neuropsychological test batteries utilising paper-pencil measures. The second study showed that older individuals performed more slowly on simple and unfamiliar visual information processing tasks, but not on familiar complex reading tasks. The third study examined eye gaze patterns as surrogate measures of visual attention, and demonstrated that slower saccades may contribute to the generalised cognitive decline seen in older populations. The final study examined temporal aspects of memory and showed that both young and older groups similarly underestimate time. Together, these findings provide novel analyses of cognitive processing in older populations and reinforce the need for a more comprehensive biopsychosocial approach to cognitive aging.

Statement of Authorship

Except where reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis submitted for the award of any other degree or diploma. No other person's work has been used without due acknowledgement in the main text of the thesis. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.

This thesis includes five co-authored manuscripts which are published or have been accepted for publication in peer-reviewed journals. The inclusion of co-authors across these chapters reflects work that originated from active collaboration between researchers and acknowledges input into team-based research. However, the theoretical framework, experimental data, data analyses, and written material presented in these manuscripts were the principal responsibility of the candidate under the supervision of Professor Sheila G. Crewther.

All research procedures within this thesis were approved by the La Trobe University Human Research Ethics Committee (FSTE HREC S15/19). Please see Appendix A. All participants within this study gave written informed consent in accordance with the Declaration of Helsinki (See Appendix B – D).

Signature:

24 June 2019

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chapter 1

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CHAPTER 1

Introduction and Thesis Overview

1.1 Background

Aging is arguably the most important medical, public health, and economic problem of the 21st century, particularly given the rapidly increasing percentage of senior citizens in the global population (see Figure 1). Though age-related changes in cognitive performance have received considerable attention in the scientific literature, gaps in knowledge still remain, resulting in discordant views of the aging brain and changes to cognitive processing across the lifespan (Salthouse, 1996; Costello, Madden, Mitroff, & Whiting, 2010; Ebaid, Crewther, MacCalman, Brown, & Crewther, 2017). Cognitive processing is a multifaceted construct, comprising many integrated processes including attention, speed of processing, perception, learning, memory, and decision making (Baddeley, 1992; Glisky, 2007; Harada, Natelson Love, & Triebel, 2013; Park & Reuter-Lorenz, 2009; Salthouse, 1996). What is widely accepted amongst the aging literature is that decline in these cognitive domains demonstrate impairments with advanced age, particularly speed of processing when measured with paper-and-pencil neuropsychological test-batteries (Salthouse, 1996 Cona, Bisiacchi, Amodio, & Schiff, 2013; Costello, Madden, Mitroff, & Whiting, 2010; Ebaid, Crewther, MacCalman, Brown, & Crewther, 2017).

What has not been well elucidated in the literature however, are the specific mechanisms that underlie the decline seen in healthy aging, and what cognitive skills may remain intact when measured with cognitive tasks that do not rely on a speeded motor response. Furthermore, cognitive performance in healthy aging is still not well understood when affective influences (i.e., depression, anxiety and stress symptoms) and sociodemographic factors such as level of education are considered between age-groups. In addition, despite several theories of aging put forward to attempt to explain the cognitive decline in aging, no single theory has adequately accounted for such decline. This in part, is likely due to most theories of aging being based on biological or psychological frameworks, without appropriate integration of both elements to provide a thorough understanding of cognitive decline across the lifespan. More specifically, cognitive changes that occur with age have seldom been explicitly discussed with consideration of the biological markers of aging including shifts in blood pressure and hypercortisolism, hypertension and increased anxiety, despite their potential to provide a more comprehensive understanding of attention, perception, memory and learning across the lifespan (Gulpers et al., 2016). Indeed, consideration of such points can enhance understanding through implementation of a systems neuroscience approach to cognitive aging. This thesis aims to address the dearth of literature in this realm of cognitive aging.

Addressing the gaps in the field of cognitive neuroscience will contribute to accurate clinical and experimental expectations of cognitive functions in a healthy aged population, which may then be applied to neuropsychological healthcare. Population aging is steadily increasing, with approximately 524 million people representing older persons aged 65 and above, comprising 8 percent of the worlds' population in 2010 (WHO, 2018). This figure is estimated to almost triple to approximately 1.5 billion in 2050, with more recent data even suggesting that adults aged 80 and above will account for approximately 20 percent of the worlds' population by 2050 (WHO, 2018; See Figure 1).

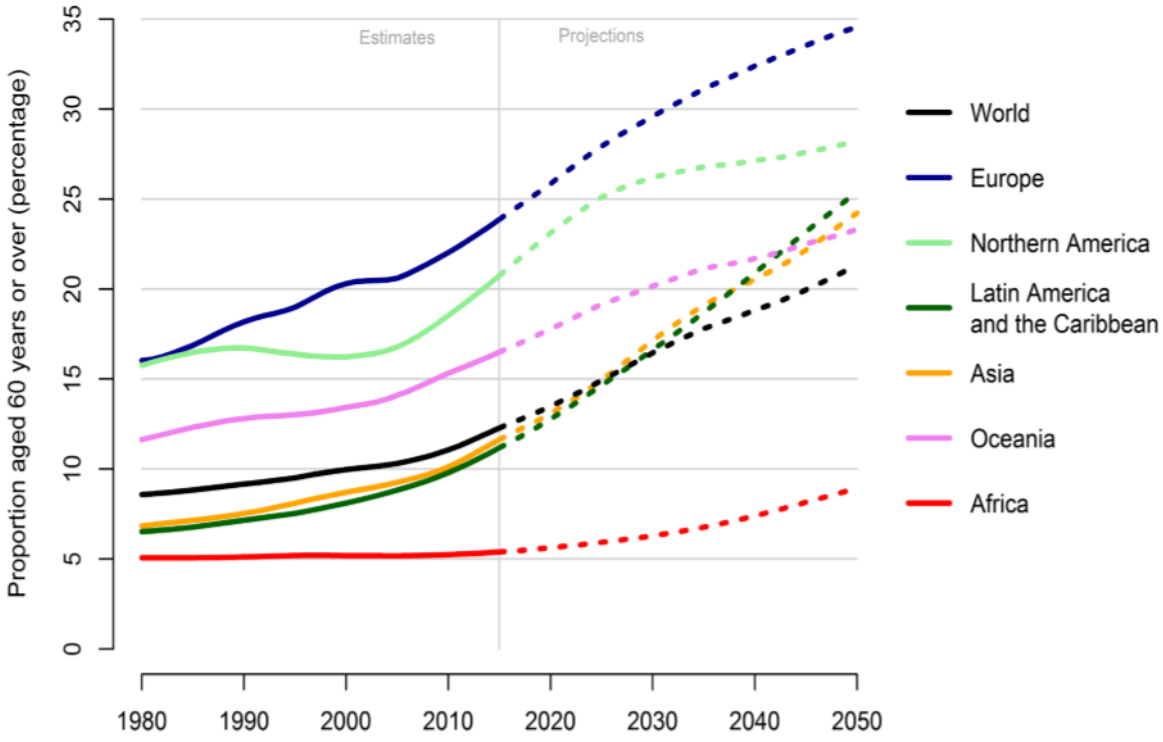

Figure 1. Percentage of the population aged 60 years or over by region, from 1980 to 2050. From "World Population Aging. Highlights" by Department of Economic and Social Affairs. United Nations (2017).

Cognitive decline across the lifespan is commonly reported in both accuracy and speed, even in the absence of any diagnosed neuropathological disease i.e., Alzheimer's Disease (see Figure 2; Bergmann, Schubert, Hagemann, & Schankin, 2016; Costello, et al., 2010; Ebaid, et al., 2017; Glisky, 2007; Salthouse, 1996; Staub, et al., 2014; Murman, 2015). Slowing of cognitive processing speed is one of the most frequently reported areas of decline in the aging literature, which has commonly been tested using motor-reaction times to visually-based cognitive tasks (Salthouse, 1996; Ebaid & Crewther, 2018; Ebaid et al., 2017; Gazzaley, Sheridan, Cooney, & D'Esposito, 2007; Cornelis et al., 2014; Salthouse, 1996; Vickers, Nettelbeck, & Willson, 1972). The use of these methods to test cognitive processing speed raises the question of whether the results are to some extent, confounded by the natural decline in motor speed that occurs across the lifespan (Liu et al., 2013; Ritchie Tucker-Drob & Deary, 2014; Johnson & Deary, 2011).

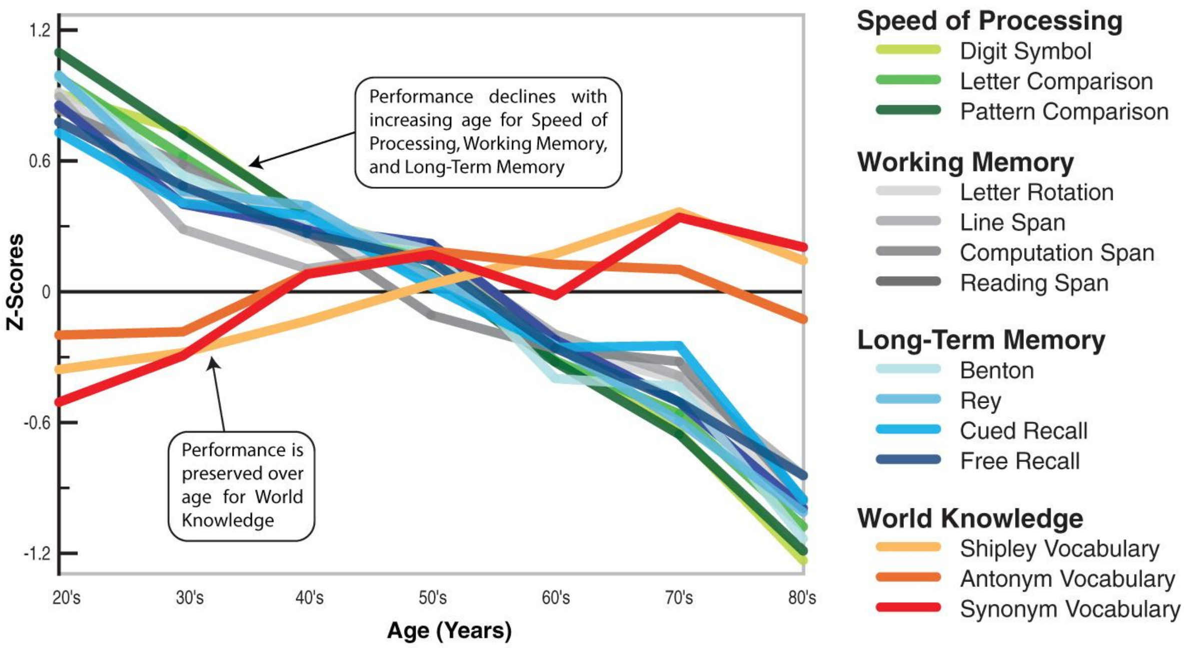

Figure 2. Cross-sectional aging data showing behavioural performance on measures of speed of processing, working memory, long-term memory, and world knowledge with age. From "The Adaptive Brain: Aging and Neurocognitive Scaffolding," by D.C. Park and P. Reuter Lorenz, 2009, Annual Review of Psychology, 60. Copyright 2019 by Annual Reviews.

Working Memory (WM) which was described by Baddeley (2003) as *"a limited capacity system, which temporarily maintains and stores information, supports human thought processes by providing an interface between perception, long-term memory and action"* (p. 829) is also a domain of cognitive processing which has received substantial attention in the aging literature (Bopp & Verhaeghen, 2005; Hester, Kinsella, & Ong, 2004). However, research into the changes that occur to WM in healthy aging largely neglects the unique cognitive process of *time estimation*, despite its ecological relevance to cognitive and functional independence. In fact, since WM was first conceptualised by Baddeley and Hitch, (1974) over 45 years ago, there has not been substantial additions to the WM model in the scientific literature. Certainly, the ability to accurately estimate time is a ubiquitous psychological process which is tightly embedded with cognitive skills including attention, memory, decision making, and is reported to be affected by age and susceptible to neurological impairments (Low et al., 2016; Baudouin, Isingrini, & Vanneste, 2018; Livesey, Wall, & Smith, 2007; Polti, Martin, & van Wassenhove, 2018; Rao, Mayer, & Harrington, 2001). Despite this, temporal aspects of WM have mainly been discussed from the viewpoint of temporary storage and encoding of static stimuli, but not from the viewpoint of the functional contribution to timing and time perception *per se*.

Much of the cognitive decline reported across the healthy lifespan have been explained in reference to the biological changes of aging including sensory system decline in the visual and auditory domain (Baltes & Lindenberger, 1997; Fozard & Gordon-Salant, 2001; Wilson et al., 1999). Indeed, aging affects peripheral hearing sensitivity (Wilson et al., 1999), suprathreshold auditory processing, and sensitivity to temporal fine structures, even in older adults with normal audiometric thresholds (Füllgrabe, 2013; Füllgrabe, Moore, & Stone, 2015). Likewise, deteriorations in vision across the lifespan are common, beginning with advent of loss of accommodation, i.e., presbyopia in midlife (Patel & West, 2007), increase in cataractous lenses, macular retinal degeneration (Friedman et al., 2004), and consequent impairments in visual acuity, temporal resolution, and contrast sensitivity (Culham & Kline, 2002). In addition, decline in the visual system has been demonstrated with decreases in flicker fusion thresholds and increased latency of conduction for the fast attention and accuracy Magnocellular (M) pathway from retina to cortex (Brown, Corner, Crewther, & Crewther, 2018). The link between sensory deficits and cognition has gained substantial interest in the aging literature and is a fundamental aspect of several influential theories including the *Common-Cause Hypothesis* (Baltes & Lindenberger, 1997), *the Sensory Deprivation Hypothesis* (Oster, 1976; Valentijn et al., 2005), and the *Information Degradation Hypothesis (*Schneider & Pichora-Fuller, 2000).

Of all senses, vision is the only modality that allows spatial and temporal coding of information and hence is the dominant sense, with neurons devoted to visual processing comprising 30 percent of the cortex, compared to approximately 8 percent for somatosensation and 3 percent for auditory processing (Van Essen, 2003; Orban, Van Essen, & Vanduffel, 2004). Furthermore, the eye is an outgrowth of the brain, which begins early during embryonic development (Sretavan, Feng, Pure, & Reichardt, 1994) and thus, performance on visual perceptual tasks can provide intricate understanding into functioning of the visual system and into other complex cognitive processes (Ritchie Tucker-Drob & Deary, 2014; Chan, Chan, Lee, & Hsiao, 2018).

Integrity of the human visual system can also be inferred by oculomotor functions including fixations and saccadic eye movements which are considered robust and non-invasive measures of visual attention and cognitive ability (Mohler, Goldberg, & Wurtz, 1973; Wurtz & Goldberg, 1989). Such measures are able to provide reliable and extensive insight into higher order cognitive processes including memory, reasoning and reading (Chan, Chan, Lee, & Hsiao, 2018; Eckstein, Guerra-Carrillo, Miller Singley, & Bunge, 2017; Nikolaev, Pannasch, Ito, & Belopolsky, 2014). As most behaviour is visually driven, factors affecting visual attention are paramount to efficient cognitive processing (Forstmann et al., 2011; Godefroy, Roussel, Despretz, Quaglino, & Boucart, 2010; Henry et al., 2016). Despite this, oculomotor performance using eye tracking as surrogate measures of cognitive processing has not been investigated in a single experimental study with a healthy young and older population.

Within the literature that examines cognitive performance in healthy older adults, a recurring issue relating to the appropriateness of the experimental design used is the choice of participants who comprise the control group for comparison against an aged population. Moreover, younger control groups utilised in aging research are usually university students, while most aged populations are less educated, and until recently had often spent their childhoods in times of wars and financial depression i.e., economic and social hardship. Presumably, such socioeconomic factors have impacted on childhood growth, health and cognitive performance later in life (NICHD, 2005). Indeed, potential moderators of the relationship between age and cognitive decline are frequently suggested to include level of education (Bennett et al., 2003), health status (Waldstein, 2000) and negative affect i.e., depression and anxiety (McDermott & Ebmeier, 2009), though these are seldom considered in cognitive aging literature.

1.2 Rationale and Aims

Although cognitive processing across the lifespan has been extensively researched, it is evident that disparity and gaps in knowledge still remain, with impairments often being theorised holistically, and concluded to decline across the lifespan even in the absence of any pathological disorder (Salthouse, 1996; Bergmann et al., 2016; Cona et al., 2013; Hedden & Gabrieli, 2004). Additionally, cognitive aging research seldom considers decline from a systems neuroscience perspective which encapsulate factors such as biological markers of aging (i.e., shifts in blood pressure, hypercortisolism, and hypertension) nor has it considered unbalanced immune responses related to increased anxiety, despite their potential to provide a more comprehensive understanding of cognitive processing (Gulpers et al., 2016; Gupta & Morley, 2011). In addition, the measures used to assess constructs of cognitive processing in aged populations are most commonly those from the Processing Speed Index (PSI) of the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 2008) which rely on gross cognitive and motor abilities, making it difficult to intricately examine specific cognitive skills which comprise broader cognitive abilities such as attention, processing speed, memory and decision making.

Although several theories have been put forward in an attempt to explain the decline seen in healthy aging, no single explanation can adequately and appropriately account for such deficits, emphasising the need for further understanding into the domains which are most susceptible to the aging process and the factors that contribute to such decline. More specifically, when examining cognitive processing between age-groups, the experimental model should consider cognitive and perceptual speed (with consideration of potential confounds of hand-motor speed), attention (transient, temporal, sustained, and selective), memory (working, storage, retrieval and its temporal aspects i.e., time estimation), as well as psychosocial characteristics regarding the chosen samples including health status, education and negative affect. Furthermore, with the advances and availability of experimental and clinical tools, novel non-invasive measures that can assess eye-gaze patterns and attentional shifting as a biobehavioural measure of cognition should be utilised when assessing cognitive performance in aging populations. Currently however, limited research is available to provide information on eye-gaze patterns and oculomotor functions alongside visuo-cognitive tasks in an apparently healthy young and older population.

Thus, this thesis aims to address the dearth of evidence in the healthy aging literature pertaining to cognitive processing across the lifespan with an emphasis on visual processing without motor confounds. Additionally, this research aims to examine the interconnected processes of cognition including visual attention, processing speed, memory, decision-making, problem solving, as well as oculomotor function, in a healthy educated sample of young and older adults, while accounting for affective influences and sociodemographic factors. Specifically, this thesis aims to address the following research questions:

1a. Do similarly educated healthy older persons show significant differences in cognitive processing speed to younger adults using traditional tests from the Processing

Speed Index (PSI) of the WAIS i.e., the Symbol Search (SS) and Coding (Cod), and on a computerised psychophysical task of perceptual speed with no reliance on hand motor speed, i.e., the Inspection time (IT) task?

1b. Is performance on the SS and Cod of older adults confounded by motor-deficits, and if so, how much of the variance in cognitive performance is motor driven?

2. How does age affect rate of visual information processing (specifically, threshold exposure time) when using computerised perceptual speed tasks varying in complexity and familiarity, while considering self-reported depression, anxiety, and stress symptoms?

3. Do oculomotor functions (number of fixations, fixation durations, saccade durations) contribute to the age-related differences in visual information processing?

4a. How does age affect processing speed and memory performance when measured traditionally and as *retrospective time estimation*, while considering self-reported depression, anxiety, and stress symptoms?

4b. Are memory and processing speed correlated to retrospective time estimation in the seconds-to-minutes range?

1.3 Thesis Outline

Chapter 2 of this thesis comprises a critical review of the existing theories of aging concerning key cognitive and neural processes associated with cognitive decline in healthy aging. This review also highlights the need for a more modern biological systems neuroscience approach to understanding cognitive aging. Chapter 2: Time for a Systems Biological Approach to Cognitive Aging? –A Critical Review, has been accepted for publication in Frontiers in Aging Neuroscience. Chapter 3 discusses the rationale behind the key methodological choices for the experimental program. Chapter 4 to 7 comprise the experimental series for this thesis. Please note that there is some repetition of methodology within the experimental chapters of this thesis, as they have individually served as published papers or manuscripts accepted for publication.

The most commonly used experimental and clinical measures to assess cognitive processing speed in healthy and clinical populations are paper-and-pencil measures from the Processing Speed Index (PSI) of the WAIS, such as the Symbol Search (SS) and Coding (Cod; Wechsler, 2008) which rely on a speeded motor response. Despite this, no single experimental study has explored the extent to which these measures are affected by motor speed. Accordingly, Chapter 4 examined the extent to which performance on traditional measures of cognitive processing speed (i.e., the SS and Cod) are confounded by motor speed in young and older adults and compared such performance to a non-motor psychophysical measure of perceptual speed, i.e., the Inspection Time (IT) task (Vickers, Nettelbeck & Willson, 1972). Chapter 4 is published as 'Cognitive Processing Speed across the Lifespan: Beyond the Influence of Motor Speed', in Frontiers in Aging Neuroscience (Ebaid, Crewther, MacCalman, Brown, & Crewther, 2017) and has been cited 20 times as of 24th June 2019.

Chapter 5 of this thesis investigated threshold rates of visual attention and information processing on computerised perceptual speed tasks varying in complexity and familiarity, in similarly educated young and older adults, while also accounting for affective factors. Specifically, Chapter 5 utilised a psychophysical IT (Vickers, Nettelbeck & Willson, 1972) and Change Detection (CD) task (Becker, Pashler & Anstis, 2000; Rutkowski et al., 2003) which assess perceptual speed and decision making without any reliance on a speeded motor response, as well as an ecologically valid measure of information processing and reading rate, i.e., the FastaReada (Elhassan, et al., 2015; Hecht et al., 2004). Chapter 5: Visual Information Processing in Young and Older Adults, has been published in Frontiers in Aging Neuroscience (Ebaid & Crewther, 2019).

Chapter 6 examined oculomotor functions including number of fixations, fixation duration, and saccade durations in young and older adults while text-reading and during a common-objects/alphanumeric Rapid Automatic Naming (RAN) task. Chapter 6 also explored whether oculomotor function contributes differentially to visual information processing and cognitive speed of both age groups. Chapter 6 has been submitted for consideration for publication to Nature Scientific Reports as 'The Contribution of Oculomotor Function to Visual Information Processing in Young and Older Adults' and has been accepted for publication.

Chapter 7 of this thesis examined age-related differences in memory and processing speed using traditional speed measures i.e., the SS and Cod, common measures of memory i.e., the forward and backward digit span (Wechsler, 2008), and an *N*-back task (Kirchener, 1958). Chapter 7 also employed a more novel approach to memory by assessing retrospective time estimation of the duration of the *N*-back task (which lasted 85 seconds) between age groups and explored whether time estimation was associated with performance on processing speed and memory measures. Chapter 7: Temporal Aspects of Memory: A Comparison of Memory Performance, Processing Speed and Time Estimation between Young and Older Adults, has been published in Frontiers in Aging Neuroscience (Ebaid & Crewther, 2018).

This thesis concludes with Chapter 8 which provides a general discussion of the key findings and highlights the importance of the experiments in understanding cognitive processing in healthy aging. The limitations associated with each study are discussed here, and suggestions for future studies are also provided, in order to expand on the research that this thesis investigated.

1.4 References

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556-559.

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829.

Baddeley, A. D., & Hitch, G. (1974). Working memory. In *Psychology of Learning and Motivation* (Vol. 8, pp. 47-89). Academic press.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychology & Aging, 12*(1), 12.

Baudouin, A., Isingrini, M., & Vanneste, S. (2018). Executive functioning and processing speed in age-related differences in time estimation: a comparison of young, old, and very old adults. *Aging, Neuropsychology, & Cognition*, 1-18.

Bennett, D. A., Wilson, R., Schneider, J., Evans, D., De Leon, C. M., Arnold, S., . . . Bienias, J. (2003). Education modifies the relation of AD pathology to level of cognitive function in older persons. *Neurology, 60*(12), 1909-1915.

Bergmann, K., Schubert, A. L., Hagemann, D., & Schankin, A. (2016). Age-related differences in the P3 amplitude in change blindness. *Psychological Research, 80*(4), 660-676. doi:10.1007/s00426-015-0669-6

Bopp, K. L., & Verhaeghen, P. (2005). Aging and verbal memory span: a meta-analysis. *Journal of Gerontology: Series B Psychological Science and Social Science, 60*(5), P223-233.

Brown, A. C., Corner, M., Crewther, D. P., & Crewther, S. G. (2018). Age related decline in cortical multifocal flash VEP: Latency increases shown to be predominately magnocellular. *Frontiers in Aging Neuroscience, 10,* 430. Buschman, T. J., & Miller, E. K. (2010). Shifting the spotlight of attention: evidence for discrete computations in cognition. *Frontiers in human neuroscience, 4*, 194.

Cattell, R. B. (1941). Some theoretical issues in adult intelligence testing. *Psychological Bulletin, 38*(592), 10.

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology, 54*(1), 1.

Chan, C. Y. H., Chan, A. B., Lee, T. M. C., & Hsiao, J. H. (2018). Eye-movement patterns in face recognition are associated with cognitive decline in older adults. *Psychonomic Bulletin and Review*. doi:10.3758/s13423-017-1419-0

Cona, G., Bisiacchi, P. S., Amodio, P., & Schiff, S. (2013). Age-related decline in attentional shifting: Evidence from ERPs. *Neuroscience Letters, 556*, 129-134. doi:10.1016/j.neulet.2013.10.008

Cornelis, C., De Picker, L. J., Hulstijn, W., Dumont, G., Timmers, M., Janssens, L., . . . Morrens, M. (2014). Preserved learning during the Symbol-Digit Substitution Test in patients with Schizophrenia, age-matched controls, and elderly. *Frontiers in Psychiatry, 5*, 189. doi:10.3389/fpsyt.2014.00189

Costello, M. C., Madden, D. J., Mitroff, S. R., & Whiting, W. L. (2010). Age-related decline of visual processing components in change detection. *Psychology & Aging, 25*(2), 356. doi:10.1037/a0017625

Culham, J. C., & Kline, D. W. (2002). The age deficit on photopic counterphase flicker: Contrast, spatial frequency, and luminance effects. *Canadian Journal of Experimental Psychology, 56*(3), 177.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*(3), 433.

Ebaid, D., & Crewther, S. G. (2019). Visual information processing in young and older adults. *Frontiers in Aging Neuroscience, 11*, 116.

Ebaid, D., & Crewther, S. G. (2018). Temporal aspects of memory: A comparison of memory performance, processing speed and time estimation between young and older adults. *Frontiers in Aging Neuroscience, 10*.

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A., & Crewther, D. P. (2017). Cognitive processing speed across the lifespan: Beyond the influence of motor speed. *Frontiers in Aging Neuroscience, 9*, 62. doi:10.3389/fnagi.2017.00062

Eckstein, M. K., Guerra-Carrillo, B., Miller Singley, A. T., & Bunge, S. A. (2017). Beyond eye gaze: What else can eyetracking reveal about cognition and cognitive development? *Developmental Cognitive Neuroscience, 25*, 69-91. doi:https://doi.org/10.1016/j.dcn.2016.11.001

Elhassan, Z., Crewther, S., Bavin, E., & Crewther, D. (2015). Preliminary validation of FastaReada as a measure of reading fluency. *Frontiers in Psychology, 6*.

Forstmann, B. U., Tittgemeyer, M., Wagenmakers, E. J., Derrfuss, J., Imperati, D., & Brown, S. (2011). The speed-accuracy tradeoff in the elderly brain: a structural model-based approach. *Journal of Neuroscience, 31*(47), 17242-17249. doi:10.1523/JNEUROSCI.0309-11.2011

Fozard, J. L., & Gordon-Salant, S. (2001). Changes in vision and hearing with aging. *Handbook of The Psychology of Aging, 5*, 241-266.

Friedman, D. S., O'Colmain, B. J., Munoz, B., Tomany, S. C., McCarty, C., De Jong, P., . . . Kempen, J. (2004). Prevalence of age-related macular degeneration in the United States. *Archives of Ophthalmology, 122*(4), 564-572.

Füllgrabe, C. (2013). Age-dependent changes in temporal-fine-structure processing in the absence of peripheral hearing loss. *American Journal of Audiology*, *22*(2), 313-315.

Füllgrabe, C., Moore, B. C., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience, 6*, 347.

Gazzaley, A., Sheridan, M. A., Cooney, J. W., & D'Esposito, M. (2007). Age-related deficits in component processes of working memory. *Neuropsychology*, *21*(5), 532-539. doi:10.1037/0894-4105.21.5.532

Glisky, E. L. (2007). Changes in cognitive function in human aging. In D. R. Riddle (Ed.), *Brain Aging: Models, Methods, and Mechanisms*. Boca Raton (FL).

Godefroy, O., Roussel, M., Despretz, P., Quaglino, V., & Boucart, M. (2010). Age-related slowing: perceptuomotor, decision, or attention decline? *Experimental Aging Research, 36*(2), 169-189. doi:10.1080/03610731003613615

Gulpers, B., Ramakers, I., Hamel, R., Köhler, S., Voshaar, R. O., & Verhey, F. (2016). Anxiety as a predictor for cognitive decline and dementia: A systematic review and meta-analysis. *The American Journal of Geriatric Psychiatry, 24*(10), 823-842.

Gupta, D., & Morley, J. E. (2011). Hypothalamic-Pituitary-Adrenal (HPA) Axis and aging. *Comprehensive Physiology*, *4*(4), 1495-1510.

Harada, C. N., Natelson Love, M. C., & Triebel, K. L. (2013). Normal cognitive aging. *Clinical Geriatric Medicine, 29*(4), 737-752. doi:10.1016/j.cger.2013.07.002

Hecht, R., Crewther, D., & Crewther, S. (2004). Rate of learning and asymptotic performance in an automatization task and the relation to reading. *Perceptual and Motor Skills, 99*, 1103-1121. doi:10.2466/pms.99.3f.1103-1121

Hedden, T., & Gabrieli, J. D. (2004). Insights into the ageing mind: A view from cognitive neuroscience. *Nature Reviews Neuroscience, 5*(2), 87.

Henry, M., Henry-Gonzalez, A. A., Gonzalez-Delgado, A. N., Acosta-Diaz, E. A. D., & Castro-Molina, F. J. (2016). Functional and cognitive independence in the elderly. *European Psychiatry, 33,* S215.

Hester, R. L., Kinsella, G. J., & Ong, B. (2004). Effect of age on forward and backward span tasks. *Journal of the International Neuropsychological Society, 10*(4), 475-481.

Johnson, W., & Deary, I. J. (2011). Placing inspection time, reaction time, and perceptual speed in the broader context of cognitive ability: The VPR model in the Lothian Birth Cohort 1936. *Intelligence*, *39*(5), 405-417.

Liu, J., Zhang, B., Lei, H., Feng, Z., Liu, J., Hsu, A.-L., & Xu, X. S. (2013). Functional aging in the nervous system contributes to age-dependent motor activity decline in C. elegans. *Cell Metabolism, 18*(3), 392-402.

Livesey, A. C., Wall, M. B., & Smith, A. T. (2007). Time perception: manipulation of task difficulty dissociates clock functions from other cognitive demands. *Neuropsychologia, 45*(2), 321-331.

Low, E., Crewther, S. G., Perre, D. L., Ong, B., Laycock, R., Tu, H., & Wijeratne, T. (2016). Beyond neglect: Preliminary evidence of retrospective time estimation abnormalities in non-neglect stroke and transient ischemic attack patients. *Scientific Reports, 6,* 22598.

Madden, D. J. (2007). Aging and visual attention. *Current Directions in Psychological Science, 16*(2), 70-74. doi:10.1111/j.1467-8721.2007.00478.x

McDermott, L. M., & Ebmeier, K. P. (2009). A meta-analysis of depression severity and cognitive function. *Journal of Affective Disorders, 119*(1-3), 1-8.

Mohler, C. W., Goldberg, M. E., & Wurtz, R. H. (1973). Visual receptive fields of frontal eye field neurons. *Brain Research, 61*(3), 85-83.

Murman D. L. (2015). The impact of age on cognition. *Seminars in Hearing, 36*(3), 111–121. doi:10.1055/s-0035-1555115.

National Institute of Child Health and Human Development Early Child Care Research Network. (2005). Duration and developmental timing of poverty and children's cognitive and social development from birth through third grade. *Child Development, 76*(4), 795-810.

Nikolaev, A. R., Pannasch, S., Ito, J., & Belopolsky, A. V. (2014). Eye movement-related brain activity during perceptual and cognitive processing. *Frontiers in Systems Neuroscience, 8,* 62.

Orban, G. A., Van Essen, D., & Vanduffel, W. (2004). Comparative mapping of higher visual areas in monkeys and humans. *Trends in Cognitive Sciences, 8*(7), 315-324.

Oster, C. (1976). Sensory deprivation in geriatric patients. *Journal of the American Geriatrics Society, 24*(10), 461-464.

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual Review of Psychology, 60,* 173-196.

Patel, I., & West, S. K. (2007). Presbyopia: prevalence, impact, and interventions. *Community Eye Health, 20*(63), 40.

Plude, D. J., Enns, J. T., & Brodeur, D. (1994). The development of selective attention: a life-span overview. *Acta Psychologia, 86*(2-3), 227-272.

Polti, I., Martin, B., & van Wassenhove, V. (2018). The effect of attention and working memory on the estimation of elapsed time. *Scientific Reports, 8*.

Rao, S. M., Mayer, A. R., & Harrington, D. L. (2001). The evolution of brain activation during temporal processing. *Nature Neuroscience, 4*(3), 317.

Ritchie, S. J., Tucker-Drob, E. M., & Deary, I. J. (2014). A strong link between speed of visual discrimination and cognitive ageing. *Current Biology*, *24*(15), 681-683.

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

Salthouse, T. A. (2009). When does age-related cognitive decline begin? *Neurobiology of Aging, 30*(4), 507-514.

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. C. T. A. Salthouse (Ed.), *The handbook of aging and cognition, 2nd ed* (pp. 155-219). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Sretavan, D. W., Feng, L., Pure, E., & Reichardt, L. F. (1994). Embryonic neurons of the developing optic chiasm express L1 and CD44, cell surface molecules with opposing effects on retinal axon growth. *Neuron*, *12*(5), 957-975.

Staub, B., Doignon-Camus, N., Bacon, E., & Bonnefond, A. (2014). The effects of aging on sustained attention ability: an ERP study. *Psychololgy and Aging*, *29*(3), 684-695. doi:10.1037/a0037067

United Nations (2017). World Population Prospects: the 2017 Revision. Retrieved from http://www.un.org/en/development/desa/population/publications/pdf/ageing/WPA2017_Highlights.pdf

Valentijn, S. A., van Boxtel, M. P., van Hooren, S. A., Bosma, H., Beckers, H. J., Ponds, R. W., & Jolles, J. (2005). Change in sensory functioning predicts change in cognitive functioning: results from a 6-year follow-up in the maastricht aging study. *Journal of the American Geriatric Society*, *53*(3), 374-380. doi:10.1111/j.1532-5415.2005.53152.x

Van Essen, D. C. (2003). Organization of visual areas in macaque and human cerebral cortex. *The Visual Neurosciences*, *1*, 507-521.

Vickers, D., Nettelbeck, T., & Willson, R. (1972). Perceptual indices of performance: the measurement of ‘inspection time’and ‘noise’in the visual system. *Perception*, *1*(3), 263-295.

Waldstein, S. R. (2000). Health effects on cognitive aging. *The Aging Mind: Opportunities in Cognitive Research*, 189-217.

Wechsler, D. (2008). *Wechsler Adult Intelligence Scale–Fourth Edition (WAIS–IV)*: San Antonio, TX: The Psychological Corporation.

WHO (2018). World Health Organization: Ageing and health.

Wilson, D., Walsh, P., Sanchez, L., Davis, A., Taylor, A., Tucker, G., & Meagher, I. (1999). The epidemiology of hearing impairment in an Australian adult population. *International Journal of Epidemiology*, *28*(2), 247-252.

Wurtz, R. H., & Goldberg, M. E. (1989). *The neurobiology of saccadic eye movements* (Vol. 3): Elsevier Science Limited.

chapter 2

02.

CHAPTER 2

Time for a Systems Biological Approach to Cognitive Aging? –A Critical Review

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2.1 Abstract

Most current theories of cognitive decline with aging tend to be primarily cognitive or biological explanations with relatively few adequately incorporating both aspects. The emphasis in the literature tends to focus on the importance of decline in sensory abilities, the effect of motor speed on paper-pencil task measures of cognitive speed, and lifestyle factors i.e., level of education, and physical activity levels. However, to date these points as well as the biological markers of aging including shifts in blood pressure and hypercortisolism, hypertension and increased anxiety have seldom been implicated into any theory of cognitive aging, despite their potential to provide a more comprehensive understanding of attention, perception, learning and memory across the lifespan. Consideration of such points can enhance understanding through implementation of a systems neuroscience approach to cognitive aging.

Keywords: cognitive aging, cognitive decline, theories of aging, processing speed decline, hypercortisolism, hypertension, systems neuroscience

2.2 Introduction

Many theories of cognitive aging have been proposed to account for the declines observed in cognitive performance across the healthy lifespan, where slowing of processing speed is one of the most common markers of cognitive aging (Salthouse, 1996; Ebaid et al., 2017; Brown et al., 2018). Some explanations are predominantly cognitive, while others have described a more biological basis to account for the decline in cognitive performance (Baltes & Lindenberger, 1997. However, to date no single explanation has incorporated all of these multiple aspects of biological change to adequately and appropriately account for the decline in cognitive processing seen in healthy aging. With the increase of life expectancy, understanding the changes that would be expected to affect cognitive processing during the healthy lifespan has become a public health and socioeconomic priority. Thus, this review will critically evaluate the more prominent theories of cognitive aging which are primarily based on the frameworks of cognitive psychology, and then highlight the need for a newer more comprehensive systems neuroscience approach to cognitive aging.

2.3 Sensory System Decline

2.3.1 The Sensory Deprivation Hypothesis, the Information Degradation Hypothesis, and the Common-Cause Hypothesis.

The *Common-Cause Hypothesis, the Sensory Deprivation Hypothesis*, and *the Information Degradation Hypothesis* collectively suggest a strong interaction between declines in sensory function i.e., vision and audition, and a decline in cognitive performance (See Figure 1).

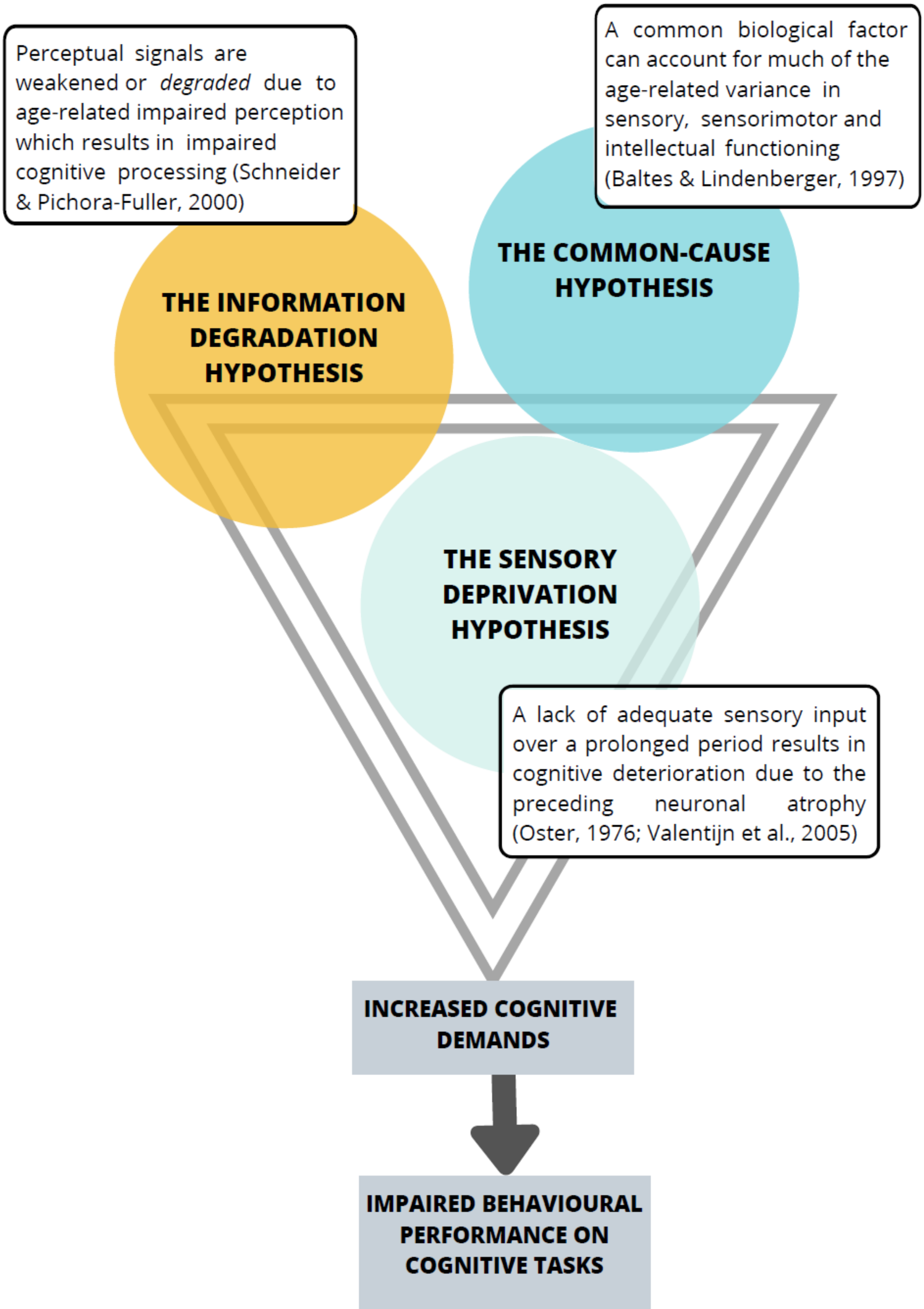

Figure 1. Theories suggesting an interaction between sensory system decline and impaired cognitive performance. Note that these theories are not conflicting and their underlying premise share some overlap.

The *Sensory Deprivation Hypothesis* suggests that a lack of adequate sensory input over a prolonged period, is likely to result in cognitive deterioration due to the preceding neuronal atrophy (Oster, 1976; Valentijn et al., 2005). Similarly the *Information Degradation Hypothesis* states that when perceptual signals are weakened or *degraded,* either due to experimental manipulations or age-related impaired perception, higher order cognitive processes are in turn affected (Schneider & Pichora-Fuller, 2000) presumably because the cognitive load is greater for weak perceptual signals, and thus requires more cognitive resources to interpret the signal, which compromises cognitive performance (Zekveld, Kramer, & Festen, 2011). *The Common-Cause Hypothesis* (Baltes & Lindenberger, 1997) suggests concurrent peripheral and central decline occurring simultaneously with declines in aspects of conscious cognition and proposes that sensory and cognitive function are both likely to be an expression of the *"physiological architecture of the aging brain"* (p. 13). More specifically, the premise of this hypothesis is that as age increases, a common biological factor can account for much of the age-related variance in sensory, sensorimotor and intellectual functioning, and where dopaminergic functioning in particular, has been proposed as that common factor (Li & Lindenberger, 1999; See Figure 2 for dopaminergic pathways in the brain). Specifically, it has been suggested that age-related differences in pre-synaptic markers such as binding potential for the dopamine (DA) transporter (Erixon-Lindroth et al., 2005) and post-synaptic markers such as D_1 receptor densities (Wang et al., 1998) and D_2 (Bäckman et al., 2000; MacDonald, Cervenka, Farde, Nyberg, & Bäckman, 2009) explain significant proportions of age-related variance in executive functioning, episodic memory and processing speed (Bäckman, Lindenberger, Li, & Nyberg, 2010). Age-related changes in the Autonomic Nervous System (ANS) and particularly in the Sympathetic Nervous System (SNS) also affect the pupils in the eyes and all other non-central nervous system organs including the heart, lungs, gut and mucous membrane (McLean & Le Couteur, 2004; Strickland et al., 2019; Parashar, Amir, Pakhare, Rathi, & Chaudhary, 2016; Shimazu, Tamura, Shimazu 2005; Pfeifer et al., 1983) and interact closely with stress hormones (i.e., cortisol) of the hypothalamus pituitary adrenal (HPA axis; Gaffey, Bergeman, Clark & Wirth, 2016; Gupta & Morley, 2011). Interestingly however, age-related changes in the functioning of the SNS have not been discussed in relation to theories of cognitive aging.

Neurocomputational work on the triad between aging, cognition and DA suggests that reduced DA activity increases neuronal noise (i.e., random electrical fluctuations generated within neuronal networks that are not associated with encoding a response to stimuli; Li, Lindenberger, & Sikström, 2001). Increases in neuronal noise has various functional consequences including less distinctive neuronal representations of perceptual stimuli, increased interference between different functional networks (Li & Sikström, 2002) and impaired interactions between intrinsic neuronal and perceptual noise which may collectively result in impaired performance on cognitive tasks (Bäckman et al., 2010; Li, von Oertzen, & Lindenberger, 2006). This suggestion is in line with other sensory theories of aging and cognitive decline i.e., the *Information Degradation Hypothesis* described above (Schneider & Pichora-Fuller, 2000).

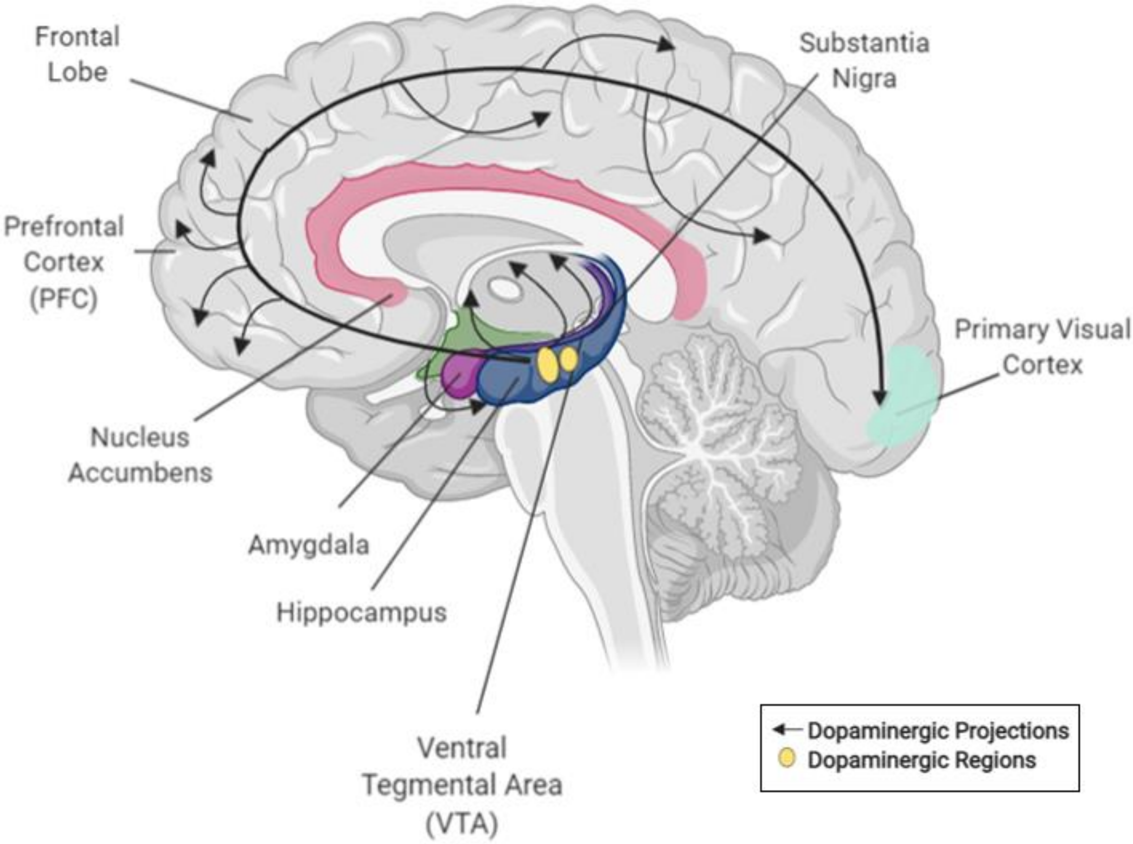

Figure 2. Dopaminergic pathways in the brain depicting dopaminergic regions in the Substantia Nigra (SN) and Ventral Tegmental Area (VTA; Luo & Huang, 2016), and dopaminergic projections to the Prefrontal Cortex (PFC; Welberg, 2008; Del Arco & Mora, 2008) and primary visual cortex (V1; Nienborg & Jacob, 2018). *Created with BioRender.com*

Despite the well-reported and accepted role of the dopaminergic system in cognitive performance (Aalto, Brück, Laine, Någren, & Rinne, 2005; Bäckman et al., 2010; Li & Sikström, 2002), the implication that it is the *cause* of cognitive decline seen across the lifespan must be interpreted with caution. Indeed, the observations of altered DA levels during cognitive behavioural tasks has been scrutinised in a systematic review by Egerton et al. (2009), who noted that uncontrolled head movements during behavioural tasks may ultimately confound the conclusions relating to regional cerebral blood flow changes during task performance. Furthermore, although dopamine is often considered as the neuromodulator effecting noise signals in neural systems (Li & Lindenberger, 1999; Erixon-Lindroth et al., 2005) there are many other monoamines such as noradrenaline and serotonin that modulate neural network activation (Nienborg & Jacob, 2018) and must eventually be researched before an entirely comprehensive model of cognitive aging can be achieved.

2.3.2 The link between perceptual abilities and decline in cognitive performance

The association between perceptual abilities and cognitive performance was demonstrated in a study conducted by Lindenberger and Baltes (1994) who reported that sensory variables such as visual acuity, auditory acuity, as well as balance-gait, predicted 59% of total variance in general intelligence. Similarly, a study conducted by Humes, Busey, Craig, and Kewley-Port (2013), indicated that the relationship between age and cognitive function (measured with WAIS subsets) was mediated by sensory function when the factor was based on a composite measure of auditory, visual and tactile perception. On the other hand, a recent study by Füllgrabe, Moore, and Stone (2015) failed to find any age group differences in the auditory forward and backward digit span tasks in a sample of healthy young and older participants who were audiometrically matched, highlighting the correlation between reduced speech intelligibility and performance on auditory based cognitive measures. Most recently, age related physiological and behavioural changes in the visual system have been demonstrated using both flicker fusion thresholds as a behavioural measure of the function of the fastest conducting Magnocellular (M) pathway and multifocal Visually Evoked Potentials (mfVEPS) as a measure of retino-cortical latency of the two major M and Parvocellular (P) subcortical visual pathways. Multifocal VEPS showed increases in latency with age of both the M and P pathways, though the M generated peak latency increases were greater than those associated with the slower P pathways (Brown, et al., 2018).

Despite the association between perceptual abilities and cognition being well-documented, some inconsistent findings still remain (see Gennis, Garry, Haaland, Yeo, & Goodwin, 1991; Hofer, Berg, & Era, 2003). In a recent review (Roberts & Allen, 2016), the authors strongly recommended assessing perceptual abilities beyond simple measures of visual and auditory acuity in order to corroborate the link between perception and cognition. Specifically, the use of more complex measures of suprathreshold temporal perceptual processing was recommended when investigating cognitive decline in healthy aging (Roberts & Allen, 2016).

Though generalised explanations specific to sensory integrity as described above have been influential in the aging literature, they certainly neglect other biological factors of aging which are related to cognition, including vascular hypertension-related changes. Furthermore, few studies have considered the contribution or confounds of long term blood pressure medication or the increasing evidence that cerebral small blood vessel disease is emerging as a principle risk factor for cognitive impairment in apparently healthy adults (Jiménez-Balado et al., 2019; Liu, Dong, Lyu, Chen, & Li, 2018)

2.4 The Processing Speed Theory

Theories postulating that processing speed underlies the observed decline in complex cognitive abilities were pioneered as early as the 1960’s by Birren (1965) who observed that processing rate for a broad range of cognitive tasks increased as a function of age. This theory was validated and expanded through an extensive body of work conducted by Salthouse (Salthouse, 1985, 1996), who postulated the influential theory of cognitive aging, namely, the *Processing Speed Theory of Adult Age Differences in Cognition* (Salthouse, 1996). This theory suggests that a slowing in the speed at which cognitive processing operations can be executed, underlies the decline observed in more complex cognitive functions, including memory, problem solving and reasoning (Salthouse, 1996). Specifically, Salthouse (1996) proposed that older adults have impairments in two interconnected mechanisms relating to processing speed, i.e., a *limited time mechanism*, and a *simultaneity mechanism*, which together underlie the deficits observed in higher order cognitive abilities. The *limited time mechanism* suggests that older adults require more time to process early operations of a cognitive task, than do younger individuals and consequently greatly restrict performance on later operations, as a large portion of available time is already occupied. The *simultaneity mechanism* is based on the notion that products of early processing may no longer be available i.e., information is forgotten by the time later processing is complete (Salthouse, 1996). This theory has been influential in the cognitive aging literature, and its fundamental underpinnings remain relevant to modern-day experimental research into cognitive aging, particularly as a means to explain age-group differences in cognitive performance (Costello, Madden, Mitroff, & Whiting, 2010; Ebaid, et al., 2017; Ebaid & Crewther, 2018, 2019; Brown et al., 2018; Eckert, 2011; Salthouse, 2000). Another major limitation of this body of work is the predominant use of paper-pencil tasks with aged populations, which inextricably introduces the confounding element of motor speed (Ebaid et al., 2017). This is even more prominent in populations with neurological impairments, i.e., following a stroke, which significantly impairs motor ability (Langhorne, Coupar, & Pollock, 2009). For example, the Digit Symbol Substitution test from the WAIS-R (Wechsler & De Lemos, 1981) was one of the measures utilised in Salthouse (1992) to inform the premise of his *Processing Speed Theory* (Salthouse; 1996). Though psychomotor speed as a factor contributing to scores, was acknowledged in early research by Salthouse, no data has been provided where motor speed was statistically covaried. Instead, the premise of the argument has assumed that even though motor speed may be a factor influencing paper-pencil performance on cognitive tasks, such tasks were adequate measures and were not substantially confounded by motor processes (Salthouse, 1992; Salthouse, 1996). Since then, several other studies based on findings from paper-pencil measures from the Processing Speed Index (PSI) of the WAIS without explicit consideration of hand-motor speed confounding results, have supported findings in line with the *Processing Speed Theory* (i.e., Joy, Fein, Kaplan, & Freedman, 2000; Lu et al., 2011; MacDonald, Hultsch, Strauss, & Dixon, 2003). Furthermore, although the *Processing Speed Theory* has considerable supporting evidence in explaining age-related decline in cognitive performance, it is important to acknowledge that the assumptions provided are broad and holistic, particularly when inferring cognitive skills from motor reaction time measures given that they are reliant on broad sets of cognitive (usually visual) and motor skills. Considering this, tests which rely on a manual response are less able to disassociate specific cognitive processes such as selective and temporal attention and perceptual rate of processing without being confounded by motor performance.

2.5 Inhibitory Deficit Hypothesis

The *Inhibitory Deficit Hypothesis* (Hasher & Zacks, 1988) is an attention-based model of age-group differences in cognitive abilities. The premise of the *Inhibitory Deficit Hypothesis* is that good task performance requires efficient processing of relevant information while simultaneously inhibiting irrelevant information, and that any deficit in this inhibitory-regulation process results in heightened distractibility and sustained access to irrelevant information, greater reliance on environmental cues, reduced working memory capacity, and poorer retrieval of task-relevant details (Hasher & Zacks, 1988). The *Inhibitory Deficit Hypothesis* suggests that age-related declines in cognitive tasks are a result of older adults being less efficient in selectively attending to task-relevant stimuli while simultaneously inhibiting task-irrelevant information. As a result, goal-irrelevant information occupies the limited attention and working memory capacity, at the expense of relevant information, thus resulting in worsened task performance by older adults

(Hasher & Zacks, 1988). Though this argument has strong theoretical merit and has been supported in several studies (i.e., Andrés, Guerrini, Phillips, & Perfect, 2008; Kramer, Humphrey, Larish, & Logan, 1994; Verhaeghen, 2011), an age-related inhibition deficit has not been consistently reported (Ludwig, Borella, Tettamanti, & De Ribaupierre, 2010; Rey-Mermet & Gade, 2018).

Several suggestions have been put forward to account for the discrepancy in results. Such suggestions include the possibility that differences in cognitive functioning and cognitive reserve in the older adult sample varied from study to study and those with more preserved cognitive function attenuated the inhibition deficit (Rey-Mermet & Gade, 2018). It has also been suggested that task-to-task discrepancy which supposedly measure inhibitory control as well as the differences in methods used by researchers to assess and statistically account for processing speed elucidate different results across studies (see Rey-Mermet & Gade., 2018 for a recent meta-analysis on this issue). Furthermore, tasks used to measure inhibitory control often rely on accuracy and response speed on a computerised task, or verbal reaction times i.e., Stroop-tasks (Stroop, 1935), which again introduce the potential confound of hand motor speed or slower orofacial movement in an aged population. A less commonly used measure is eye-tracking, despite its known usefulness and robustness in measuring cognitive domains such as attention and inhibition (Harkin, Miellet, & Kessler, 2012). More specifically, oculomotor functions including visual fixations and saccade duration are surrogate measures of visual attention shifting (Mohler, Goldberg, & Wurtz, 1973; Wurtz & Goldberg, 1989) and are known to be affected by rate of conduction of major retino-cortical pathways i.e., the M pathway from stimulus onset to arrival in cortex (Brown, et al., 2018). Thus, increased age related conduction latency and age related motor decline would be expected to influence eye movements associated with activation and shifts in attention that can provide insight into other complex cognitive abilities such as time taken to process visual information (Chan, Chan, Lee, & Hsiao, 2018).

2.6 The Scaffolding Theory of Aging and Cognition (STAC)

The Scaffolding Theory of Aging and Cognition (STAC; Park & Reuter-Lorenz, 2009) integrates evidence from structural and functional neuroimaging to provide a conceptual model of cognitive aging. The model proposes that the level of cognitive functioning that an older individual achieves is a consequence of both neural/functional deterioration as well as 'compensatory scaffolding' which is utilised to attenuate the adverse effects of the neural and functional decline (See Figure 3). The neural and biological deterioration that occurs with normal aging has been recently shown to include latency of visual information conduction from retina to cortex (Brown et al., 2018) and has been suggested to include cortical thinning, regional atrophy, loss of white matter integrity, dopamine depletion, decreased memory-related recruitment of medial temporal lobe regions (Cabeza et al., 2004; Gutchess et al., 2005) and dysregulation of the default mode network (Park & Reuter-Lorenz, 2009). Authors describe compensatory scaffolding as a 'positive' or adaptive form of plasticity that enables older adults to engage supplementary neural circuits that provide the additional computational support required to preserve cognitive function in the face of neurofunctional decline. For example, the theory postulates that increased frontal activation exhibited by healthy older adults when working on the same cognitive task as younger adults, is a marker of an adaptive brain which engages in 'scaffolding' in response to declines posed by deficits in efficiency of neural structures (Park & Reuter-Lorenz, 2009).

Despite such suggestions, it is unclear exactly how compensatory or scaffolding mechanisms are utilized, and how much these compensatory pathways actually contribute to 'better' performance. According to the theory, the scaffolding mechanisms are suggested to be protective in the aging brain, and the ability for older persons to use such mechanisms are reportedly strengthened by lifestyle factors including higher levels of education, physical activity and exercise (Erickson & Kramer, 2009), while depression is reported to impair scaffolding abilities (Tsai, 2003). However, from the viewpoint of the STAC, it is still unclear as to how such lifestyle factors strengthen the 'scaffolding' mechanisms. If lifestyle factors had this type of positive impact, it can be assumed that increased level of education and physical activity may *protect* against cognitive decline by means of cognitive reserve and healthy vascular systems with minimal associated neuroinflammations, however, mixed results still exist within this realm (Stern, 2002; discussed in more detail below).

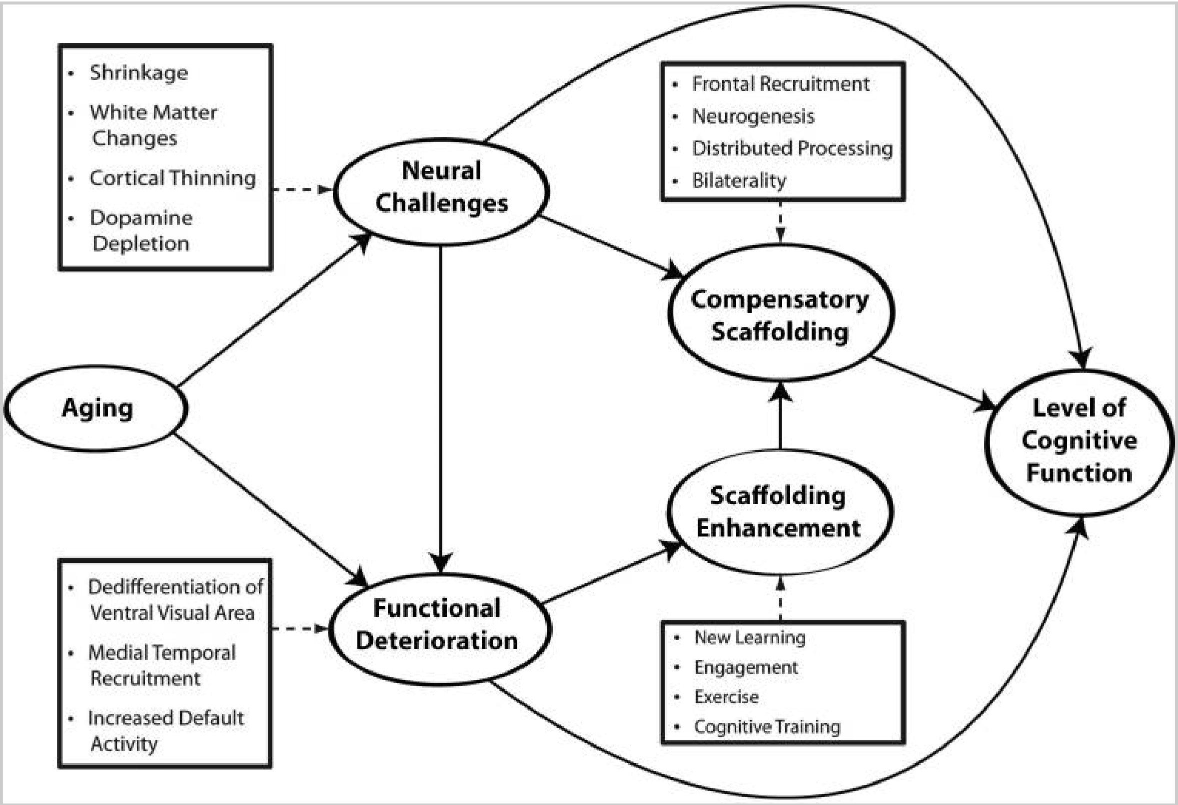

Figure 3. A conceptual model of the Scaffolding Theory of Aging and Cognition (STAC). From "The Adaptive Brain: Aging and Neurocognitive Scaffolding," by D.C.

Park and P. Reuter-Lorenz, 2009, Annual Review of Psychology, 60. Copyright 2019 by Annual Reviews.

2.7 The Cognitive Reserve Hypothesis

The *Cognitive Reserve Hypothesis* postulates that individuals who possess a greater ability to recruit particular brain regions and utilise available neural regions are better able to cope with a greater level of age-related brain pathology i.e., that associated with mild cognitive impairment (MCI), before clinical diagnosis is reached (Stern, 2002). It has also been suggested that this is enabled by means of neural compensation and recruitment of additional brain regions that lead to unimpaired behavioural performance (Stern, 2002). This notion stems from the observation of individuals who were functioning below levels of clinical impairment, despite brain pathology that other individuals who demonstrated clinical impairments also showed (Davis, Schmitt, Wekstein, & Markesbery, 1999; Riley, Snowdon, & Markesbery, 2002). Methods of quantifying 'cognitive reserve' typically involve inferring *reserve* from proxy measures such as educational attainment or current occupation (Jones et al., 2011) which are suggested to "*supply reserve in the form of a set of skills or repertoires that allows some people to cope with pathology better than others*" (Scarmeas & Stern, 2003, p. 625). Indeed, several studies have supported the notion that greater educational attainment can slow the trajectory of age-related cognitive decline and can promote the capacity to process tasks more efficiently (Bennett et al., 2003; Cabeza, Nyberg & Park, 2016). Though this theory has been influential in providing a framework for intact cognitive function in the face of pathology, the body of research is based on proxy measures of 'cognitive reserve' which vary from study to study. More specifically, 'cognitive reserve' is not merely represented using one accepted measure across the scientific literature. Rather, the measures chosen to represent 'cognitive reserve' in the literature, depend on the researchers' theoretical concept of what *reserve* means (Stern, 2002). Anatomical measures including brain size, head circumference, dendritic branching and synaptic count have been suggested as effective measures of reserve (Stern, 2002) though are seldom utilised in cognitive aging research. Although the *Cognitive Reserve Hypothesis* has provided insight into cognitive aging, caution must be taken when interpreting such findings.

2.8 The Frontal Aging Hypothesis

The *Frontal Aging Hypothesis* (Dempster, 1992; Jackson, 1958) is based on the suggestion that selective frontal lobe pathology in the form of reduced volume, metabolism and simultaneous decline in grey matter (Raz et al., 2005) and white matter integrity (Barrick, Charlton, Clark, & Markus, 2010) underlie the cognitive deficits observed in healthy aging, which has mainly been demonstrated using function magnetic resonance imaging (fMRI) or positron emission tomography (PET; Dempster, 1992; Jackson, 1958; West, 2000). This notion is also fundamental to the view that age-related ‘involution’ initiates in the frontal lobe, in turn leading to cognitive decline in apparently healthy aging (Dempster, 1992). The basis of this theory is still relied upon in recent aging literature (i.e., Calso, Besnard & Allain, 2019), with some research even concluding that *“the prefrontal cortex leads most, if not all, other areas in the aging process”* (Dempster, 1992, p. 51). In line with the *Frontal Aging Hypothesis*, research suggests that unlike anterior cortical regions, posterior brain regions are spared through the aging process (Hartley, 1993). The theory that frontal areas of the brain are particularly vulnerable to insult has even extended to theories into the origins of Alzheimer’s disease (AD; Rapoport, 1990). However, criticisms to this theory was pioneered by Greenwood (2000) who provided a thorough critical review of the *Frontal Aging Hypothesis*, and highlighted that healthy older adults are also impaired in cognitive abilities that are largely independent of prefrontal areas, such as visuospatial attention, face recognition, and repetition priming. Furthermore, most recent literature particularly that associated with whole brain imaging demonstrates that additional cortical areas including the temporal and parietal lobes also show compromised integrity with age (McGinnis, Brickhouse, Pascual, & Dickerson, 2011; Klöppel et al., 2018; Fukuda et al., 2018; Grassi et al., 2018; Farina et al., 2017). Such findings suggest against localizing general cognitive decline to the frontal lobe, given that most cognitive functions rely on networks of regions (Greenwood, 2000; Klöppel et al., 2018; Fukuda et al., 2018; Grassi et al., 2018; Farina et al., 2017). Indeed, it has since been suggested that a network-based approach is a better way to conceptualize cognitive aging, as this approach also emphasizes the role of broader neural networks without minimizing the role of the frontal lobes (see Greenwood, 2000).

2.9 Hemispheric Asymmetry Reduction in Older Age (HAROLD) model

The Hemispheric Asymmetry Reduction in Older Age (HAROLD) model (Cabeza, 2002) is based on the premise that age is related to decreases in lateralisation, which stem from fMRI observations that young and older adults recruit different neural networks during the same cognitive task (particularly episodic and working memory tasks). Specifically, it has been reported that young adults display left prefrontal cortex (PFC) activation during verbal working memory tasks and right PFC activation during spatial working memory tasks (Reuter-Lorenz et al., 2000), whereas older adults demonstrate bilateral activation of the PFC while engaging in both verbal and spatial working memory tasks (Reuter-Lorenz et al., 2000). The age-related decreases in lateralisation proposed by this model are suggested to occur due to neural changes and a global reorganisation of neurocognitive networks which result in bilateral activation during cognitive tasks, which may be reflective of compensatory processes (Cabeza, 2002). It is important to note that the HAROLD model has been exclusively described for the PFC, and insight into this model has come from studies predominantly using episodic and working memory tasks (for a review see Berlingeri, Danelli, Bottini, Sberna and

Paulesu, 2013). Again, such explanations are limited to specific brain regions and neglect the more commonly accepted neural network-based perspective of the human brain.

2.10 The Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH)

The CRUNCH model is based on the idea of neural compensation and attempts to explain the distinctiveness of neural representations between young and older adults while performing the same cognitive task (Reuter-Lorenz & Cappell, 2008). Specifically, the CRUNCH model suggests that declines in neural efficiency across the lifespan results in older adults recruiting more neural resources predominantly in the dorsolateral prefrontal cortex compared to young adults when task demands are low (Reuter-Lorenz & Cappell, 2008). However, as task demands increase, neural activation for younger adults exceeds that of older adults, and task performance for older adults is also impaired. Put simply, when task demands exceed a certain level of difficulty, the aging-brain 'falls short' of sufficient activation levels, and task performance declines compared to the younger adults, and this trade-off underpins the premise of the CRUNCH model (Reuter-Lorenz & Cappell, 2008). Task demands have also recently been shown to alter time perception of task duration, whereby duration of a low-cognitive demand task is perceived as substantially shorter than objective time in healthy young and older adults (Ebaid & Crewther, 2018).

Models such as the STAC, HAROLD and the CRUNCH are based on neural compensation in one way or another, and postulate that older adults can perform as well as young adults on cognitive tasks depending on the capacity to recruit additional neural networks which is often indicated by increased effort i.e., increases in energy/neural activation. Another important consideration which opposes the notion that increased activation is indicative of an adaptive brain, stems from the *Neural Efficiency Hypothesis* (Haier et al., 1988) which postulates that more efficient brain functioning is indicated by *lower* brain activation compared to less intelligent individuals, while working on the same cognitive task (predominantly memory tasks). This phenomenon was first described by Haier et al. (1988) using positron emission tomography (PET). More specifically, Haier et al. (1988) demonstrated that healthy young adults with a lower non-verbal IQ score on the Ravens Advanced Progressive Matrices (RAPM) showed more cortical activity throughout the brain when working on the same cognitive task, compared to those individuals with higher RAPM scores. However, this hypothesis was based on a relatively small sample of 30 right-handed healthy young male volunteers and has not been explicitly translated to the healthy aging literature.

2.11 Blood Pressure and Hypertension in Aging

More than 60% of individuals aged 65 years or older, are diagnosed with hypertension, with prevalence rates as high as 80% for individuals older than 85 years of age (Banegas et al., 2012; Buford, 2016), which in turn is a risk factor for cerebral small blood vessel disease (CSVD) and neuroinflammation (Allison & Ditor, 2014; Chen, Zhang, & Huang, 2016). The link between characteristics of CSVD and cognitive decline has been reviewed in a recent study conducted by Liu et al. (2018) who explored hypertensive vasculopathy factors including small vascular lesions, inflammatory reactions, hypoperfusions, and blood-brain barrier damage. They found that all factors associated with hypertension are vital prognostic indicators of the development of cognitive impairment particularly when blood pressure management is poor (Liu et al., 2018). As alluded to earlier in this review, ANS dysregulation has been suggested as a pathophysiological link between hypertension and negative affect, particularly anxiety (Bajkó et al., 2012). In another study investigating how changes in CSVD lesions over 4 years, relate to cognitive decline and incident mild cognitive impairment in 345 hypertensive patients (median age, 65) Jiménez-Balado et al. (2019) found that patients with marked progression of periventricular white matter hyperintensities showed a significant decrease in global cognition (as measured by the Dementia Rating Scale – second version). Jiménez-Balado et al. (2019) also reported that patients with marked progression of periventricular white matter hyperintensities had a higher risk of MCI (i.e., subjective cognitive impairments below clinical thresholds) compared to those without progression. In addition, a longitudinal study examining the association between cognitive dysfunction, hypertension and cognitive deterioration over 5 years in 990 subjects (mean age of 83 years) with cognitive impairment but no diagnosis of dementia, demonstrated that among the individuals with executive function deficits but no memory impairments, 57.7% of subjects with hypertension progressed to dementia compared with only 28.0% with normotension (Oveisgharan & Hachinski, 2010). It was concluded that hypertension predicts progression to dementia in older subjects, and control of hypertension could prevent progression to dementia in one-third of subjects with cognitive impairment (Oveisgharan & Hachinski, 2010).

The relationship between hypertension and cognitive impairments is not always consistently reported however, with some studies that have examined hypertensive vasculopathies such as cerebral microbleeds and cognitive abilities reporting no difference in performance based on the presence of vascular pathologies (Rabelo et al., 2017). Specifically, Rabelo et al. (2017) assessed cognitive performance using neuropsychological measures including the Mini-Mental State Exam (MMSE), the Rey Auditory Verbal Learning Test (RAVLT) and the auditory forward and backward digit span in a sample of patients with AD, MCI, and cognitively healthy adults. The results showed no association between cerebral microbleeds and cognitive performance, as well as no significant differences in cognitive performance when considering the presence of cerebral microbleeds (Rabelo et al., 2017). It may be the case that some markers of hypertensive vasculopathies are not universally effective tools as biomarkers for AD and MCI, particularly in the early phases (Liu et al., 2018). As 20% of cardiac output of the human body is devoted to meeting the brains energy demands (Attwell et al., 2010), protection from hypofusion and ischemic damage is vital, in order to enable cerebral blood flow during fluctuations in arterial pressure (Jackman & Iadecola, 2015). This process is significantly and chronically impaired by CSVD, and consequently takes a large toll on the individual as well as the health care system (see De Silva & Miller, 2016 for a recent review).

Indeed, vascular integrity and cognition in aging is gaining increased attention in the literature and making such issues necessary for future considerations in work pertaining to theories of cognitive aging (De Silva & Miller, 2016; Wang et al., 2015; Gąsecki, Kwarciany, Nyka, Narkiewicz 2013).

2.12 Anxiety in Aging

Lastly, chronic negative affect, i.e., depression and anxiety are often associated with aging (Perna et al., 2016; Burhanullah et al., 2019; Bryant, Jackson, & Ames, 2008). However, it must be emphasised that acute anxiety is an innate biologically adaptive response to potential environmental threats mediated by the hypothalamic-pituitary-adrenal (HPA) axis that affects human behaviour and cognition (Robinson, Vytal, Cornwell, & Grillon, 2013). On the other hand, prolonged anxiety and over-activation of the HPA-axis can also be maladaptive, leading to distortions to the stress response (Strickland & Yacoubi-Loueslati, 2019; Vashist & Schneider, 2014; Herman, et al., 2016; See Figure 4). Thus, prolonged anxiety has been proposed as a causal factor influencing the role of neuropathologic processes and leading to cognitive decline and dementia (Gulpers et al., 2016). Unlike depression which has received substantial attention in the cognitive aging literature in relation to its link with MCI and dementia (Diniz, Butters, Albert, Dew, & Reynolds, 2013), the effects of state and trait anxiety are still unclear (Beaudreau & O'Hara, 2008). What is known, however, are the biological characteristics of chronic anxiety, which in turn may negatively impact cognitive performance (See

Gulpers et al., 2016 and Robinson et al., 2013 for a recent systematic review and meta-analysis).

Gulpers et al. (2016) proposed several potential hypotheses for anxiety leading to cognitive decline, one of which included hypercortisolism, i.e., higher levels of cortisol which in turn negatively affects performance on cognitive tests (Rosnick, Rawson, Butters, & Lenze, 2013). This effect has been suggested to result from overstimulation of glucocorticoid receptors in the medial temporal lobe which in turn leads to hippocampal atrophy (Kristine Erickson, Drevets, & Schulkin, 2003). Furthermore, a role for inflammation i.e., increased levels of cytokines including interleukin-6 and tumor necrosis factor (TNF), has also been suggested as a possible causal pathway between anxiety and cognitive impairment (Gulpers et al., 2016; Reichenberg et al., 2001). Indeed, previous research conducted by Menza et al. (2010) have reported that increased levels of inflammatory cytokines are significantly correlated to worse cognitive performance, where cognitive performance was examined using a composite score comprised of raw scores on tests including the MMSE, the forward and backward digit span tests, and Stroop colour word tests (Stroop, 1935). In addition, Gulpers et al. (2016) have also suggested that decreased levels of brain-derived neurotrophic factor (BDNF) associated with anxiety may also explain the relationship between anxiety and cognitive impairment, given BDNF's essential role in regulating cellular processes that underlie cognition (Nagappan, & Lu, 2014). The prevalence of anxiety in older adults (i.e., those aged over 60 years) can range from 15% in community samples and 56% in clinical samples i.e., hospitalised populations (see Bryant, Jackson, & Ames, 2008 for a review). Despite this, anxiety as a factor contributing to task performance is seldom explicitly addressed in theories of cognitive aging. Cognitive aging research may even benefit from utilising an anxiety screening instrument such as the Depression Anxiety Stress Scale (DASS-21; Lovibond & Lovibond, 1995).

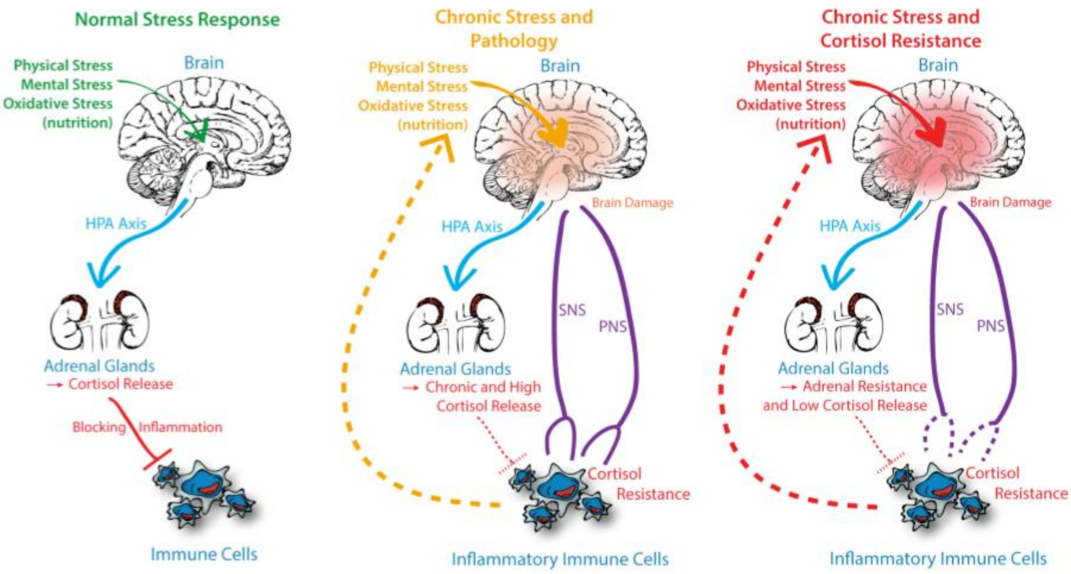

Figure 4. Role of stress induced activation of HPA axis, cortisol, and sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) neurotransmitter release to combat immune cell activation. From "Depression: An Insight and Need for Personalized Psychological Stress Monitoring and Management" by S. K. Vashist and E.M. Schneider, 2014, Journal of Basic & Applied Sciences. Copyright Lifescience Global 2014

2.13 Conclusions

Collectively, these theories have been influential in the cognitive aging literature and have emphasised the importance of considering factors including sensory abilities in all aged populations when assessing cognitive performance, and the effect of motor speed on cognitive processing speed when utilising paper-pencil measures of cognition. Some of these theories have also highlighted the impact of lifestyle factors including level of education, physical activity levels which may play a role in cognitive reserve (Stern, 2002). Despite this, much of the neuropsychological literature does not assess perceptual ability beyond the basic level of acuity (Füllgrabe et al., 2015; Roberts & Allen, 2016) and the most common measures of cognitive processing speed are still reliant on motor speed (see Ebaid et al., 2017). With the advances in neuroscientific tools (i.e., psychophysical measures of perceptual threshold and cognitive processing [Vickers, Nettelbeck, & Willson, 1972], and eye-tracking) future theories of cognitive aging should aim to employ robust and diverse measures, such that a more accurate and holistic understanding of cognitive processing is encapsulated. In addition, the biological markers of aging including changes to hypertension and hypercortisolism associated with anxiety (Gulpers et al., 2016) have the potential to provide in-depth understanding into cognition across the lifespan (see Figure 5). Indeed, consideration of such points could enhance understanding by implementation of a systems neuroscience approach to cognitive aging.

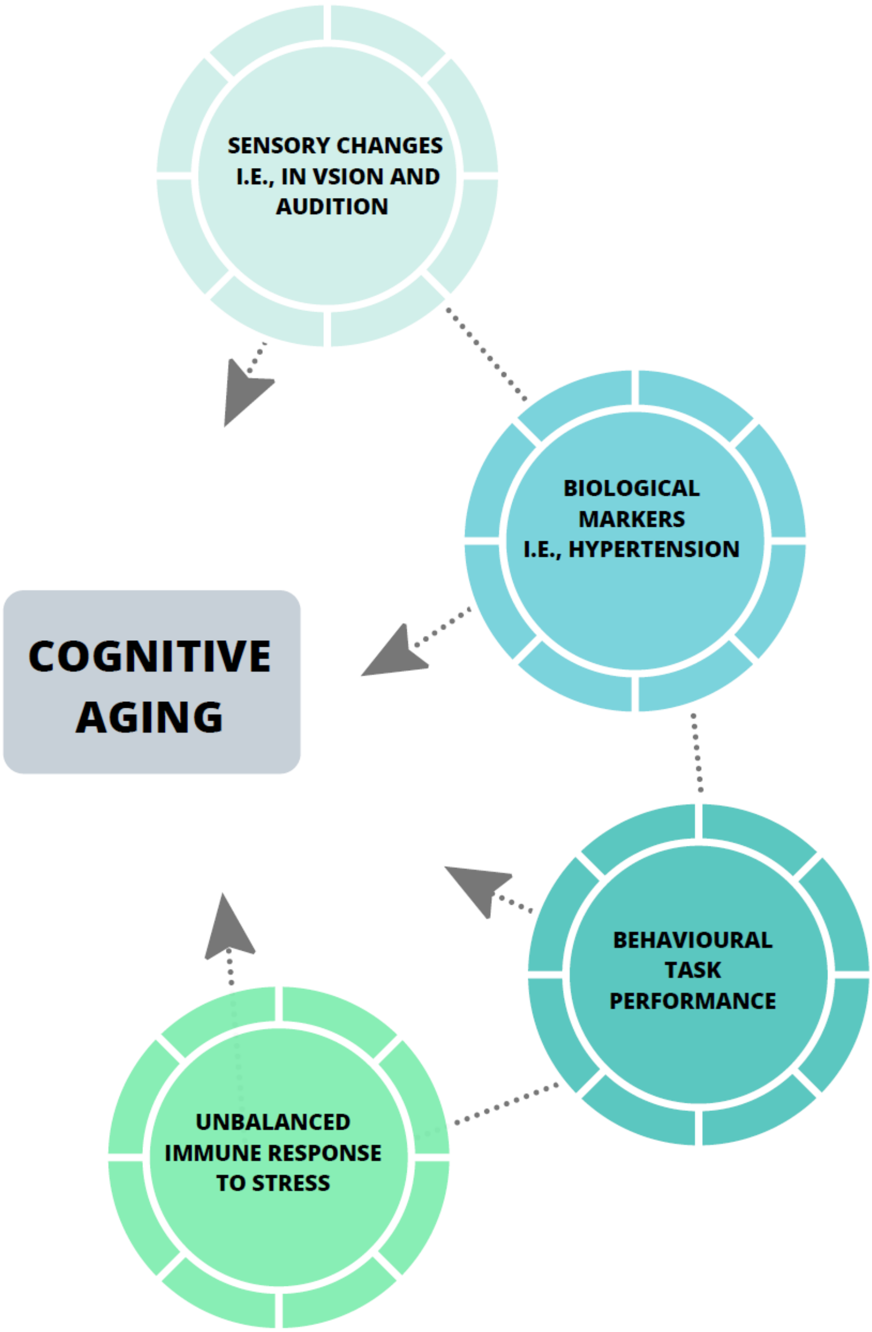

Figure 5. A psychoneuroimmunology viewpoint to cognitive aging.

2.14 References

Aalto, S., Brück, A., Laine, M., Någren, K., & Rinne, J. O. (2005). Frontal and temporal dopamine release during working memory and attention tasks in healthy humans: a positron emission tomography study using the high-affinity dopamine D2 receptor ligand [11C] FLB 457. *Journal of Neuroscience, 25*(10), 2471-2477.

Allison, D. J., & Ditor, D. S. (2014). The common inflammatory etiology of depression and cognitive impairment: a therapeutic target. *Journal of Neuroinflammation, 11*(1), 151.

Andrés, P., Guerrini, C., Phillips, L. H., & Perfect, T. J. (2008). Differential effects of aging on executive and automatic inhibition. *Developmental Neuropsychology, 33*(2), 101-123.

Attwell, D., Buchan, A. M., Charpak, S., Lauritzen, M., MacVicar, B. A., & Newman, E. A. (2010). Glial and neuronal control of brain blood flow. *Nature, 468*(7321), 232.

Bäckman, L., Ginovart, N., Dixon, R. A., Wahlin, T.-B. R., Wahlin, Å., Halldin, C., & Farde, L. (2000). Age-related cognitive deficits mediated by changes in the striatal dopamine system. *American Journal of Psychiatry, 157*(4), 635-637.

Bäckman, L., Lindenberger, U., Li, S.-C., & Nyberg, L. (2010). Linking cognitive aging to alterations in dopamine neurotransmitter functioning: recent data and future avenues. *Neuroscience & Biobehavioral Reviews, 34*(5), 670-677.

Bajkó, Z., Szekeres, C.-C., Kovács, K. R., Csapó, K., Molnár, S., Soltész, P., . . . Bereczki, D. (2012). Anxiety, depression and autonomic nervous system dysfunction in hypertension. *Journal of the Neurological Sciences, 317*(1-2), 112-116.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology and Aging, 12*(1), 12-21. doi:Doi 10.1037/0882-7974.12.1.12

Banegas, J. R., Graciani, A., de la Cruz-Troca, J. J., León-Muñoz, L. M., Guallar-Castillón, P., Coca, A., . . . Rodríguez-Artalejo, F. (2012). Achievement of cardiometabolic goals in aware hypertensive patients in Spain: a nationwide population-based study. *Hypertension, 60*(4), 898-905.

Barrick, T. R., Charlton, R. A., Clark, C. A., & Markus, H. S. (2010). White matter structural decline in normal ageing: A prospective longitudinal study using tract-based spatial statistics. *NeuroImage, 51*(2), 565-577. doi:10.1016/j.neuroimage.2010.02.033

Beaudreau, S. A., & O'Hara, R. (2008). Late-life anxiety and cognitive impairment: a review. *The American Journal of Geriatric Psychiatry, 16*(10), 790-803.

Bennett, D. A., Wilson, R., Schneider, J., Evans, D., De Leon, C. M., Arnold, S., . . . Bienias, J. (2003). Education modifies the relation of AD pathology to level of cognitive function in older persons. *Neurology, 60*(12), 1909-1915.

Berlingeri, M., Danelli, L., Bottini, G., Sberna, M., & Paulesu, E. (2013). Reassessing the HAROLD model: is the hemispheric asymmetry reduction in older adults a special case of compensatory-related utilisation of neural circuits? *Experimental Brain Research, 224*(3), 393-410.

Birren, J. E. (1965). Age changes in speed of behavior: Its central nature and physiological correlates. *Behavior, Aging, and the Nervous System*, 191-216.

Brown, A. C., Corner, M., Crewther, D. P., & Crewther, S. G. (2018). Age related decline in cortical multifocal flash VEP: Latency increases shown to be predominately magnocellular. *Frontiers in Aging Neuroscience*, *10*, 430.

Bryant, C., Jackson, H., & Ames, D. (2008). The prevalence of anxiety in older adults: methodological issues and a review of the literature. *Journal of Affective Disorders, 109*(3), 233-250.

Buford, T. W. (2016). Hypertension and aging. *Ageing Research Reviews*, *26*, 96-111.

Burhanullah, M. H., Tschanz, J. T., Peters, M. E., Leoutsakos, J. M., Matyi, J., Lyketsos, C. G., ... & Rosenberg, P. B. (2019). Neuropsychiatric symptoms as risk factors for cognitive decline in clinically normal older adults: The cache county study. *The American Journal of Geriatric Psychiatry 28*(1), 64-71.

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging, 17*(1), 85-100.

Cabeza, R., Daselaar, S. M., Dolcos, F., Prince, S. E., Budde, M., & Nyberg, L. (2004). Task-independent and task-specific age effects on brain activity during working memory, visual attention and episodic retrieval. *Cerebral Cortex*, *14*(4), 364-375.

Cabeza, R., Nyberg, L., & Park, D. C. (2016). *Cognitive neuroscience of aging: Linking cognitive and cerebral aging*: Oxford University Press.

Calso, C., Besnard, J., & Allain, P. (2019). Frontal lobe functions in normal aging: metacognition, autonomy, and quality of life. *Experimental Aging Research, 45*(1), 10-27.

Chen, W. W., Zhang, X. I. A., & Huang, W. J. (2016). Role of neuroinflammation in neurodegenerative diseases. *Molecular Medicine Reports*, *13*(4), 3391-3396.

Costello, M. C., Madden, D. J., Mitroff, S. R., & Whiting, W. L. (2010). Age-related decline of visual processing components in change detection. *Psychology and Aging, 25*(2), 356. doi:10.1037/a0017625

Davis, D., Schmitt, F., Wekstein, D., & Markesbery, W. (1999). Alzheimer neuropathologic alterations in aged cognitively normal subjects. *Journal of Neuropathology & Experimental Neurology, 58*(4), 376-388.

De Silva, T. M., & Miller, A. A. (2016). Cerebral small vessel disease: targeting oxidative stress as a novel therapeutic strategy? *Frontiers in Pharmacology, 7,* 61.

Del Arco, A., & Mora, F. (2008). Prefrontal cortex–nucleus accumbens interaction: in vivo modulation by dopamine and glutamate in the prefrontal cortex. *Pharmacology Biochemistry & Behavior*, *90*(2), 226-235.

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review, 12*(1), 45-75.

Diniz, B. S., Butters, M. A., Albert, S. M., Dew, M. A., & Reynolds, C. F. (2013). Late-life depression and risk of vascular dementia and Alzheimer's disease: systematic review and meta-analysis of community-based cohort studies. *The British Journal of Psychiatry, 202*(5), 329-335.

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A., & Crewther, D. P. (2017). Cognitive processing speed across the lifespan: Beyond the influence of motor speed. *Frontiers in Aging Neuroscience, 9*, 62. doi:10.3389/fnagi.2017.00062

Ebaid, D., & Crewther, S. G. (2018). Temporal aspects of memory: A comparison of memory performance, processing speed and time estimation between young and older adults. *Frontiers in Aging Neuroscience*, *10*.

Ebaid, D., & Crewther, S. G. (2019). Visual information processing in young and older adults. *Frontiers in Aging Neuroscience, 11*, 116.

Eckert, M. (2011). Slowing down: Age-related neurobiological predictors of processing speed. *Frontiers in Neuroscience, 5*(25). doi:10.3389/fnins.2011.00025

Egerton, A., Mehta, M. A., Montgomery, A. J., Lappin, J. M., Howes, O. D., Reeves, S. J., . . . Grasby, P. M. (2009). The dopaminergic basis of human behaviors: a review of molecular imaging studies. *Neuroscience & Biobehavioral Reviews, 33*(7), 1109-1132.

Erickson, K., Drevets, W., & Schulkin, J. (2003). Glucocorticoid regulation of diverse cognitive functions in normal and pathological emotional states. *Neuroscience & Biobehavioral Reviews, 27*(3), 233-246.

Erickson, K., & Kramer, A. F. (2009). Aerobic exercise effects on cognitive and neural plasticity in older adults. *British Journal of Sports Medicine, 43*(1), 22-24.

Erixon-Lindroth, N., Farde, L., Wahlin, T.-B. R., Sovago, J., Halldin, C., & Bäckman, L. (2005). The role of the striatal dopamine transporter in cognitive aging. *Psychiatry Research: Neuroimaging, 138*(1), 1-12.

Farina, E., Baglio, F., Pomati, S., D'Amico, A., Campini, I. C., Di Tella, S., ... & Pozzo, T. (2017). The mirror neurons network in aging, mild cognitive impairment, and Alzheimer disease: a functional MRI study. *Frontiers in Aging Neuroscience, 9*, 371.

Fukuda, M., Omodaka, K., Tatewaki, Y., Himori, N., Matsudaira, I., Nishiguchi, K. M., ... & Nakazawa, T. (2018). Quantitative MRI evaluation of glaucomatous changes in the visual pathway. *PloS One, 13*(7), e0197027.

Füllgrabe, C., Moore, B. C., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience, 6*, 347.

Gaffey, A. E., Bergeman, C. S., Clark, L. A., & Wirth, M. M. (2016). Aging and the HPA axis: Stress and resilience in older adults. *Neuroscience & Biobehavioral Reviews*, *68*, 928-945.

Gąsecki, D., Kwarciany, M., Nyka, W., & Narkiewicz, K. (2013). Hypertension, brain damage and cognitive decline. *Current Hypertension Reports*, *15*(6), 547-558.

Gennis, V., Garry, P. J., Haaland, K. Y., Yeo, R. A., & Goodwin, J. S. (1991). Hearing and cognition in the elderly: new findings and a review of the literature. *Archives of Internal Medicine, 151*(11), 2259-2264.

Grassi, M., Loewenstein, D. A., Caldirola, D., Schruers, K., Duara, R., & Perna, G. (2018). A clinically-translatable machine learning algorithm for the prediction of Alzheimer's disease conversion: further evidence of its accuracy via a transfer learning approach. *International Psychogeriatrics,* 1-9.

Greenwood, P. M. (2000). The frontal aging hypothesis evaluated. *Journal of the International Neuropsychological Society, 6*(6), 705-726.

Gulpers, B., Ramakers, I., Hamel, R., Köhler, S., Voshaar, R. O., & Verhey, F. (2016). Anxiety as a predictor for cognitive decline and dementia: a systematic review and meta-analysis. *The American Journal of Geriatric Psychiatry*, *24*(10), 823-842.

Gupta, D., & Morley, J. E. (2011). Hypothalamic-Pituitary-Adrenal (HPA) Axis and Aging. *Comprehensive Physiology*, *4*(4), 1495-1510.

Gutchess, A. H., Welsh, R. C., Hedden, T., Bangert, A., Minear, M., Liu, L. L., & Park, D. C. (2005). Aging and the neural correlates of successful picture encoding: frontal activations compensate for decreased medial-temporal activity. *Journal of Cognitive Neuroscience, 17*(1), 84-96.

Haier, R. J., Siegel, B. V., Nuechterlein, K. H., Hazlett, E., Wu, J. C., Paek, J., . . . Buchsbaum, M. S. (1988). Cortical glucose metabolic-rate correlates of abstract reasoning and attention studied with Positron Emission Tomography. *Intelligence, 12*(2), 199-217. doi:10.1016/0160-2896(88)90016-5

Harkin, B., Miellet, S., & Kessler, K. (2012). What checkers actually check: An eye tracking study of inhibitory control and working memory. *PloS One, 7*(9), e44689.

Hartley, A. A. (1993). Evidence for the selective preservation of spatial selective attention in old age. *Psychology and Aging, 8*(3), 371.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In *Psychology of Learning and Motivation* (Vol. 22, pp. 193-225): Elsevier.

Herman, J. P., McKlveen, J. M., Ghosal, S., Kopp, B., Wulsin, A., Makinson, R., ... & Myers, B. (2016). Regulation of the hypothalamic-pituitary-adrenocortical stress response. *Comprehensive Physiology, 6*(2), 603.

Hofer, S. M., Berg, S., & Era, P. (2003). Evaluating the interdependence of aging-related changes in visual and auditory acuity, balance, and cognitive functioning. *Psychology and Aging, 18*(2), 285.

Humes, L. E., Busey, T. A., Craig, J., & Kewley-Port, D. (2013). Are age-related changes in cognitive function driven by age-related changes in sensory processing? *Attention, Perception, & Psychophysics, 75*(3), 508-524.

Jackman, K., & Iadecola, C. (2015). Neurovascular regulation in the ischemic brain. *Antioxidants & Redox Signaling, 22*(2), 149-160.

Jackson, J. H. (1958). *Selected writings of John Hughlings Jackson* (Vol. 1): Staples Press.

Jiménez-Balado, J., Riba-Llena, I., Abril, O., Garde, E., Penalba, A., Ostos, E., . . . Mundet, X. (2019). Cognitive Impact of Cerebral Small Vessel Disease Changes in Patients With Hypertension. *Hypertension, 73*(2), 342-349.

Jones, R. N., Manly, J., Glymour, M. M., Rentz, D. M., Jefferson, A. L., & Stern, Y. (2011). Conceptual and measurement challenges in research on cognitive reserve. *Journal of the International Neuropsychological Society, 17*(4), 593-601.

Joy, S., Fein, D., Kaplan, E., & Freedman, M. (2000). Speed and memory in WAIS–R–NI Digit Symbol performance among healthy older adults. *Journal of the International Neuropsychological Society, 6*(7), 770-780.

Klöppel, S., Yang, S., Kellner, E., Reisert, M., Heimbach, B., Urbach, H., ... & Lahr, J. (2018). Voxel-wise deviations from healthy aging for the detection of region-specific atrophy. *NeuroImage: Clinical, 20*, 851-860.

Kramer, A. F., Humphrey, D. G., Larish, J. F., & Logan, G. D. (1994). Aging and inhibition: beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9*(4), 491.

Langhorne, P., Coupar, F., & Pollock, A. (2009). Motor recovery after stroke: a systematic review. *The Lancet Neurology, 8*(8), 741-754.

Li, S.-C., & Lindenberger, U. (1999). Cross-level unification: A computational exploration of the link between deterioration of neurotransmitter systems and dedifferentiation of cognitive abilities in old age. In *Cognitive neuroscience of memory* (pp. 103-146): Hogrefe & Huber.

Li, S.-C., Lindenberger, U., & Sikström, S. (2001). Aging cognition: from neuromodulation to representation. *Trends in Cognitive Sciences, 5*(11), 479-486.

Li, S.-C., & Sikström, S. (2002). Integrative neurocomputational perspectives on cognitive aging, neuromodulation, and representation. *Neuroscience & Biobehavioral Reviews, 26*(7), 795-808.

Li, S.-C., von Oertzen, T., & Lindenberger, U. (2006). A neurocomputational model of stochastic resonance and aging. *Neurocomputing, 69*(13-15), 1553-1560.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: a strong connection. *Psychology and Aging, 9*(3), 339-355.

Liu, Y., Dong, Y.-H., Lyu, P.-Y., Chen, W.-H., & Li, R. (2018). Hypertension-Induced Cerebral Small Vessel Disease Leading to Cognitive Impairment. *Chinese Medical Journal, 131*(5), 615.

Lovibond, S. H., & Lovibond, P. F. (1995). Manual for the depression anxiety stress scale (2nd ed.). Sydney: Psychology Foundation of Australia.

Lu, B., Nagappan, G., & Lu, Y. (2014). BDNF and synaptic plasticity, cognitive function, and dysfunction. In *Neurotrophic Factors* (pp. 223-250): Springer.

Lu, P. H., Lee, G. J., Raven, E. P., Tingus, K., Khoo, T., Thompson, P. M., & Bartzokis, G. (2011). Age-related slowing in cognitive processing speed is associated with myelin integrity in a very healthy elderly sample. *Journal of Clinical and Experimental Neuropsychology, 33(*10), 1059-1068.

Ludwig, C., Borella, E., Tettamanti, M., & De Ribaupierre, A. (2010). Adult age differences in the Color Stroop Test: A comparison between an Item-by-item and a Blocked version. *Archives of Gerontology and Geriatrics, 51*(2), 135-142.

Luo, S. X., & Huang, E. J. (2016). Dopaminergic neurons and brain reward pathways: from neurogenesis to circuit assembly. *The American Journal of Pathology, 186*(3), 478-488.

MacDonald, S. W., Cervenka, S., Farde, L., Nyberg, L., & Bäckman, L. (2009). Extrastriatal dopamine D2 receptor binding modulates intraindividual variability in episodic recognition and executive functioning. *Neuropsychologia, 47*(11), 2299-2304.

MacDonald, S. W., Hultsch, D. F., Strauss, E., & Dixon, R. A. (2003). Age-related slowing of digit symbol substitution revisited: what do longitudinal age changes reflect? *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 58*(3), P187-P194.

McGinnis, S. M., Brickhouse, M., Pascual, B., & Dickerson, B. C. (2011). Age-related changes in the thickness of cortical zones in humans. *Brain topography, 24*(3-4), 279.

Menza, M., Dobkin, R. D., Marin, H., Mark, M. H., Gara, M., Bienfait, K., . . . Kusnekov, A. (2010). The role of inflammatory cytokines in cognition and other non-motor symptoms of Parkinson’s disease. *Psychosomatics, 51*(6), 474-479.

Mohler, C. W., Goldberg, M. E., & Wurtz, R. H. (1973). Visual receptive fields of frontal eye field neurons. *Brain Research, 61*(3), 85-83.

Nienborg, H., & Jacob, S. (2018). Monoaminergic neuromodulation of sensory processing. *Frontiers in Neural Circuits, 12*, 51.

Oster, C. (1976). Sensory deprivation in geriatric patients. *Joural of the American Geriatric Society*, *24*(10), 461-464.

Oveisgharan, S., & Hachinski, V. (2010). Hypertension, executive dysfunction, and progression to dementia: the canadian study of health and aging. *Archives of Neurology*, *67*(2), 187-192.

Parashar, R., Amir, M., Pakhare, A., Rathi, P., & Chaudhary, L. (2016). Age related changes in autonomic functions. *Journal of Clinical and Diagnostic Research 10*(3), CC11.

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual Review of Psychology, 60*, 173-196.

Perna, G., Iannone, G., Alciati, A., & Caldirola, D. (2016). Are anxiety disorders associated with accelerated aging? A focus on neuroprogression. *Neural Plasticity, 2016*.

Pfeifer, M. A., Weinberg, C. R., Cook, D., Best, J. D., Reenan, A., & Halter, J. B. (1983). Differential changes of autonomic nervous system function with age in man. *The American Journal of Medicine, 75*(2), 249-258.

Rabelo, A. G., Teixeira, C. V., Magalhães, T. N., Carletti-Cassani, A. F. M., Amato Filho, A. C., Joaquim, H. P., . . . Secolin, R. (2017). Is cerebral microbleed prevalence relevant as a biomarker in amnestic mild cognitive impairment and mild Alzheimer's disease? *The Neuroradiology Journal, 30*(5), 477-485.

Rapoport, S. (1990). Topography of Alzheimer's disease: Involvement of association neocortices and connected regions; pathological, metabolic and cognitive correlations; relation to evolution. In *Imaging, Cerebral Topography And Alzheimer's Disease* (pp. 1-17): Springer.

Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., . . . Acker, J. D. (2005). Regional brain changes in aging healthy adults: general trends, individual differences and modifiers. *Cerebral Cortex, 15*(11), 1676-1689. doi:10.1093/cercor/bhi044

Reichenberg, A., Yirmiya, R., Schuld, A., Kraus, T., Haack, M., Morag, A., & Pollmächer, T. (2001). Cytokine-associated emotional and cognitive disturbances in humans. *Archives of General Psychiatry, 58*(5), 445-452.

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science, 17*(3), 177-182.

Reuter-Lorenz, P. A., Jonides, J., Smith, E. E., Hartley, A., Miller, A., Marshuetz, C., & Koeppe, R. A. (2000). Age differences in the frontal lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience, 12*(1), 174-187.

Rey-Mermet, A., & Gade, M. (2018). Inhibition in aging: What is preserved? What declines? A meta-analysis. *Psychonomic Bulletin & Review, 25*(5), 1695-1716.

Riley, K. P., Snowdon, D. A., & Markesbery, W. R. (2002). Alzheimer's neurofibrillary pathology and the spectrum of cognitive function: findings from the Nun Study. *Annals of Neurology, 51*(5), 567-577.

Roberts, K. L., & Allen, H. A. (2016). Perception and cognition in the ageing brain: a brief review of the short-and long-term links between perceptual and cognitive decline. *Frontiers in Aging Neuroscience, 8*, 39.

Robinson, O. J., Vytal, K., Cornwell, B. R., & Grillon, C. (2013). The impact of anxiety upon cognition: perspectives from human threat of shock studies. *Frontiers in Human Neuroscience, 7*, 203.

Rosnick, C. B., Rawson, K. S., Butters, M. A., & Lenze, E. J. (2013). Association of cortisol with neuropsychological assessment in older adults with generalized anxiety disorder. *Aging & Mental Health, 17*(4), 432-440.

Salthouse. (1985). Speed of behavior and its implications for cognition.

Salthouse, T. A. (1992). Influence of processing speed on adult age differences in working memory. *Acta Psychologica, 79*(2), 155-170.

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

Salthouse, T. A. (2000). Aging and measures of processing speed. *Biological Psychology, 54*(1-3), 35-54.

Scarmeas, N., & Stern, Y. (2003). Cognitive reserve and lifestyle. *Journal of Clinical and Experimental Neuropsychology, 25*(5), 625-633.

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. C. T. A. Salthouse (Ed.), *The Handbook of Aging and Cognition, 2nd ed* (pp. 155-219). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Shimazu T, Tamura N, & Shimazu K. (2005) Aging of the autonomic nervous system. N*ihon Rinsho, 63*(6), 973-977.

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

Strickland, M., Yacoubi-Loueslati, B., Bouhaouala-Zahar, B., Pender, S. L., & Larbi, A. (2019). Relationships between ion channels, mitochondrial functions and inflammation in human aging. *Frontiers in Physiology*, *10*.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643.

Telzer, E. H. (2016). Dopaminergic reward sensitivity can promote adolescent health: A new perspective on the mechanism of ventral striatum activation. *Developmental Cognitive Neuroscience, 17*, 57-67.

Tsai, S.-J. (2003). Brain-derived neurotrophic factor: a bridge between major depression and Alzheimer's disease? *Medical hypotheses, 61*(1), 110-113.

Valentijn, S. A., van Boxtel, M. P., van Hooren, S. A., Bosma, H., Beckers, H. J., Ponds, R. W., & Jolles, J. (2005). Change in sensory functioning predicts change in cognitive functioning: results from a 6-year follow-up in the maastricht aging study. *Journal of the American Geriatric Society, 53*(3), 374-380. doi:10.1111/j.1532-5415.2005.53152.x

Vashist, S. K., & Schneider, E. M. (2014). Depression: An insight and need for personalized psychological stress monitoring and management. *Journal of Basic and Applied Sciences, 10,* 177-182.

Verhaeghen, P. (2011). Aging and executive control: Reports of a demise greatly exaggerated. *Current Directions in Psychological Science, 20*(3), 174-180.

Vickers, D., Nettelbeck, T., & Willson, R. (1972). Perceptual indices of performance: the measurement of 'inspection time'and 'noise'in the visual system. *Perception, 1*(3), 263-295.

Wang, R., Fratiglioni, L., Laukka, E. J., Lövdén, M., Kalpouzos, G., Keller, L., . . . Qiu, C. (2015). Effects of vascular risk factors and APOE ε4 on white matter integrity and cognitive decline. *Neurology, 84*(11), 1128-1135.

Wang, Y., Chan, G. L., Holden, J. E., Dobko, T., Mak, E., Schulzer, M., . . . Calne, D. B. (1998). Age-dependent decline of dopamine D1 receptors in human brain: A PET study. *Synapse, 30*(1), 56-61.

Wechsler, D., & De Lemos, M. M. (1981). *Wechsler Adult Intelligence Scale-Revised*: Harcourt Brace Jovanovich.

Welberg, L. (2008). A split (mid)brain for dopamine. *Nature Reviews Neuroscience, 9,* 326. doi:10.1038/nrn2381

West, R. (2000). In defense of the frontal lobe hypothesis of cognitive aging. *Journal of the International Neuropsychological Society, 6*(6), 727-729. doi:10.1017/S1355617700666109

Wurtz, R. H., & Goldberg, M. E. (1989). *The neurobiology of saccadic eye movements* (Vol. 3): Elsevier Science Limited.

Zekveld, A. A., Kramer, S. E., & Festen, J. M. (2011). Cognitive load during speech perception in noise: the influence of age, hearing loss, and cognition on the pupil response. *Ear Hear, 32*(4), 498-510. doi:10.1097/AUD.0b013e31820512bb

chapter 3

03.

CHAPTER 3

Methodological Issues

3.1 Chapter Overview

Specific details of the methods used in each study are provided in the relevant/appropriate chapters of this thesis. This chapter provides an additional brief discussion of key methodological choices and will specifically address the choice of population, screening procedures and the choice of experimental measures and analysis.

3.2 Choice of Population

3.2.1 Age

In current literature, research consistently suggests that cognitive decline in domains such as processing speed and working memory begin from age 30 in healthy individuals (Salthouse, 2009; Park & Reuter-Lorenz, 2009). Furthermore, in cognitive aging literature, the arbitrary category of 'older adults' mainly considers those adults aged 60 years or older (Salthouse, 2009; Park & Reuter-Lorenz, 2009). Thus, we selected a population that included 107 healthy adults aged between 18 - 81 years, that we divided into a young, middle-age and older adult group. Specifically, we chose 67 young adults aged between 18-29 (*M*age=19.64, SD = 2.26), of whom 59 were female and 8 were male. We also selected 7 middle-age adults (*M*age = 49.85, SD = 2.31, age range = 40-59) who were all male, and 33 older adults (*M*age=66.70, SD = 9.72, age range = 60-81) of whom 8 were male and 25 were female. Given that the main aim of this thesis was to examine cognitive processing in young and older adults, the majority of our analyses do not include the middle-aged participants and are conducted solely on the young and older sample. This is specified in the appropriate section in the experimental chapters. Furthermore, the results reported in the different experimental chapters are based on independent sub-samples of the aforementioned population, and this is also mentioned in the appropriate section of each experimental chapter.

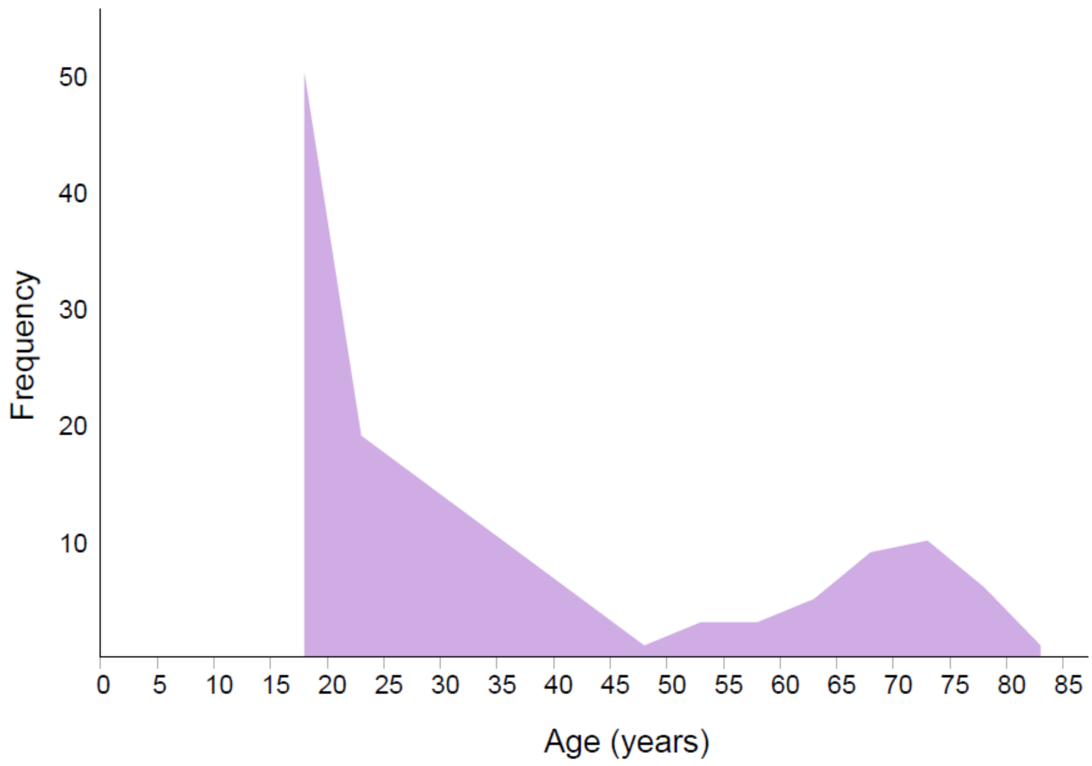

Figure 1. Area chart depicting the age distribution of participants.

3.2.2 Gender

To date, there is little robust evidence to suggest gender-differences in cognitive performance in any age-group. Indeed, much of the research in this area remains inconclusive and is mainly studied with neuroimaging (see Hill et al 2014; Reed et al., 2017; Ritchie et al., 2018). Thus, since the overarching aim of our experimental program was not to directly assess gender differences in cognitive performance within or between age-groups, it was deemed acceptable to have a sample that were predominantly female and not statistically different in any other important variable relevant to this thesis.

3.2.3 Education

Research has consistently suggested that education provides an advantage on cognition, such that persons with more years of education have higher levels of cognitive function throughout their adult life (Bennett et al., 2003; Harada, Love & Triebel, 2013;

Ritchie et al., 2013). However, research also suggests cognitive performance decrements to be related to time since completion of education as measured by tests of working memory, flexibility, processing speed, and verbal and non-verbal reasoning (Guerra-Carrillo, Katovich, & Bunge, 2017). Indeed, this may be due to individuals not maintaining a high level of cognitive function after completion of education. To date, much of the research that examines cognitive performance between young and older adults, simply reports on years of completed education in the young and older sample without considering time since completion of education, or whether those older participants are currently engaged in education programs at the time of the experiment (Ball, et al., 2002; Baudouin, Isingrini & Vanneste, 2018). Thus, with consideration of such points, we chose to use two educated age-groups who were both currently enrolled in tertiary education at the time of participation in our experimental program.

The young sample chosen for this thesis were first year Psychology students who were enrolled in their course at La Trobe University, Melbourne campus, at the time of the experiment. Given this, our young sample, at the very least, had all obtained the Victorian Certificate of Education (VCE), signifying satisfactory completion of secondary education. Accordingly, we chose an older sample who had a similar education profile as the young adults. Although, it is near impossible to balance years of education when comparing an older population with a younger population due to age constraints in the young sample, level and type of education can be accounted for, as well as current enrolment in education, whether that be for leisure or for attainment of a degree. Thus, we recruited the older population from the University of the Third Age (U3A) Manningham, Melbourne, Victoria which is an international volunteer organization where interested older individuals can come together and collaboratively learn for vocational purposes, rather than for any qualifications (for more information please visit www.u3a.org.au). Older adults from our sample were highly educated, and at the least had all completed secondary school, with some holding masters and doctoral degrees (Table 1a in Chapter 3 depicts this information). Despite past research sometimes using an older sample who have obtained university degrees several years prior, we aimed to recruit an older sample who were educated and continuing to engage in study even for vocational purposes.

3.3 Exclusion criteria

As the aim of this thesis was to examine cognitive processing in healthy aging, exclusion criteria included previous diagnosis of a neurological disorder given its potential impact on performance on the cognitive tasks used in our experimental program (Hachinski, et al., 2006). This information was obtained through self-reports during the recruitment stage via phone or face-to-face interview.

3.4 Choice of Screening Measures

Sensory system declines in the vision and auditory domain that occur in healthy aging are suggested to be interconnected with cognitive decline observed across the lifespan (Baltes & Lindenberger, 1997). Accordingly, vision and hearing were screened in all participants for pathology beyond age-related decline that may independently affect cognitive task performance.

3.4.1 Vision

Normal or corrected-to-normal vision was screened by Professor Sheila G. Crewther who is an optometrist. Visual domains which were screened included near and far visual acuity using a Snellen chart, and visual acuity, in which 6/6 was ensured. Colour vision was tested using the Ishihara test, and participants were asked for any current or previous history of optical disease. Participants were also asked if their optometric script had been updated within the last 2 years.

3.4.2 Hearing

Adequate hearing was indicated by the participants being able to comprehend verbal instructions. Verbal instructions from the computer were first presented to participants with low volume which we gradually increased until the participant reported adequate hearing. Supra-threshold volume was then chosen. Any participant who wore hearing aids were able to keep them in during the experimental procedure. Given that most of our tasks relied on visual information processing and that vision was the main sensory domain of interest for this thesis, hearing sensitivity, i.e., pure-tone or speech audiometry was not explicitly assessed.

3.4.3 Depression Anxiety and Stress

Previous research has reported that mood and cognitive performance are closely related, particularly in the elderly (Beaudreau & O'Hara, 2008; Beaudreau & O'Hara, 2009). Hence, the Depression Anxiety and Stress Scale (DASS-21; Lovibond & Lovibond, 1995) which is a 21-item self-report instrument that measures negative emotional states relating to depression, anxiety and stress, was used as a screening tool. The DASS-21 identified whether participants had negative emotional states beyond a 'mild' level (i.e., depression > 6, anxiety > 5, or stress > 9) that might independently affect performance on the cognitive tasks (Beaudreau & O'Hara, 2008; Beaudreau & O'Hara, 2009). Exclusion of any participant on this basis was not necessary. Rather, the DASS-21 scores allowed us to experimentally examine the effect of depression, anxiety, and stress symptoms on cognitive performance.

3.5 Experimental Tasks

As the aim of this thesis was to investigate cognitive performance changes with age, choices of experimental tasks were restricted to those that contribute to speed and accuracy of visual and motor performance. These tasks are individually described in more detail below.

3.5.1 Wechsler Adult Intelligence Scale (WAIS; Wechsler, 2008) Subsets

Cognitive processing in the healthy aging literature is predominantly tested using paper-pencil tasks from the WAIS which mainly rely on a written response (i.e., Cornelis et al., 2014; Joy, Kaplan, & Fein, 2004). Thus, we chose to use WAIS subsets in our experimental program as traditional measures of cognitive performance, as well as correlative measures of intellectual functioning (Lichtenberger & Kaufman, 2009). The Symbol Search and Coding subtests from the Information Processing Speed Index (PSI) of WAIS-IV were administered for two minutes each as per the WAIS-IV kit instructions. These tests were used as common classical measures of processing speed that rely on fast motor responses for overall rapid performance. Furthermore, the forward and backward digit span tasks were adapted from the Auditory Digit Span subset of the WAIS 4th Edition (Wechsler, 2008) and used as measures of memory. A customized digit span task made using Authorware Professional Software was administered visually and auditorally on an Apple iMac (Retina 4K) computer with a 21.5-inch monitor. These subtests from the WAIS were compared against age appropriate norms to ensure adequate performance. Given this and the fact that our older participants were highly educated and still participating in vocational tertiary education, it was decided not to administer an independent screening of intellectual function such as the Mini-Mental State Exam (MMSE; McHugh, 1975).

3.5.2 Traditional Measures of Motor Dexterity: The Purdue Pegboard (Reddon, Gill, Gauk, & Maerz, 1988)

Given that past research examining cognitive processing speed in an aged population have not experimentally accounted for the contribution of motor speed to such

WAIS tasks (i.e., Cornelis et al., 2014; Joy, Kaplan, & Fein, 2004), we chose to use the Purdue Pegboard (Reddon, Gill, Gauk, & Maerz, 1988) as a measure of motor dexterity (Tiffin & Asher, 1948) in addition to our WAIS subtests. This Purdue Pegboard was utilised to enable statistical control of hand-motor speed from the aforementioned paper-pencil measures of cognitive processing speed.

3.5.3 Psychophysical Measures

Alternative measures to assess aspects of cognitive processing were chosen based on their ability to measure speed of visual processing without any confound of motor speed. Specifically, psychophysical measures were used to examine threshold estimation times and rates of visual information processing during visual tasks, which allowed statistical comparison to traditional measures of cognitive performance mentioned above. In particular, a modified Inspection Time (IT) task, based on the version of Vickers, Nettelbeck, and Willson (1972), was adapted using Vpixx (www.vpixx.com) by Brown and Crewther (2012) and was used as a measure of early perceptual speed by estimating threshold exposure duration required to successfully discriminate and identify a familiar visual stimulus. Changes in performance on the IT task was recently shown to be strongly correlated with changes in intelligence in a healthy older population (Ritchie, Tucker-Drob & Deary, 2014). Similarly, a Change Detection task (CD) based on the Becker, Pashler, and Anstis (2000) version, as adapted by Rutkowski et al. (2003) was incorporated into the testing battery. The CD examines threshold exposure duration required to identify change between two visual arrays. Both tasks employ an inbuilt Visual Parameter Estimation by Sequential Testing (VPEST) algorithm, designed to estimate the exposure threshold required to accurately identify a visual stimulus or detect change between two visual arrays. We also used a computerised reading task, namely, the FastaReada task (Elhassan, et al., 2015; Hecht et al., 2004) as an ecologically valid measure of rapid visual information processing. In addition, a modified version of the *N*-

Back task originally developed by (Kirchner, 1958) was administered to participants as a measure of sustained attention and working memory. Indeed, the FastaReada and *N*-back tasks do not rely on a fast motor response, and so threshold duration is calculated without any confound of motor reaction time.

3.5.4 Oculomotor Measures

Oculomotor measures were incorporated into the battery of tests as they are the ultimate measure of temporal and spatial attention shifting (Awh, Armstrong, & Moore, 2006; Bisley & Goldberg, 2006, 2010; Mohler, Goldberg, & Wurtz, 1973; Sun & Goldberg, 2016; Wurtz & Goldberg, 1989). Patterns of oculomotor functions including fixations and saccadic eye movements are considered robust and non-invasive measures of cognitive ability (Mohler et al., 1973; Wurtz & Goldberg, 1989) which are able to provide reliable and extensive insight into higher order cognitive abilities including memory, face recognition, reasoning and reading. Thus, Rapid Automatic Naming (RAN; Lyytinen et al., 2006; Norton & Wolf, 2012) tasks which require participants to rapidly and accurately name an array of common objects or alphanumeric symbols was chosen for the current study in order to simultaneously measure oculomotor function using an eye-gaze tracker. The RAN tests were administered on a computer via the Gazepoint program (www.gazept.com) where the software allows for tracking and recording of oculomotor function during visual tasks (further detail provided in Chapter 6). The eye tracker used was the Gazepoint GP3 and a 60Hz system with 9-point calibration which was mounted onto a 24-inch Dell computer monitor with a 60 Hertz screen refresh rate. We chose to use eye-gaze tracking as biobehavioural measures of speed of visual processing, transient, spatial and sustained attention.

3.6 References

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., ... & Unverzagt, F. W. (2002). Effects of cognitive training interventions with older adults: a randomized controlled trial. *Journal of the American Medical Association*, *288*(18), 2271-2281.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychology and Aging*, *12*(1), 12.

Baudouin, A., Isingrini, M., & Vanneste, S. (2018). Executive functioning and processing speed in age-related differences in time estimation: a comparison of young, old, and very old adults. *Aging, Neuropsychology, and Cognition, 1*-18.

Beaudreau, S. A., & O'hara, R. (2008). Late-life anxiety and cognitive impairment: a review. *The American Journal of Geriatric Psychiatry*, *16*(10), 790-803.

Beaudreau, S. A., & O'Hara, R. (2009). The association of anxiety and depressive symptoms with cognitive performance in community-dwelling older adults. *Psychology & Aging*, *24(*2), 507-512. doi: 10.1037/a0016035

Bennett, D. A., Wilson, R., Schneider, J., Evans, D., De Leon, C. M., Arnold, S., . . . Bienias, J. (2003). Education modifies the relation of AD pathology to level of cognitive function in older persons. *Neurology*, *60*(12), 1909-1915.

Becker, M. W., Pashler, H., & Anstis, S. M. (2000). The role of iconic memory in change-detection tasks. *Perception, 29*(3), 273-286. doi: 10.1068/p3035

Bisley, J. W., & Goldberg, M. E. (2006). Neural correlates of attention and distractibility in the lateral intraparietal area. *Journal of Neurophysiology, 95*(3), 1696-1717.

Bisley, J. W., & Goldberg, M. E. (2010). Attention, intention, and priority in the parietal lobe. *Annual Review of Neuroscience, 33,* 1-21.

Brown, A., & Crewther, D. (2012). Autistic children show more efficient parvocellular visual processing. *Frontiers in Human Neuroscience,* doi: 10.3389/conf.fnhum.2012.208.00021 [Epub ahead of print].

Cornelis, C., De Picker, L. J., Hulstijn, W., Dumont, G., Timmers, M., Janssens, L., . . . Morrens, M. (2014). Preserved Learning during the symbol-digit substitution test in patients with schizophrenia, age-matched controls, and elderly. *Frontiers in Psychiatry, 5*, 189. doi:10.3389/fpsyt.2014.00189

Elhassan, Z., Crewther, S., Bavin, E., & Crewther, D. (2015). Preliminary validation of FastaReada as a measure of reading fluency. *Frontiers in Psychology, 6*.

Guerra-Carrillo, B., Katovich, K., & Bunge, S. A. (2017). Does higher education hone cognitive functioning and learning efficacy? Findings from a large and diverse sample. *PloS One, 12*(8), e0182276.

Hachinski, V., Iadecola, C., Petersen, R. C., Breteler, M. M., Nyenhuis, D. L., Black, S. E., ... & Vinters, H. V. (2006). National Institute of Neurological Disorders and Stroke–Canadian stroke network vascular cognitive impairment harmonization standards. *Stroke*, *37*(9), 2220-2241.

Harada, C. N., Love, M. C. N., & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in Geriatric Medicine, 29*(4), 737-752.

Hecht, R., Crewther, D., & Crewther, S. (2004). Rate of learning and asymptotic performance in an automatization task and the relation to reading. *Perceptual and Motor Skills, 99*, 1103-1121. doi:10.2466/pms.99.3f.1103-112.

Hill, A. C., Laird, A. R., & Robinson, J. L. (2014). Gender differences in working memory networks: A BrainMap meta-analysis. *Biological Psychology*, 102, 18-29.

Joy, S., Kaplan, E., & Fein, D. (2004). Speed and memory in the WAIS-III Digit Symbol--Coding subtest across the adult lifespan. *Archives of Clinical Neuropsychology, 19*(6), 759-767. doi:10.1016/j.acn.2003.09.009

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*(4), 352-358.

Lovibond, S. H., & Lovibond, P. F. (1995). Manual for the depression anxiety stress scale (2nd ed.). Sydney: Psychology Foundation of Australia.

Lichtenberger, E. O., & Kaufman, A. S. (2009). Essentials of WAIS-IV assessment (Vol. 50): John Wiley & Sons.

Lyytinen, H., Erskine, J., Tolvanen, A., Torppa, M., Poikkeus, A.-M., & Lyytinen, P. (2006). Trajectories of reading development: A follow-up from birth to school age of children with and without risk for dyslexia. *Merrill-Palmer Quarterly* (1982-), 514-546.

McHugh, P. R. (1975). Mini-mental state. A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189-198.

Norton, E. S., & Wolf, M. (2012). Rapid automatized naming (RAN) and reading fluency: Implications for understanding and treatment of reading disabilities. *Annual Review of Psychology, 63*, 427-452.

Mohler, C. W., Goldberg, M. E., & Wurtz, R. H. (1973). Visual receptive fields of frontal eye field neurons. *Brain Research*, *61*(3), 85-83.

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual Review of Psychology, 60*, 173-196.

Reed, J. L., Gallagher, N. M., Sullivan, M., Callicott, J. H., & Green, A. E. (2017). Sex differences in verbal working memory performance emerge at very high loads of common neuroimaging tasks. *Brain and Cognition, 113,* 56-64.

Reddon, J. R., Gill, D. M., Gauk, S. E., & Maerz, M. D. (1988). Purdue Pegboard: test-retest estimates. *Perceptual Motor Skills, 66*(2), 503-506. doi:10.2466/pms.1988.66.2.503

Ritchie, S. J., Bates, T. C., Der, G., Starr, J. M., & Deary, I. J. (2013). Education is associated with higher later life IQ scores, but not with faster cognitive processing speed. *Psychology & Aging*, *28*(2), 515.

Ritchie, S. J., Tucker-Drob, E. M., & Deary, I. J. (2014). A strong link between speed of visual discrimination and cognitive ageing. *Current Biology, 24*(15), R681-R683.

Ritchie, S. J., Cox, S. R., Shen, X., Lombardo, M. V., Reus, L. M., Alloza, C., ... & Liewald, D. C. (2018). Sex differences in the adult human brain: evidence from 5216 UK Biobank participants. *Cerebral Cortex*, *28*(8), 2959-2975.

Rutkowski, J. S., Crewther, D. P., & Crewther, S. G. (2003). Change detection is impaired in children with dyslexia. *Journal of Vision, 3*(1), 95.

Salthouse, T. A. (2009). When does age-related cognitive decline begin? *Neurobiology of. Aging 30*, 507–514.

Sun, L. D., & Goldberg, M. E. (2016). Corollary discharge and oculomotor proprioception: Cortical mechanisms for spatially accurate vision. *Annual Review of Vision Science, 2*, 61-84.

Tiffin, J., & Asher, E. J. (1948). The Purdue pegboard; norms and studies of reliability and validity. *Journal of Applied Psychology*, *32*(3), 234-247.

Vickers, D., Nettelbeck, T., & Willson, R. J. (1972). Perceptual indices of performance: the measurement of 'inspection time' and 'noise' in the visual system. *Perception, 1*(3), 263-295.

Wurtz, R. H., & Goldberg, M. E. (1989). The neurobiology of saccadic eye movements (Vol. 3): Elsevier Science Limited.

chapter 4

04.

CHAPTER 4

Cognitive Processing Speed across the Lifespan: Beyond the Influence of Motor Speed

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4.1 Abstract

Traditional neuropsychological measurement of cognitive processing speed with tasks such as the Symbol Search and Coding subsets of the WAIS-IV, consistently show decline with advancing age. This is potentially problematic with populations where deficits in motor performance are expected, i.e., in aging or stroke populations. Thus, the aim of the current study was to explore the contribution of hand motor speed to traditional paper-and-pencil measures of processing speed and to a simple computer-customized non-motor perception decision task, the Inspection Time (IT) task. Participants were 67 young university students aged between 18 and 29 (59 females), and 40 older adults aged between 40 and 81 (31 females) primarily with a similar education profile. As expected, results indicated that age group differences were significant on the motor dexterity, Symbol Search and Coding tasks. However, no significant differences or correlations were seen between age groups and the simple visual perceptual IT task. Furthermore, controlling for motor dexterity did not remove significant age-group differences on the paper-and-pencil measures. This demonstrates that although much of past research into cognitive decline with age is confounded by use of motor reaction times as the operational measure, significant age differences in cognitive processing also exist on more complex tasks. The implications of the results are crucial in the realm of aging research, and caution against the use of traditional WAIS tasks with a clinical population where motor speed may be compromised, as in stroke.

4.2 Introduction

Cognitive processing speed when defined as the ability to process information rapidly, is closely related to the ability to perform higher-order cognitive tasks (Lichtenberger & Kaufman, 2012) and is often assumed to be the core issue responsible for deficits in performance on complex cognitive tasks in aging populations (Salthouse, 1996; Salthouse & Ferrer-Caja, 2003). Neuropsychological testing has traditionally assessed processing speed across the lifespan with paper-and-pencil tests such as the Symbol Search and Coding tasks from the Information Processing Speed Index of the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 2008a, 2008b) i.e., Cornelis et al. (2014); Joy, Kaplan, and Fein (2004); Kreiner and Ryan (2001). Such tests are reported to measure working memory, psychomotor and visuomotor processing speed, visual discrimination and attention; See Holdnack, Drozdick, Weiss, and Iverson (2013); Wechsler (2008a, 2008b). However, despite the natural decline in motor speed and function with age, the extent that motor speed affects age-related performance on such tasks has not been analysed in detail.

Current theories of processing speed and age include the Sensory Deprivation Hypothesis, the Common-Cause Hypothesis, and the Information Degradation Hypothesis. Though these theories may sometimes be considered as competing theories, they are relatively similar in suggesting a strong interaction between declines in sensory function i.e., vision and audition, and a slowing in cognitive processing speed. A potential explanation for the link between sensory and cognitive decline was provided by Baltes and Lindenberger (1997) who concluded that sensory and cognitive function are both likely to be an expression of the “physiological architecture of the aging brain” (p. 13). Lindenberger and Baltes (1994) had previously reported that sensorimotor variables such as visual acuity, balance-gait, and auditory acuity, predicted 59% of total reliable variance in general intelligence. For a review on the interaction between perceptual and cognitive decline with aging, see Schneider and Pichora-Fuller (2000) and Roberts and Allen (2016) for a brief, more recent review. Considering that sensory function, particularly for hearing and vision is commonly reported to decline with age (for review see Fozard, 1990), the sensory deprivation hypothesis states that a lack of adequate sensory input over a prolonged period is likely to result in cognitive deterioration due to the preceding neuronal atrophy (Oster, 1976; Valentijn et al., 2005). Similarly the information degradation hypothesis states that when perceptual signals are weakened or degraded, either due to experimental manipulations or age-related impaired perception, higher order cognitive processes are in turn affected (Schneider & Pichora-Fuller, 2000), possibly because the cognitive load is greater for weak perceptual signals, and thus require more cognitive resources to interpret the signal, which as a result, compromises cognitive performance (Zekveld, Kramer, & Festen, 2011). The major difference in the sensory deprivation hypotheses and the Common-Cause hypothesis lies in the interpretation as to when sensory and cognitive decline occur, with the Common-Cause hypothesis suggesting concurrent peripheral and central decline occurring simultaneously with declines in aspects of cognition, such as memory and processing speed (Fozard, 1990; Lindenberger & Baltes, 1994). This may be indicative of common declining attention and efficiency of all the neuronal networks in the brain as well as the eyes. Variations in interpretation are often dependent on neuroanatomical explanations of processing speed decline across the lifespan; a realm of which an abundance of research exists (Bendlin et al., 2010; Chee et al., 2009; Eckert, 2011; Fjell & Walhovd, 2010; Hong et al., 2015; Kerchner et al., 2012).

Addressing the potential confound of motor performance on paper-and-pencil tasks designed to measure cognitive processing speed, Crowe et al. (1999) investigated cognitive determinants of performance on the Digit Symbol-Coding Test and Symbol

Search, with particular attention to motor execution. It was concluded that motor speed was a significant predictor of scores, highlighting the large contribution of motor ability to variance in performance on these paper-and-pencil measures of processing speed. Kreiner and Ryan (2001) also examined the contribution of motor skill versus memory ability to scores on the Digit Symbol-Coding subtest of the WAIS-III in a clinical sample of patients with substance abuse, depression, or post-traumatic stress disorder and concluded that hand motor skill explained a large portion of the variance in Digit Symbol-Coding variance, whereas memory ability explained little additional variance in Digit Symbol Copy variance when motor skill scores were controlled. Similar results were reported by Joy, Fein, Kaplan, and Freedman (2000), in a further clinical sample of patients with diagnoses such as alcoholism and other substance abuse, depression, and post-traumatic stress disorder, emphasising that motor skill may be a more important contributor than cognitive performance to scores on traditional paper-and-pencil tasks in the WAIS.

An alternative, though not commonly used clinically or even experimentally in older participants, is computer-based measures of processing speed that do not require a motor response. The simplest of such tasks is the Inspection Time as a measure of perceptual processing speed. Inspection Time (IT; Vickers, Nettelbeck, and Willson (1972) is a psychophysical computer-based task that has often been reported to measure time required to assess perceptual thresholds, without reliance on manual dexterity (Deary & Stough, 1996) or even eye movements. Indeed, Gregory, Nettelbeck, Howard, and Wilson (2008) have found that momentary changes in performance on IT predicts future performance on cognitive tests measuring perceptual speed, working memory, and fluid reasoning, and may also serve as a biomarker for cognitive decline (Nettelbeck & Wilson, 2004, 2005).

Thus, the current study aimed to compare the extent to which performance on traditional measures of cognitive processing speed (i.e., the Symbol Search and Coding) is confounded by motor speed in young and older adults. It was hypothesised that younger adults would outperform older adults on the Symbol Search, Coding, and Pegboard tasks but not on the IT task and not when controlling for motor dexterity. It was also hypothesised that the Symbol Search and Coding tasks would be significantly correlated with motor dexterity (i.e., Pegboard scores).

4.3 Method

4.3.1 Participants

The present study included two age groups: 67 young adults (Females = 59, *M* age = 19.6, age range: 18 – 29), and 40 healthy older adults (Females = 31, *M* age = 66.7, age range: 40 - 81). The young adult group predominantly consisted of first year Psychology students, who received course credit, while the older adult group were predominantly recruited through personal networks or recruited through the University of the Third Age (U3A) and received a $20 Coles-Myer voucher. Exclusion criteria included previous diagnosis of a neurological disorder and the inability to understand and speak English with basic competence. A demographic questionnaire elicited information on age, lifestyle status, and education level. A measure of general negative affect: The Depression Anxiety and Stress Scale (DASS-21; (Lovibond & Lovibond, 1995) was administered as a screening tool.

4.3.2 Materials

Purdue Pegboard

The three subtasks of the Purdue Pegboard (Reddon, Gill, Gauk, & Maerz, 1988) were used as a measure of fine motor dexterity, specifically, finger dexterity (Tiffin & Asher, 1948). Performance on the Pegboard has previously been reported to decline with advanced age (Desrosiers, Hebert, Bravo, & Dutil, 1995). The Purdue Pegboard comprises a wooden board with two parallel rows of 25 holes each, into which as many cylindrical metal pegs (1mm in diameter and 25mm in length) are sequentially moved from a groove at the top of the board and placed in one of the holes by the participant in 30 seconds. Three sets of trials (dominant hand, then the non-dominant hand, and finally bimanually) are completed after instructions. The score is the number of pins successfully placed. In the current study, individual scores across all three conditions of the pegboard were used.

Symbol Search and Coding (WAIS-IV)

The Symbol Search and Coding subtests from the WAIS-IV were administered for two minutes each as per the WAIS-IV kit instructions. During Symbol Search, two target symbols appearing on the left of a row are sought among an array of five symbols on the right. The individual responds by either marking the identical symbol, or a “no” box (if the matching symbol is not present in the array) with a pencil. Performance was measured as the number of symbols accurately identified in two minutes. In healthy adults, raw scores on Symbol Search have been shown to decline by more than 50% between the ages of 25 and 65 (Wechsler, 2008b). However, this measure is still commonly used as an indicator of processing speed without accounting for possible age related decline that is often associated with healthy aging (Seidler, Alberts, & Stelmach, 2002; Seidler et al., 2010)

The Coding task requires an individual to copy (with a pencil) the appropriate symbol in a box underneath a digit (one-to-nine), using a key at the top of the page containing digits and their corresponding symbols. Performance is based on the number of pairs correctly copied in two minutes.

Modified Inspection Time (IT)

A modified IT task, based on the version of Vickers et al. (1972) was adapted by (Brown & Crewther, 2012) and programmed using the psychophysics program, Vpixx (www.Vpixx.com). Stimuli were presented on an Apple eMac Computer running at 89 Hz screen refresh rate. Across the trials, a fixation cross was presented for a random duration between 700-1,000ms, followed by a blank screen for 50ms, then the target stimulus was presented at variable exposure times beginning at 1 second, immediately followed by a mask, presented for 500ms. These exposure times were not altered between the various age groups. Target stimulus was either a fish, truck, or butterfly (See Figure 1). Participants were required to indicate what target stimulus they had been presented by pressing the appropriate one of three buttons on the keyboard. A response triggered the start of the next trial. The task employs an inbuilt Visual Parameter Estimation by Sequential Testing (VPEST) algorithm, designed to estimate the exposure threshold required to discriminate and identify which of the three possible stimuli was presented: fish, truck or butterfly. Confidence intervals and estimations of exposure time were calculated as part of the Vpixx program. A lower estimated exposure time indicated a faster cognitive processing speed threshold (specifically, perceptual speed). See Figure 1 for an example trial of IT task.

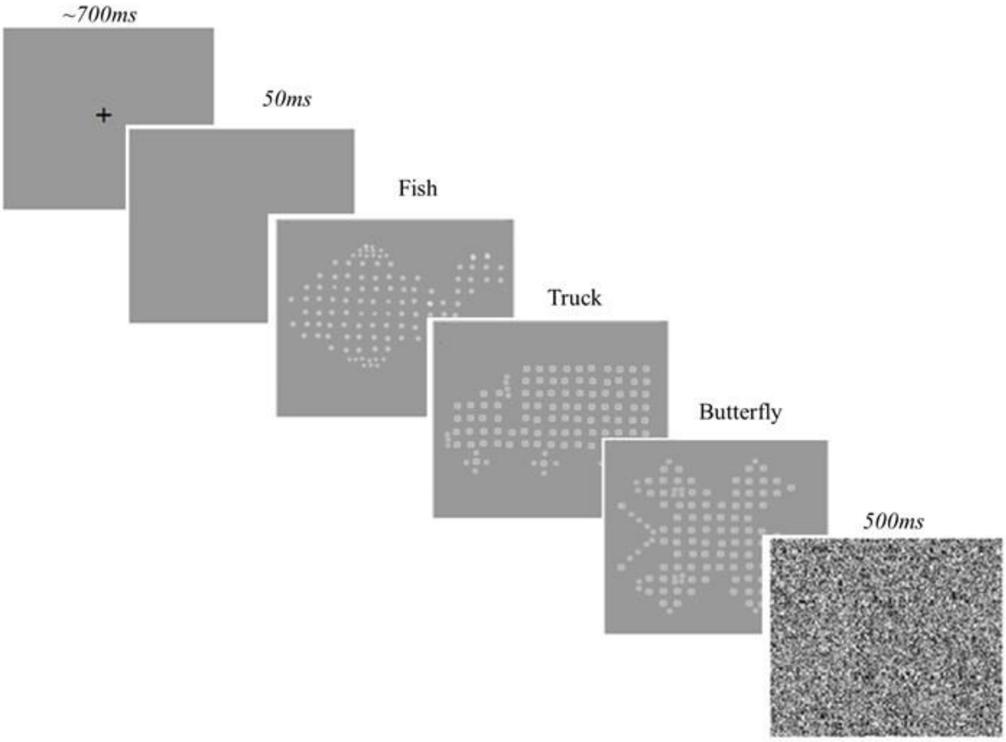

Figure 1. Modified Inspection Time (IT) task trial. Note. Only one target stimuli of fish, truck, or butterfly is presented per trial

4.3.3 Procedure

All participants were guided through the tests outlined above and all tasks were preceded by practice trials. Total testing time was approximately one hour. Practice trials for each condition on the Purdue Pegboard were usually only done once, unless the participant requested further practice trials. For the Symbol Search task, three arrays of untimed practice items were completed prior to attempting the test. Similarly, for the Coding task, there were nine untimed practice trials. The IT task was also preceded with five practice trials, or until the participant was satisfied they did not need more practice. To ensure accurate results for the IT, the task was re-done if the confidence interval as indicated by the Vpixx data output was below 80%.

4.4 Data analysis

An independent samples t-test was used to compare performance on dependent measures between age-groups. This was followed by an Analysis of Covariance (ANCOVA) aimed at exploring performance on dependent measures between age-groups while controlling for motor dexterity. An independent samples t-test on IT performance between age-groups was also conducted to explore performance between young and older adults on all dependent measures. To explore the relationship between the Symbol Search and Coding with motor dexterity, correlation analyses were conducted between Pegboard scores and Symbol Search and Coding tasks. A second analysis was then conducted after splitting participants into three age groups, namely, young adults aged 18-29 (N = 67), middle-aged adults aged 40-59 (*N* = 9), and older adults aged 61-81 (*N* = 31).   Though we acknowledge that the small numbers in the middle-aged group is a limitation to an ANOVA, analyses were conducted to determine whether any absence of significance using two age groups was due to the nine participants in the intermediate age-group (i.e. middle-age group).

4.4.1 Analyses of results using two age groups (young and older adults)

Preliminary analysis of results between education levels in age-groups

Given the various levels of education within the sample, an ANOVA was conducted to determine whether performance on dependent measures (i.e., IT, Symbol Search, Coding, and Pegboard) were significantly different between participants ‘highest level of completed education’ within young and older adults. See Table 1a for descriptive statistics of highest level of completed education for young and older adults. Results of the ANOVA indicate that there were no significant differences between participants’ highest level of completed education and performance on dependent measures in both the young and older adult groups (See Table 1b-1c)

Table 1a. Highest Level of Completed Education in Young and Older Adults**.**

Highest Level of Completed Education	Younger Adults	Older Adults
	%	%
Secondary School	91	27.5
Diploma	4.5	20
Bachelor's degree	4.5	20
Post-Graduate Degree	0	17.5
Masters	0	12.5
Doctorate/PhD	0	2.5

Table 1b. Analysis of Variance (ANOVA) between Highest Level of Completed Education and Performance on Dependent Measures in Young Adults

Variable	Sum of Squares	*df*	Mean Square	*F*	*p*	Partial η^2
SymS	135.039	66	67.520	1.148	0.324	.035
Cod	323.055	66	161.527	.941	0.396	.029
IT	0.147	61	0.073	2.715	0.074	.084
Pgb.dom	1.868	66	0.934	0.265	0.768	.008
Pgb.non	1.235	66	0.617	0.236	0.790	.007
Pgb.2	48.865	66	24.432	1.642	0.202	.049

Table 1c. Analysis of Variance (ANOVA) between Highest Level of Completed Education and Performance on Dependent Measures in Older Adults

Variable	Sum of Squares	*df*	Mean Square	F	*p*	Partial η^2
SymS	386.487	39	77.297	1.601	0.186	.191
Cod	1073.241	39	214.648	1.271	0.299	.157
IT	0.40	32	0.008	1.506	0.216	.190
Pgb.dom	4.829	39	0.966	0.197	0.962	.028
Pgb.non	5.402	39	1.080	0.307	0.905	.043
Pgb.2	113.860	39	22.772	1.257	0.305	.156

4.4.2 Preliminary analysis of results between genders

Given the uneven spread of genders within our sample (i.e., 90 Females, 17 Males), an independent samples t-test was conducted to determine whether there were differences in performance on any dependent measures within each age group across genders.

Results revealed no significant differences on any dependent measure between genders in the younger group. However, results demonstrated significant difference for Coding performance between genders for the older adults showing that males outperformed females, *M*difference = 11.66, $t(38)=2.478$ p = .018. See Table 2.

Table 2. Mean Difference between Genders and Scores on Dependent Measures in Young and Older Adults

Variable	t	df	*Mean Difference*	*95% C.I. Mean Difference*	η^2
Younger Adults					
SymS	.326	65	.951	-4.87–6.78	.002
Cod	-.626	65	-3.10	-12.99–6.794	.006
IT	1.515	60	.109	-.035 – .253	.037
Pgb.dom	-.216	65	-.153	-1.56–1.26	.001
Pgb.non	.832	65	.502	-.70 – 1.71	.011
Pgb.2	-1.152	65	-1.68	-4.61 – 1.24	.020
Older Adults					
SymS	-1.11	38	-3.02	-8.53 – 2.49	.031
Cod	2.478*	38	11.66	2.14 – 21.184	.139
IT	.709	36	.02	-.040 - .083	.014
Pgb.dom	-.890	38	-.71	-2.32 - 0.90	.020
Pgb.non	-.983	38	-.67	-2.04 - 0.707	.025
Pgb.2	-1.381	38	-2.24	-7.53 – 1.49	.048

Note: SymS = Symbol Search, Coding = Coding, IT = Inspection Time, Pgb.dom = Pegboard (dominant hand condition), Pgb.non = Pegboard (non-dominant hand condition), Pgb.2 = Pegboard (both hands condition)

** p = <.01, * p = <.05

4.5 Results

Table 3 depicts demographic information, i.e., age and education of the sample. Sample size, means, standard deviations and range for each of the variables by age-group is shown in Table 4.

Table 3. Descriptive Statistics for Age and Years of Education for Younger and Older Adults.

	Younger Adults			
Variable	*N*	*M*	*SD*	Range
Age	67	19.64	2.26	18–29
YrsEdu	67	7.64	1.06	7–11
	Older Adults			
Age	40	66.7	9.72	40–81
YrsEdu	40	10.4	3.37	4–21

Note. Age = age in years; YrsEdu = years of education since Year 7 (start of high school).

Table 4. Descriptive Statistics for Each Dependent Variable

		Younger Adults		
Variable	*N*	*M*	*SD*	*Range*
SymS	67	39.537	7.688	24-60
Cod	67	78.731	13.090	37-121
IT	62	.077	0.169	.008-1.028
Pgb.dom	67	16.134	1.858	11-20
Pgb.non	67	14.433	1.598	11-18
Pgb.2	67	23.99	3.894	9-31
		Older Adults		
SymS	40	28.450	7.211	12-48
Cod	40	54.075	13.212	30-91
IT	38	0.124	0.075	0.016-0.343
Pgb.dom	40	13.550	2.099	9-18
Pgb.non	40	12.850	1.791	9-16
Pgb.2	40	20.400	4.325	7-31

Note: SymS = Symbol Search, Coding = Coding, IT = Inspection Time, Pgb.dom = Pegboard (dominant hand condition), Pgb.non = Pegboard (non-dominant hand condition), Pgb.2 = Pegboard (both hands condition)

4.5.1 Relationships among age and dependent measures

Correlational analyses were performed to investigate the strength, direction and significance of associations between age and dependent measures of motor dexterity and processing speed. Results revealed significant moderate to strong positive correlations with increasing age and scores on all three conditions of the Pegboard, indicating age-related motor dexterity decline. Significant strong negative correlations were also demonstrated between increasing age and scores on the Symbol Search and Coding tasks, indicating a slower processing speed as age increases. A significant weak correlation was also exhibited between increasing age and higher scores on the IT, indicating that a longer stimulus exposure duration was required to identify a visual stimulus as age increased.

4.5.2 Relationships between motor dexterity and measures of processing speed

Correlational analyses were performed to investigate the strength, direction and significance of associations between the Pegboard and measures of processing speed, namely, Symbol Search, Coding, and IT. Results demonstrated significant positive correlations between each condition of the Pegboard and both paper-and pencil measures of Processing speed, i.e., the Symbol Search and Coding. This indicated that better motor dexterity was associated with a faster processing speed, as measured by the Symbol Search and Coding. Contrary to this, there was no significant relationship between any condition of the Pegboard and performance scores on the IT, indicating that motor dexterity is unlikely to impede or improve performance on the IT. A full correlation table of all measures is shown in Table 5.

Table 5. Pearson Product-Moment Correlations Between Dependent Measures

Measure	Age	SymS	Coding	IT	Pgb.dom	Pgb.non	Pgb.2
1. Age	-						
2. SymS	-.613**	-					
3. Cod	-.673**	.671**	-				
4. IT	.208*	-.081	-.086	-			
5. Pgb.dom	-.603**	.439**	.440**	-.093	-		
6. Pgb.non	-.496**	.454**	.434**	.034	.640**	-	
7. Pgb.2	-.433**	.376**	.335**	-.193	.560**	.619**	-

Note: SymS = Symbol Search, Cod = Coding, IT = Inspection Time, Pgb.dom = Pegboard (dominant hand condition), Pgb.non = Pegboard (non-dominant hand condition), Pgb.2 = Pegboard (both hands condition)

** p = <.01, * p = <.05

4.5.3 Differences in performance on dependent measures by age-group

An Independent-samples t-test was conducted to compare performance on dependent measures between younger and older adults. Significant age-group differences were found for mean scores on all paper-and-pencil measures, namely, Symbol Search and Coding, as well as on all Pegboard tasks. However, significant age group differences were not demonstrated for performance on psychophysical measure of processing speed, i.e., the IT task. The results of the independent-samples t-tests are shown in Table 6.

Table 6. Mean Difference between Age Group and Scores on Dependent Measures

Variable	*t*	df	Mean Difference	95% C.I. Mean Difference	η^2
SymS	7.385**	105	11.087	8.110 - 14.064	.342
Cod	9.392**	105	24.656	19.45 - 29.861	.457
IT	-1.618	98	-0.047	-0.104 - 0.010	.026
Pgb.dom	6.629**	105	2.584	1.811 – 3.357	.295
Pgb.non	4.738**	105	1.58	0.920 – 2.245	.176
Pgb.2	4.419**	105	3.58	1.977 – 5.193	.157

Note: SymS = Symbol Search, Cod = Coding, IT = Inspection Time, Pgb.dom = Pegboard (dominant hand condition), Pgb.non = Pegboard (non-dominant hand condition), Pgb.2 = Pegboard (both hands condition)
** p = <.01, * p = <.05

4.5.4 Performance on processing speed measures while controlling for motor dexterity

An ANCOVA was conducted to explore performance on processing speed measures (i.e., Symbol Search, Coding, and IT) between age groups while controlling for motor dexterity of the dominant hand, given that participants used their dominant hand to complete the paper-and-pencil tasks used in the current study. Despite controlling for motor dexterity, age still had a large significant effect on Symbol Search scores $F(1, 104) = 27.751$, $p < .01$, partial $\eta 2 = .211$ and on Coding scores $F(1, 104) = 52.464$, $p < .01$, partial $\eta 2 = .335$, and thus, there were still significant differences on paper-and-pencil task scores (i.e., Symbol Search and Coding) between young and older adults, even when controlling for motor dexterity.

An inspection of zero order correlation revealed that controlling for motor dexterity influenced the strength of the relationship between age and Symbol Search scores ($r = -.466$) and age and Coding scores ($r = -.573$). However, controlling for motor dexterity had little impact on the strength of the relationship between age and IT scores ($r = .190$). See Table 7 for Analysis of Covariance table between age and Symbol Search and Coding while controlling for motor dexterity.

4.5.5 Analyses of results using three age groups (young, middle-aged and older adults)

Mean Differences in Performance on Dependent Measures by Three Age-Groups

To ensure that the nine participants aged between 40 and 59 did not bias results when using only two age groups, analyses were run using three age groups. Specifically,

Table 7. Analysis of Covariance (ANCOVA) between Age and Performance on Paper-and-Pencil Tasks While Controlling for Motor Dexterity

Variable	Sum of Squares	*df*	Mean Square	*F*	*p*	Partial η^2
SymS	3099.43	106	1549.72	27.28	<.01	.344
Cod	15298.25	106	7649.12	44.07	<.01	.459
IT	0.071	99	0.036	1.79	0.174	.035
Pgb.dom	224.92	106	112.46	34.19	<.01	.397
Pgb.non	111.03	106	55.51	22.54	<.01	.312
Pgb.2	407.28	106	203.64	12.87	<.01	.198

Note: SymS = Symbol Search, Cod = Coding, IT = Inspection Time, Pgb.dom = Pegboard (dominant hand condition), Pgb.non = Pegboard (non-dominant hand condition), Pgb.2 = Pegboard (both hands condition)

the sample was divided into young adults aged 18-29 (*N* = 67), middle-aged adults aged 40-59 (*N* = 9), and older adults aged 61-81 (*N* = 31). An ANOVA was conducted to assess mean differences in performance on dependent measures by age-group. Results demonstrated significant age-group differences for mean scores on all paper-and-pencil measures (i.e., Symbol Search and Coding), as well as on all conditions of the Pegboard task. However, significant age-group differences were not demonstrated for performance on the IT task. These results coincide with results found with the sample divided into two age groups (i.e., young adults aged 18-29 and older adults aged 40-81). Results of the ANOVA are shown in Table 8.

Table 8. Analysis of Variance (ANOVA) between Age Group and Performance on Dependent Measures

Variable	Type III Sum of Squares	*df*	Mean Square	F	*p*	Partial η^2
SymS	1531.735	104	1531.735	27.751	< .01	.211
Cod	9014.634	104	9014.634	52.464	< .01	.335

Note: SymS = Symbol Search, Cod = Coding

4.5.6 Analyses of results between genders within three age groups

An analysis of results between genders within each age groups was also conducted with the sample divided into three age-groups. An independent samples t-test was conducted to determine whether there were differences in performance on any dependent measures within each age group across genders.

Results revealed no significant differences on any dependent measure between genders in the younger group, as well as in the middle-aged group. However, results again demonstrated significant differences in Coding performance between genders for the older adults with males outperforming females, M difference = 12.46, t(29)=2.485 p = .019. See Table 9. These results also mirror those demonstrated with the sample divided into two groups (i.e., young and older adults)

Table 9. Mean Difference between Genders and Scores on Dependent Measures in Young, Middle-Aged, and Older Adults.

	Younger Adults					Middle-Aged Adults					Older Adults				
Variable	*t*	*df*	*Mean Difference*	*95% C.I. Mean Difference*	η^2	*t*	*df*	*Mean Difference*	*95% C.I. Mean Difference*	η^2	*t*	*df*	*Mean Difference*	*95% C.I. Mean Difference*	η^2
SymS	.326	65	0.951	-4.873-6.775	.002	.130	7	0.929	-15.941-17.798	.002	-1.409	29	-4.143	-10.157-1.871	.064
Cod	-.626	65	-3.102	-12.997-6.794	.006	.689	7	8.929	-21.711-39.568	.064	2.485*	29	12.458	2.205-22.712	.176
IT	1.515	60	0.109	-.0349-.253	.037	.475	7	0.011	-.0452-0.068	.031	.688	27	0.026	-.051-.102	.017
Pgb.dom	-.216	65	-0.153	-1.560 - 1.255	.001	-.350	7	-0.357	-2.772-2.058	.017	-1.004	29	-0.798	-2.4230-.8278	.034
Pgb.non	.832	65	0.502	-.703-1.707	.011	.143	7	0.143	-2.218-2.504	.003	-1.416	29	-0.887	-2.168-.394	.065
Pgb.2	-1.152	65	-1.686	-4.609-1.237	.020	-.557	7	-1.429	-7.497-4.639	.042	-1.327	29	-2.452	-6.232-1.327	.057

Note: SymS = Symbol Search, Cod = Coding, IT = Inspection Time, Pgb.dom = Pegboard (dominant hand condition), Pgb.non = Pegboard (non-dominant hand condition), Pgb.2 = Pegboard (both hands condition), ** p = <.01, * p = <.05

4.5.7 Age-group differences while controlling for motor dexterity with three age groups

An ANCOVA was conducted to explore the relationship between age and outcome on processing speed measures (i.e., Symbol Search, Coding, and IT) while controlling for motor dexterity of the dominant hand. Despite controlling for motor dexterity, age still had a large significant effect on Symbol Search scores $F(1, 106) = 13.748$, $p < .01$, partial $\eta 2 = .344$ and on Coding scores $F(1, 106) = 26.009$, $p < .01$, partial $\eta 2 = .459$, and thus, there were still significant differences on paper-and-pencil task scores (i.e., Symbol Search and Coding) between young, middle-aged, and older adults, even when controlling for motor dexterity. Results of the ANCOVA are presented in Table 10.

Table 10. Analysis of Covariance (ANCOVA) between Age and Performance on Paper-and-Pencil Tasks While Controlling for Motor Dexterity

Variable	Type III Sum of Squares	*df*	Mean Square	F	*p*	Partial η^2
SymS	1532.283	106	766.141	13.748	< .01	.344
Cod	9021.356	106	4510.678	26.009	< .01	.459

Note: SymS = Symbol Search, Cod = Coding

4.6 Discussion

The most important findings of this study are that although motor reaction times were correlated with age, decline in cognitive processing speed across the lifespan is not fully/completely explained by motor performance. This is the case whether using traditional paper-and-pencil measures from the WAIS-IV; or IT, a non-motor measure of visual perceptual processing speed.

4.6.1 Age and performance on measures of processing speed

As expected, significant age group differences were demonstrated on the Symbol Search and Coding tasks but not on the Inspection Time task. Declines in performance on the Symbol Search and Coding demonstrated in the current study are in line with the body of evidence referenced earlier that indicates processing speed declines with age (Cerella & Hale, 1994; Holdnack et al., 2013; Hong et al., 2015; Salthouse, 1996; Tam, Lam, Huang, Wang, & Lee, 2015). Furthermore, findings are consistent with research indicating that age related processing slowing is reflected on tasks such as the Symbol Search and Coding (Gilmore, Spinks, & Thomas, 2006), where declines in performance are generally most prominent from the age of 45 (Hoyer, Stawski, Wasylyshyn, & Verhaeghen, 2004). Findings from the current study are in line with and may be explained by current theories of processing speed decline across the lifespan, though this study cannot determine the temporal relationship between sensory processing and neural networks.

Results from the current study are also consistent with those found in a study conducted by Gilmore et al. (2006) who used multiple forms of a symbol-digit substitution task (similar to the Symbol Search and Coding used in the current study), where significant differences in performance between young and older adults were demonstrated. Interestingly however, when visual contrast sensitivity deficit of older adults was simulated on tasks by applying a digital filter, this markedly reduced the number of items that younger participants could complete on the coding task. Gilmore et al. (2006) concluded that contrast sensitivity deficits were linked to visual search speed, affecting overall performance on cognitive tasks, further lending support to the Information Degradation Hypothesis, Sensory Deprivation Hypothesis, and Common-Cause Hypotheses. In line with these findings, various longitudinal studies have demonstrated that impairments in sensory perception are progressively associated with cognitive decline. For example, Lin et al. (2004) and Lin et al. (2013) reported that women with impaired vision or hearing had a faster rate of cognitive decline over a four or six year period compared to those without sensory impairment An explanation for this is provided by Rabbitt (1991) who suggested that an increased effort was necessary to recognize words when perceptual signals are weak, as the extra effort encoding or interpreting the degraded sensory signal commands cognitive resources that would otherwise be used in encoding and rehearsal. In turn, this results in a slower overall processing speed. Zekveld et al. (2011), also found this using pupillometry to demonstrate the effects of varying strengths of perceptual signals (i.e., verbal sentence intelligibility) in older adults with and without hearing loss.

Although significant age related group differences for performance on IT were not demonstrated in the current study, IT performance did significantly correlate with age (see Table 5), and this is in line with research suggesting that IT performance declines with increased age (Gregory et al., 2008; Nettelbeck & Rabbitt, 1992). Interestingly, IT has been demonstrated to account for 25% of the variance in human intelligence (Deary & Stough, 1996). With this in mind, it may be the case that the results from the current study that showed no significant differences between age-groups and threshold times on the IT, may be partly due to the highly-educated sample across both age groups. Indeed, the majority of participants were university educated and over 30% of the older participants held post-graduate academic degrees. It may be the case then, that IT is a more accurate representation of cognitive performance in similarly educated populations, a suggestion made by Deary, Johnson, and Starr (2010) who also propose that the IT may be an effective biomarker of cognitive aging. It is also apparent that the IT is a quick, useful test for aging and health research.

4.6.2 Motor Dexterity and its Relationship with Age and Processing Speed Measures

As expected, motor dexterity on the Purdue Pegboard was significantly negatively correlated with age (Seidler et al., 2002; Seidler et al., 2010), an observation prominent particularly for participants aged over 65 (Carmeli, Patish, & Coleman, 2003; Murata et al., 2010). Furthermore, and contrary to expectations, even when motor dexterity on the Purdue Board was controlled, Symbol Search and Coding still correlated with age. This indicated that older participants still performed worse on the Symbol Search and Coding tasks that are designed to measure cognitive processing speed, short-term visual memory, visual-motor coordination, visual discrimination, speed of mental operation, attention, concentration, as well as psychomotor speed (Wechsler, 2008a) even when motor dexterity was statistically controlled.

4.6.3 Limitations

The populations used were both limitations and strengths of the current study, as it is unusual to include similarly educated young and older groups given the commonly reported link between education and cognitive performance (Stern, 2002; Zahodne et al., 2011), and association with higher IQ scores in later life. Samples varying in education levels may be of interest in future research assessing similar cognitive constructs. The uneven sex distribution of the sample was a further limitation of the study. As there were significant differences on performance scores on the Coding task between genders in the older adults, this relationship may be of interest for future research. Furthermore, to avoid any confound of genders on performance scores on similar cognitive tasks, a more even spread of genders in a sample may ensure a more robust design for future research. The sample sizes of the experimental groups also serve as a limitation in the current study especially in regards to statistical analyses of the middle-aged group. To ensure robustness of analyses and results, future research investigating similar constructs should aim to have an even number of participants in the various age groups.

4.6.4 Conclusions and Future Direction

The current study aimed to explore the issue of whether traditional measures of cognitive processing speed such as the Symbol Search and Coding Subsets of the WAIS-IV accurately reflect cognitive processing speed, or whether they are confounded by motor speed in older participants. Thus, to our knowledge the current study was one of the first to explicitly explore the issue of motor confounds and age and extract the value of the WAIS subtests as measures of complex cognition in comparison to the Simple IT task in groups of similar education level. This issue has been acknowledged in other realms of research such as Autism, where children with autism have a 'slower' cognitive processing speed when measured with paper-and-pencil tasks, but not when measured with psychophysical IT tasks (Scheuffgen, Happe, Anderson, & Frith, 2000). Given that IT enables a non-motor rapid and accurate assessment of the speed of visual processing and discrimination of a visual stimulus, it our results suggests that the IT task would be a quick and effective addition to cognitive measures in many clinical health related disciplines. Thus, the implications of the results are important to aging research, and especially for use with clinical populations where motor speed may be severely compromised, i.e., in stroke.

4.7 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

4.8 Author Contributions

Sheila G Crewther initiated the project, designed the outline and content and has contributed to the writing. Deena Ebaid has contributed to most of the writing, and developed the first and final draft of the manuscript. Kirsty MacCalman has contributed to some of the writing. Deena Ebaid, Kirsty MacCalman, and Daniel Crewther largely contributed to participant recruitment, data collection and data analysis. Alyse Brown developed the modified Inspection Time task, and provided clear protocols on how to conduct the task with participants. Alyse Brown also ran practice trials using the task with all researchers, which in turn thoroughly assisted in data collection.

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4.11 References

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology & Aging*, *12*(1), 12-21. doi: 10.1037/0882-7974.12.1.12

Bendlin, B. B., Fitzgerald, M. E., Ries, M. L., Xu, G., Kastman, E. K., Thiel, B. W., . . . Johnson, S. C. (2010). White matter in aging and cognition: a cross-sectional study of microstructure in adults aged eighteen to eighty-three. *Developmental Neuropsychology, 35*(3), 257-277. doi:10.1080/87565641003696775

Brown, A., & Crewther, D. (2012). Autistic children show more efficient parvocellular visual processing. *Frontiers in Human Neuroscience,* doi: 10.3389/conf.fnhum.2012.208.00021 [Epub ahead of print].

Carmeli, E., Patish, H., & Coleman, R. (2003). The aging hand. *Journal of Gerontology: Series A: Biological Sciences & Medical Science*, *58*(2), 146-152.

Cerella, J., & Hale, S. (1994). The rise and fall in information-processing rates over the life span. *Acta Psychologia*, *86*(2-3), 109-197.

Chee, M. W., Chen, K. H., Zheng, H., Chan, K. P., Isaac, V., Sim, S. K., . . . Ng, T. P. (2009). Cognitive function and brain structure correlations in healthy elderly East Asians. *NeuroImage*, *46*(1), 257-269. doi:10.1016/j.neuroimage.2009.01.036

Cornelis, C., De Picker, L. J., Hulstijn, W., Dumont, G., Timmers, M., Janssens, L., . . . Morrens, M. (2014). Preserved Learning during the Symbol-Digit Substitution Test in patients with Schizophrenia, age-matched controls, and elderly. *Frontiers in Psychiatry*, *5*, 189. doi:10.3389/fpsyt.2014.00189

Crowe, S. F., Benedict, T., Enrico, J., Mancuso, N., Matthews, C., & Wallace, J. (1999). Cognitive determinants of performance on the Digit Symbol-Coding Test, and the Symbol Search Test of the Wais-III, and the Symbol Digit Modalities Test: An analysis in a healthy sample. *Australian Psychologist*, *34*(3), 204-210. doi:10.1080/00050069908257455

Deary, I. J., Johnson, W., & Starr, J. M. (2010). Are processing speed tasks biomarkers of cognitive aging? *Psychology & Aging*, *25*(1), 219-228. doi:10.1037/a0017750

Deary, I. J., & Stough, C. (1996). Intelligence and inspection time: Achievements, prospects, and problems. *American Psychologist, 51*(6), 599-608. doi:10.1037/0003-066X.51.6.599

Desrosiers, J., Hebert, R., Bravo, G., & Dutil, E. (1995). The Purdue Pegboard Test: normative data for people aged 60 and over. *Disability & Rehabilitation, 17*(5), 217-224.

Eckert, M. (2011). Slowing down: Age-related neurobiological predictors of processing speed. *Frontiers in Neuroscience, 5*(25). doi:10.3389/fnins.2011.00025

Fjell, A. M., & Walhovd, K. B. (2010). Structural brain changes in aging: courses, causes and cognitive consequences. *Reviews in Neurosciences, 21*(3), 187-221.

Fozard, J. L. (1990). *Vision & Hearing in Aging*: Elsevier B.V.

Gilmore, G. C., Spinks, R. A., & Thomas, C. W. (2006). Age effects in coding tasks: componential analysis and test of the sensory deficit hypothesis. *Psychology & Aging, 21*(1), 7-18. doi:10.1037/0882-7974.21.1.7

Gregory, T., Nettelbeck, T., Howard, S., & Wilson, C. (2008). Inspection Time: A biomarker for cognitive decline. *Intelligence, 36*(6), 664-671. doi:http://dx.doi.org/10.1016/j.intell.2008.03.005

Holdnack, J. A., Drozdick, L., Weiss, L. G., & Iverson, G. L. (2013). *WAIS-IV, WMS-IV, and ACS: Advanced Clinical Interpretation*: Academic Press.

Hong, Z., Ng, K. K., Sim, S. K., Ngeow, M. Y., Zheng, H., Lo, J. C., . . . Zhou, J. (2015). Differential age-dependent associations of gray matter volume and white matter integrity with processing speed in healthy older adults. *Neuroimage, 123*, 42-50. doi:10.1016/j.neuroimage.2015.08.034

Hoyer, W. J., Stawski, R. S., Wasylyshyn, C., & Verhaeghen, P. (2004). Adult age and digit symbol substitution performance: a meta-analysis. *Psychology & Aging, 19*(1), 211-214. doi:10.1037/0882-7974.19.1.211

Joy, S., Fein, D., Kaplan, E., & Freedman, M. (2000). Speed and memory in WAIS-R-NI Digit Symbol performance among healthy older adults. *Journal of the International Neuropsychological Society, 6*(7), 770-780.

Joy, S., Kaplan, E., & Fein, D. (2004). Speed and memory in the WAIS-III Digit Symbol--Coding subtest across the adult lifespan. *Archives of Clinical Neuropsychology, 19*(6), 759-767. doi:10.1016/j.acn.2003.09.009

Kerchner, G. A., Racine, C. A., Hale, S., Wilheim, R., Laluz, V., Miller, B. L., & Kramer, J. H. (2012). Cognitive processing speed in older adults: relationship with white matter integrity. *PLoS One, 7*(11), e50425. doi:10.1371/journal.pone.0050425

Kreiner, D. S., & Ryan, J. J. (2001). Memory and motor skill components of the WAIS-III Digit Symbol-Coding subtest. *The Clinical Neuropsychologist, 15*(1), 109-113. doi:10.1076/clin.15.1.109.1906

Lichtenberger, E. O., & Kaufman, A. S. (2012). *Essentials of WAIS-IV Assessment*: Wiley.

Lin, F. R., Yaffe, K., Xia, J., Xue, Q. L., Harris, T. B., Purchase-Helzner, E., . . . Health, A. B. C. S. G. (2013). Hearing loss and cognitive decline in older adults. *JAMA Internal Medicine, 173*(4), 293-299. doi:10.1001/jamainternmed.2013.1868

Lin, M. Y., Gutierrez, P. R., Stone, K. L., Yaffe, K., Ensrud, K. E., Fink, H. A., . . . G, S. O. F. R. (2004). Vision impairment and combined vision and hearing impairment predict cognitive and functional decline in older women. *Journal of the American Geriatrics Society 52*(12), 1996-2002. doi:DOI 10.1111/j.1532-5415.2004.52554.x

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: a strong connection. *Psychology & Aging, 9*(3), 339-355.

Lovibond, S. H., & Lovibond, P. F. (1995). *Manual for the depression anxiety stress scale* (2nd ed.). Sydney: Psychology Foundation of Australia.

Murata, J., Murata, S., Hiroshige, J., Ohtao, H., Horie, J., & Kai, Y. (2010). The influence of age-related changes in tactile sensibility and muscular strength on hand function in older adult females. *International Journal of Gerontology, 4*(4), 180-183. doi:http://dx.doi.org/10.1016/j.ijge.2010.11.004

Nettelbeck, T., & Rabbitt, P. M. A. (1992). Aging, cognitive performance, and mental speed. *Intelligence, 16*(2), 189-205. doi:http://dx.doi.org/10.1016/0160-2896(92)90004-B

Nettelbeck, T., & Wilson, C. (2004). The Flynn effect: Smarter not faster. *Intelligence, 32*(1), 85-93. doi:http://dx.doi.org/10.1016/S0160-2896(03)00060-6

Nettelbeck, T., & Wilson, C. (2005). Uncertainty about the biology of intelligence: A role for a marker task. *Cortex, 41*(2), 234-235. doi:http://dx.doi.org/10.1016/S0010-9452(08)70904-3

Oster, C. (1976). Sensory deprivation in geriatric patients. Journal of the American Geriatrics Society, *24*(10), 461-464.

Rabbitt, P. (1991). Mild hearing loss can cause apparent memory failures which increase with age and reduce with IQ. *Acta Oto-Laryngologica, 111*(476), 167-176. doi:10.3109/00016489109127274

Reddon, J. R., Gill, D. M., Gauk, S. E., & Maerz, M. D. (1988). Purdue Pegboard: test-retest estimates. *Perceptual Motor Skills, 66*(2), 503-506. doi:10.2466/pms.1988.66.2.503

Roberts, K. L., & Allen, H. A. (2016). Perception and cognition in the ageing brain: A brief review of the short- and long-term links between perceptual and cognitive decline. *Frontiers in Aging Neuroscience, 8*, 39. doi:10.3389/fnagi.2016.00039

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

Salthouse, T. A., & Ferrer-Caja, E. (2003). What needs to be explained to account for age-related effects on multiple cognitive variables? *Psychology & Aging, 18*(1), 91-110.

Scheuffgen, K., Happe, F., Anderson, M., & Frith, U. (2000). High "intelligence," low "IQ"? Speed of processing and measured IQ in children with autism. *Development & Psychopathology, 12*(1), 83-90.

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. C. T. A. Salthouse (Ed.), *The handbook of aging and cognition, 2nd ed* (pp. 155-219). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Seidler, R. D., Alberts, J. L., & Stelmach, G. E. (2002). Changes in multi-joint performance with age. *Motor Control, 6*(1), 19-31.

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., . . . Lipps, D. B. (2010). Motor control and aging: links to age-related brain structural, functional, and biochemical effects. *Neuroscience & Biobehavioral Reviews, 34*(5), 721-733. doi:10.1016/j.neubiorev.2009.10.005

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

Tam, H. M., Lam, C. L., Huang, H., Wang, B., & Lee, T. M. (2015). Age-related difference in relationships between cognitive processing speed and general cognitive status. *Applied Neuropsychology: Adult, 22*(2), 94-99. doi:10.1080/23279095.2013.860602

Tiffin, J., & Asher, E. J. (1948). The Purdue pegboard; norms and studies of reliability and validity. *Journal of Applied Psychology, 32*(3), 234-247.

Valentijn, S. A., van Boxtel, M. P., van Hooren, S. A., Bosma, H., Beckers, H. J., Ponds, R. W., & Jolles, J. (2005). Change in sensory functioning predicts change in cognitive functioning: results from a 6-year follow-up in the maastricht aging study. *Journal of the American Geriatric Society, 53*(3), 374-380. doi:10.1111/j.1532-5415.2005.53152.x

Vickers, D., Nettelbeck, T., & Willson, R. J. (1972). Perceptual indices of performance: the measurement of 'inspection time' and 'noise' in the visual system. *Perception, 1*(3), 263-295.

Wechsler, D. (2008a). *WAIS-IV administration and scoring manual*. San Antonio, TX: The Psychological Corporation.

Wechsler, D. (2008b). *WAIS-IV administration and scoring manual*. San Antonio, TX: The Psychological Corporation.

Zahodne, L. B., Glymour, M. M., Sparks, C., Bontempo, D., Dixon, R. A., MacDonald, S. W. S., & Manly, J. J. (2011). Education does not slow cognitive decline with aging: 12-Year Evidence from the Victoria longitudinal study. *Journal of the International Neuropsychological Society, 17*(06), 1039-1046. doi:doi:10.1017/S1355617711001044

Zekveld, A. A., Kramer, S. E., & Festen, J. M. (2011). Cognitive load during speech perception in noise: the influence of age, hearing loss, and cognition on the pupil response. *Ear & Hearing, 32*(4), 498-510. doi:10.1097/AUD.0b013e31820512bb

chapter 5

05.

CHAPTER 5

Visual Information Processing in Young and Older Adults

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5.1 Abstract

Decline in information processing with age is well-documented in the scientific literature. However, some discrepancy remains in relation to which cognitive domains are most susceptible to the aging process and which may remain intact. Furthermore, information processing has not been investigated nor considered as a function of affect, familiarity and complexity of tasks in a single experimental study. Thus, the current study investigated rate of visual information processing in 67 young university students (*M*age=19.64 years) and 33 educated healthy older adults (*M*age=70.33 years), while accounting for depression, anxiety and stress symptoms using the DASS. Rates of visual processing were measured as minimum time of stimulus exposure duration required for correct object recognition on a simple visual task (Inspection Time [IT]), and on a more complex visual cognitive task known as Change Detection [CD]) as well as words per minute on a text reading task (FastaReada). Results demonstrated significantly slower performance by older adults on the IT and CD, but comparable rates of text reading on a semantically more complex, but ecologically valid and familiar visual task that requires organized sequential shifts in attention via eye movements, continuous visual processing, access to working memory and semantic comprehension. The results also demonstrated that affective influences did not play a role in the older adults task performance, and that changes in cognitive domains may begin with older adults being slower to attend to and identify newly appearing familiar objects, as well as slower to encode and embed new information in memory during tasks that require a less practiced/familiar task strategy.

5.2 Introduction

A decline in cognitive functions including attention, speed of visual information processing, working memory, and dual task performance associated with the normal aging process is commonly reported in the scientific literature (Harada, Natelson Love, & Triebel, 2013; Ritchie Tucker-Drob & Deary, 2014; Salthouse, 1996; Deary et al., 2009; Hedden & Gabrieli, 2004, Cona et al., 2013; Bashore, Ridderinkhof, & van der Molen, 1997; Eckert, 2011; Ebaid, et al., 2017; Ebaid & Crewther, 2018; Lu et al., 2011; Finkel, Reynolds, McArdle, & Pedersen, 2007). Indeed, affective factors such as elevated levels of depression and anxiety symptoms are reported to exacerbate such decline (Hammar & Årdal, 2009; Beaudreau & O'hara, 2008; Beaudreau & O'Hara, 2009) while higher levels of education are often reported to mitigate cognitive decline in healthy older adults (Archer, Lee, Qiu, & Chen, 2018, Elgamal, Roy & Sharratt, 2011). Some cognitive abilities reliant on acquired knowledge (primarily verbal or language based) and defined by Cattell (1941) as Crystallized Intelligence (Gc), are reported to remain intact or even improve with increased age (Elgamal, Roy & Sharratt, 2011; Baltes, Staudinger, & Smith, 1995; Hedden, Lautenschlager & Park, 2005). By comparison, Fluid Intelligence (Gf) that includes skills such as inductive and deductive reasoning, problem solving, and manipulation of new information, are reportedly most sensitive to age-related declines (Cattell, 1963; Horn & Cattell, 1966).

Much of the impairments in cognitive function measured with sensory (visual and auditory) tasks are exacerbated by morphological and physiological changes in auditory function (Jayakody, Friedland, Martins & Sohrabi, 2018) and the eye (i.e., retinal integrity [reviewed in Brown, Corner, Crewther, & Crewther, 2018]). Brown et al. (2018) also demonstrated that conduction rates of visual information to cortex, and activation of visual attention as measured by decreases in flicker fusion thresholds, decline with age. A review by Wayne and Johnsrude (2015) also attests to the correlation between hearing loss and neurocognitive function and seems to support the decline in cognitive function in healthy aging that Salthouse (1996) has associated with a slower processing speed. Indeed, Salthouse' *Processing Speed Theory of Adult Age Differences in Cognition*, has become influential across the aging literature in providing an underlying basis for the decline observed in other complex cognitive abilities (i.e., Lemke & Zimprich, 2005; Zimprich, 2002; Salthouse & Ferrer-Caja, 2003; Eckert, 2011; Bashore, Ridderinkhof, & van der Molen, 1997; Eckert, 2011; Ebaid, et al., 2017; Lu et al., 2011; Finkel, Reynolds, McArdle, & Pedersen, 2007).

Impaired sensory processing i.e., visual and auditory processing has also gained substantial attention in providing explanation for deficits in cognitive processing across the lifespan (Schneider & Pichora-Fuller, 2000; Baltes & Lindenberger, 1997; Peelle & Wingfield, 2016; Bowl & Dawson 2015; Uchida, et al., 2018), and this argument has been incorporated into several other theories of cognitive aging such as the *Sensory Deprivation Hypothesis, the Common-Cause Hypothesis* (Lindenberger & Baltes, 1994; Baltes & Lindenberger, 1997), *and the Information Degradation Hypothesis* (Schneider & Pichora-Fuller, 2000). Such theories collectively suggest a strong interaction between declines in sensory ability i.e., impaired vision and audition with age, and declines in cognitive abilities (See Roberts & Allen 2016 for a review). Indeed, the first study to explicitly control for such age-related sensory decline and measure cognitive performance on an auditory digit span task was conducted by Füllgrabe, Moore and Stone (2015), who used a sample of audiometrically matched healthy young and older participants. Participants were also matched on age-corrected performance IQ scores and years of education, and did not demonstrate any significant differences in auditory digit span performance performance between older and younger adults (Füllgrabe, Moore & Stone, 2015).

Other psychological explanations of cognitive decline with aging such as the *Inhibitory Deficit Hypothesis* (Hasher & Zacks, 1988) suggest that older adults may perform worse on cognitive tasks compared to younger populations because they are more susceptible to irrelevant stimuli and have greater difficulty inhibiting distractions, resulting in heightened distractibility, poorer retrieval of task-relevant details, and overall worsened task performance. A further hypothesis derived from a *disuse perspective* (Salthouse, 1991), posits that differences in cognitive performance between age groups are at least in part due to changes in the nature of the activities performed or *not* performed by people of various age groups. Such ideas were conceptualised as early as the 1930's when Sorenson (1933, p.736) suggested that *'A decrease in test ability probably is caused by the fact that adults, as they grow older, exercise their minds less and less with materials found on psychological tests'.*

Visual attention and information processing are particularly relevant to study of cognitive decline as most human behaviour is visually driven (Mundinano et al., 2018), with visual attention considered the key driver of most perceptual, cognitive, and behavioural process (Crewther, Goharpey, Carey, & Crewther, 2013; Godefroy, Roussel, Despretz, Quaglino, & Boucart, 2010). Visual attention has often been conceptualized as three cognitive networks that carry out the functions of alerting, orienting and executive control (Posner & Petersen, 1990; Petersen & Posner, 2012) where alerting is defined as achieving and maintaining an alert state, orienting as the selection of information for sensory input, and executive control is defined as resolving conflicting information among responses and about task relevant stimuli (Posner & Petersen, 1990; Fan et al., 2002; Petersen & Posner, 2012). Whether attention is captured in a "bottom up" or a "top-down" manner has been suggested to affect cognitive task performance by older adults. Specifically, top-down or goal directed control of attention is facilitated by an individual's internal valuations, goals, or perceptual-sets and studies have reported that when tasks are reliant on top-down control of attention, older adults perform as fast and as accurately as older adults (Madden, 2007). On the other hand, when visual tasks require bottom-up control of attention, i.e., inhibition of distractors and are driven by salient differences among the features of the stimuli, older adults typically demonstrate a slower response rate or reaction time (Madden, 2007). Such findings have led to the conclusion that bottom-up control of attention is most susceptible to age-related decrements while top-down control of visual attention remains relatively intact across the lifespan (Madden, 2007).

Behavioural data using the the Attention Network Task (ANT; Fan et al., 2002) has demonstrated that healthy older adults have less efficient attentional networks compared to younger adults (Gamboz, Zamarian & Cavellero, 2010; Kaufman, Sozda, Dotson & Perlstein, 2016; Jennings, Dagenbach, Engle, & Funke, 2007; Mahoney, et al., 2010), however discrepency in findings still remain (MacLeod et al., 2010). For example, this was recently assessed in a study conducted by Kaufman et al. (2016) who reported slower button-press reaction times for older adults across all three attention networks, though after controlling for generalised slowing, only the alerting system remained significantly reduced. However, button-press reaction times are problematic when measuring domains of cognitive speed in a healthy aging population, given the potential contamination of motor slowing that may be contributing to seemingly slower task performance (Ebaid et al., 2017; Ritchie Tucker-Drob & Deary, 2014), and this is not often accounted for in the aging literature.

To date, visual information processing in healthy older adults in terms of rate of information processing in context of Posners three attentional networks (Posner & Petersen, 1990; Petersen & Posner, 2012), has not been investigated especially while accounting for affective influences, complexity and familiarity of tasks in a single experimental study. Visual tasks varying in complexity are necessary to determine which aspect of attentional control and cognitive processing is most susceptible to the aging process and whether any may remain intact. More specifically, if older adults are slower at identifying visual stimuli without any excess demands on working memory, as in a simple object recognition task requiring conscious access to visual perception and minimal decision making demands, then it is likely that older adults will also be slower when faced with the more complex task of change detection, that requires embedding in short-term memory of several objects in a visual array prior to decision making of same/different comparison of a second array presented soon after. Furthermore, in addition to such tasks, it is unknown whether a cognitively complex visual task that is more familiar and ecologically valid, i.e., reading, will elicit similar age-group differences.

Thus, the current study aimed to compare rate of visual information processing (specifically, threshold exposure time) in young and older adults of similar educational backgrounds, using computerised perceptual speed tasks varying in complexity and familiarity, while considering depression, anxiety, and stress symptoms. We aimed to measure rate of visual information processing and attention using an Inspection Time (IT) task requiring object recognition, a Change Detection (CD) task, and a rapid reading task known as the FastaReada which is an ecologically valid measure of visual attention and processing amongst an educated population (Hecht, Crewther, & Crewther, 2004; Elhassan, Crewther, Bavin, & Crewther, 2015). Each of our three tasks requires alerting, orientation and executive control of attention, though to different degrees. Based on the results from Ebaid et al. (2017) it was hypothesised that young and older adults would again demonstrate comparable results on the simple visual perceptual IT task but that younger adults would perform faster than older adults on the more complex CD task, given the additional requirement for executive control of attention, new learning, and memory. We also hypothesised that older adults would demonstrate a slower rate of reading than the young adults on the cognitively complex FastaReada task due to excess demands on all attentional networks and for fast visual processing of stimuli prior to comprehension of text, even though fast and fluent reading is likely to be a familiar and well-practiced task amongst an educated sample.

5.3. Method

5.3.1 Participants

The sample included 100 healthy participants who were derived from a larger pool of participants from previous studies conducted by our lab (Ebaid et al., 2017; Ebaid & Crewther, 2018) and were divided into a young adult and older adult group. The younger group included 67 individuals between the age of 18 – 29 years (*M*age = 19.64, SD = 2.26) and comprised 59 females, and 8 males, while the older group included 33 individuals of whom 25 were females and 8 were males between the age of 60 - 81 years (*M*age = 70.33, SD = 5.62). Younger adults were recruited from La Trobe University, Melbourne, and consisted of first year Psychology students who received course credit, while the older adults were recruited through the University of the Third Age (U3A) and received a $20 Coles-Myer voucher for participation. U3A is an international volunteer organization where interested older individuals attend for their own interest and not for any qualifications (for more information please visit www.u3a.org.au). Both groups had tertiary education with the younger sample reporting an average of 7.64 years (SD = 1.06), and the older sample had an average of 10.91 years (SD = 3.38) of post-primary education, with number of years of formal education recorded from the first year of secondary school onwards. All participants had normal or corrected-to-normal visual acuity whereby 6/6 visual acuity was ensured. Participants self-reported whether volume on computerized tasks was adequate for comprehension, and for performance on the auditory digit span task. Participants who wore hearing aids were able to keep them in during the study. Pure-tone or speech audiometry was not explicitly assessed as all experimental tasks were visually based and were all presented at suprathreshold visual contrast. Exclusion criteria included previous diagnosis of a neurological disorder and the inability to hear, understand and/or read in English with basic competence. A demographic questionnaire elicited information on age and education level. This study was carried out in accordance with the recommendations of the National Statement on Ethical Conduct in Human Research, La Trobe University Human Ethics Committee (UHEC) and all subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by La Trobe University Human Ethics Committee, approval number S15/19.

5.3.2 Materials

5.3.3 Screening Measures

Depression Anxiety and Stress Scale DASS-21 (Lovibond & Lovibond, 1995)

The Depression Anxiety and Stress Scale (DASS-21; Lovibond & Lovibond, 1995) is a 21-item self-report instrument that measures negative emotional states relating to depression, anxiety and stress. The DASS-21 was administered as a screening tool to identify whether participants had negative emotional states beyond a ‘mild’ level (i.e., depression > 6, anxiety > 5, or stress > 9) that might independently affect performance on the cognitive tasks (Beaudreau & O'Hara, 2008; Beaudreau & O'Hara, 2009).

Auditory and Visual Backward Digit Span (DSB) task as a Correlative Measure of Intellectual Functioning

Automated auditory and visual backward digit span tasks were administered to assess working memory capacity as a correlative measure of intellectual functioning (Lichtenberger & Kaufman, 2009) on the basis that working memory capacity has previously been reported to positively correlate with Full Scale IQ (Griffin & Heffernan, 1983 Salthouse & Pink, 2008), fluid intelligence and executive functioning (Fukuda, et al., 2010; Cowan, et al., 2005). Scores on the DSB were compared against appropriate age and education level norms.

The DSB tasks adapted from the Auditory Digit Span subset of the Wechsler Adult Intelligence Scale 4th Edition (WAIS; Wechsler, 2008) using Authorware Professional Software, and administered in both auditory and visual conditions on an Apple iMac (Retina 4K) computer with a 21.5-inch monitor. In the auditory condition, a series of random digits ranging from 1-9 were verbally presented to participants via a voice over on loudspeaker and participants were required to type the digits back in the *reverse* order using a keyboard. The auditory version has no visual representation of the numbers on the screen. In the *visual* digit span condition, digits were presented in black Ariel 92pt font against a white background, at a rate of one digit per second, with no sound/voiceover reading the numbers. If successful, the participant was given a longer sequence. The number sequence began at a span length of two, and increased by one every two trials, i.e., participants were given two trials per span length. The task ceased when two consecutive responses were entered incorrectly, and the previously correct span length was recorded as the participants 'backward digit span capacity'. Volume was set to the preferred level chosen by the participant after adjustment during the instructions phase, prior to formal commencement of the task.

5.3.4 Experimental Measures

Inspection Time (IT) task

A modified Inspection Time (IT) task, based on the version of Vickers, Nettelbeck, and Willson (1972), was adapted using Vpixx (www.vpixx.com) by Brown and Crewther (2012) and was used as a measure of early cortical perceptual speed by estimating threshold exposure duration required to successfully discriminate and identify a familiar visual stimulus, without any confound of motor reaction time thus ensuring that task performance is not confounded by age related motor slowing (Ebaid et al., 2017). The task employs an inbuilt Visual Parameter Estimation by Sequential Testing (VPEST) algorithm, designed to estimate the exposure threshold required to discriminate and identify which of the three possible stimuli consisting of either a fish, truck or butterfly was presented (See Figure 1). The task was presented at suprathreshold contrast (well above each individuals contrast threshold) on an Apple eMac computer running at 89 Hz screen refresh rate. Participants were required to identify the target stimulus from the 3 options (fish, truck or butterfly) by manually responding on a keyboard after the stimulus had disappeared. Prior to each trial, a fixation cross was presented for a random duration between 700-1000ms, followed by a blank screen for 50ms, after which the target stimulus was presented for variable exposure times for no greater than 1000ms. Presentation of target stimulus was immediately followed by a mask, presented for 500ms. The start of the next trial was triggered 100ms after the termination of the mask. One thousand milliseconds was the maximum exposure time for any target stimulus. Confidence intervals and estimations of exposure time were calculated as part of the Vpixx program, where the lowest reoccurring exposure time is used to estimate and indicate the threshold duration of each individuals perceptual time required to discriminate and accurately identify visual stimuli, with a shorter threshold exposure time indicative of a faster speed of processing of visual information. See Figure 1 for example of task.

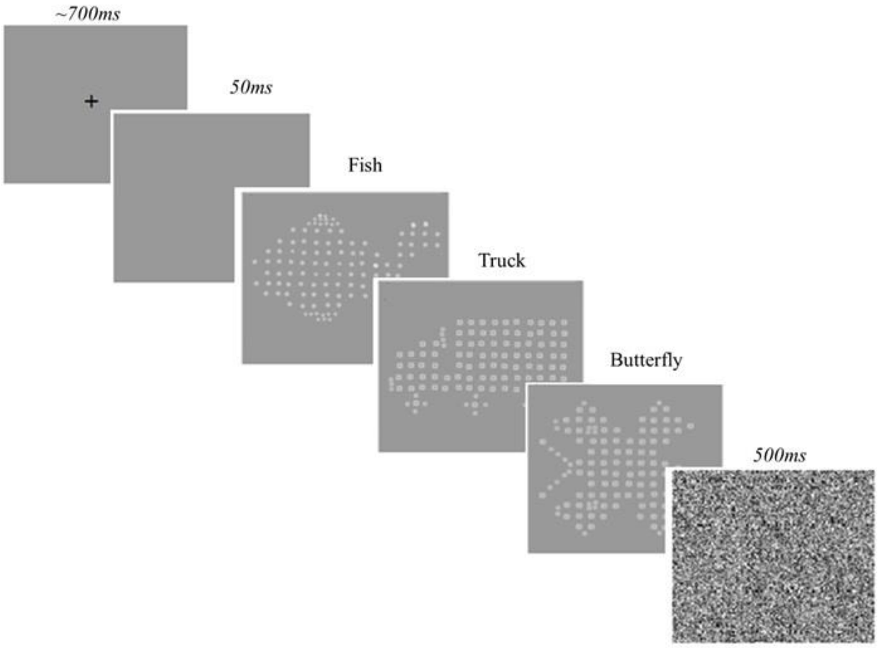

Figure 1. Modified Inspection Time (IT) task trial. *Note.* Only one target stimuli of fish, truck, or butterfly is presented per trial

Change Detection

The Change Detection task (CD) was based on the Becker, Pashler, and Anstis (2000) version, as adapted by Rutkowski et al. (2003). The task consisted of the same software, computer, and VPEST technique as the modified IT task. The stimuli were four different alphabetic letters with a hash (#) symbol on either side of each letter, contained in a circle. The four circles were arranged into a square shape (See Figure 2). The addition of hash symbols around each letter were included to create visual crowding (Whitney & Levi, 2011), and as non-alphabetic task-irrelevant stimuli, as the 4 alphabetic letters alone in a single array is within the limit of visual-short term memory capacity (Cowan, 2001). A fixation cross was presented for 2 seconds at the start of each trial for variable exposure times, followed by the first stimulus array of four letters for variable exposure times, and immediately followed by a 250ms delay, and then another array of four letters (presented for a period of 3 seconds). In the *change* condition, one of the four letters were changed in the final presentation. In the *no-change* condition, the exact same letters were shown in both presentations. The two conditions were presented in random order. Participants were asked to indicate whether there was a *change* or *no-change* after each set of visual arrays, and the estimated exposure time for detection of change between two visual arrays was calculated. Again, the task does not measure motor reaction time nor is reliant on time taken to make a response, thus ensuring that task performance is not confounded by age-based motor speed (Ebaid et al., 2017). Confidence intervals and threshold estimations of exposure time were calculated by Vpixx where a lower estimated exposure time indicated a faster threshold response time required to detect change between visual stimuli. An example of the task is shown in Figure 2.

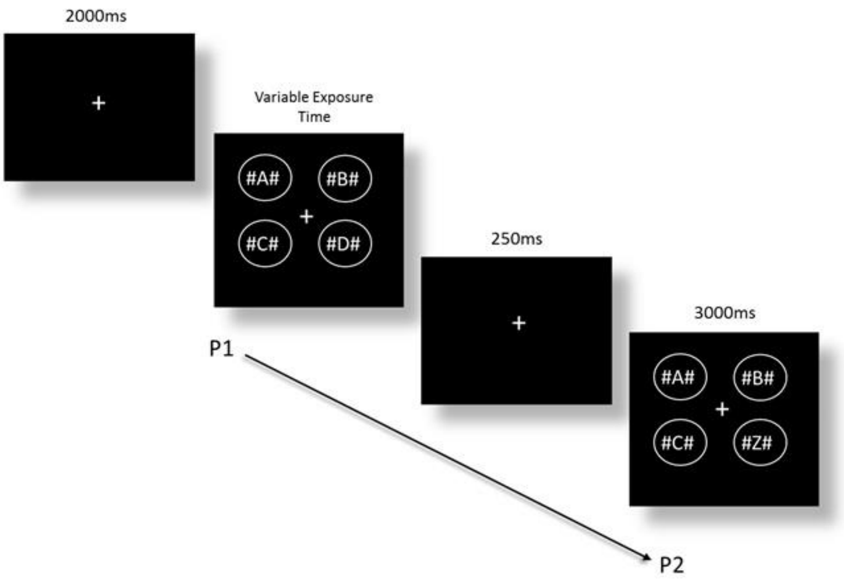

Figure 2. Change Detection (CD) task where a change has occurred from presentation 1 (P1) to presentation 2 (P2).

FastaReada

FastaReada is a customised computer-generated task formulated using VPixx (www.VPixx.com), (Elhassan, et al., 2015; Hecht et al., 2004) and designed to measure reading fluency by determining the number of words an individual can accurately read per minute. The task is reliant on visual attention, rapid processing of visual information, working memory, continuous inhibition of distractors, continuous access to lexical storage, integration of sublexical, orthographic, phonological, and lexico-semantic information to achieve fast semantic understanding of the text Elhassan et al., 2015; Crewther & Cotton, 2009; Daneman & Hannon, 2001). During the task, an excerpt from a children's Penguin novel (permission received from Penguin Group) was presented on a computer screen in Lucida Grande font, in 60 pt, six words at a time in narrative order (see Appendix E for copy of script). Presentation time was controlled via the PEST adaptive staircase algorithm based on a maximum-likelihood threshold estimation. Participants were asked to read the words out loud as accurately as possible and were informed that presentation will eventually become so short (i.e., in order to measure thresholds), that reading the six words on the screen would be impossible. Participants were encouraged to attempt this to the best of their ability. After each trial (i.e., after each set of 6 words), the investigator indicated accurate or inaccurate decoding by pressing a key on the keyboard, and this triggered the next presentation of words. Similar to the IT and CD tasks, the FastaReada does not measure response time nor reaction time. The score obtained at the end of the task provided an estimation of the number of words the participant can accurately read per minute.

5.3.5 Procedure

Total testing time was approximately 1 hour. The CD and IT tasks were preceded with five practice trials. To ensure accurate results for the CD and IT, the task was re-done if the confidence interval as indicated by the Vpixx data output was below 80%. The FastaReada task was not preceded with a practice trial as this was likely to confound performance on the task if participant had knowledge about the upcoming text on the screen. All testing was conducted in a quiet room either at La Trobe University or U3A, where only the participant and experimenter were present.

5.3.6 Data analysis

All analyses were performed using SPSS v. 25.0 (IBM Corp., Armonk, NY, USA). Data was screened for outliers on individual tasks and for any result indicating inconsistent performance across tasks. None were found.

5.4 Results

5.4.1 Relationships between negative affect and performance on the IT, CD, and FastaReada

Results revealed that DASS scores for each subcategory were less than ‘mild’ and were in the normal range for both young and older adults. Interestingly, mean DASS scores for the older adults were lower than those in the younger population across all three subcomponents. Descriptive statistics are reported in Table 1. Correlation analyses also revealed no significant relationships between depression, anxiety or stress symptoms and performance on the IT, CD, or FastaReada in the older sample. In the younger sample, correlation analyses revealed a marginal significant positive correlation between depression scores and performance on the CD task, indicating that increased depression scores were correlated with a higher (i.e., slower) threshold estimation time to detect change between two visual arrays. The correlation matrix is presented in Table 2.

Table 1. Descriptive Statistics of Age, Gender, Negative Affect (DASS), and Backwards Digit Span for Young and Older Adults

	Age (Years)							
	Younger Adults (M = 8, F = 59)				Older Adults (M = 8, F = 25)			
	N	Range	*M*	*SD*	*N*	Range	*M*	*SD*
	67	18 - 29	19.64	2.26	33	60 - 81	70.33	5.62
	Years of Formal Education							
	67	7-11	7.64	1.06	33	7-21	10.91	3.38
	Scores on Depression Anxiety Stress Scale (DASS-21)							
DASS.dep	67	0-11	3.09	2.51	33	0-8	1.88	2.42
DASS.anx	67	0-12	3.34	3.03	33	0-7	1.79	1.93
DASS.str	67	0-14	5.89	3.49	33	0-13	3.91	2.88
Scores on Backwards Digit-Span (DSB) task								
DSB.Aud	67	3-8	5.88	1.87	33	3-7	5.06	1.12
DSB.Vis	67	3-8	5.72	1.23	33	2-7	5.27	1.28

Note: DASS.dep = DASS-21 depression score, DASS.anx = DASS-21 anxiety score, DASS.str = DASS-21 stress score, DSB.Aud = Auditory Digit Span Backward

Table 2. Correlation Coefficients (*r*) for Depression, Anxiety, Stress Scores and Performance on IT, CD, and FastaReada for Young and Older Adults

Younger Adults

Measure	DASS.dep	DASS.anx	DASS-str	IT	CD	FastaReada
DASS.dep	-					
DASS.anx	.522**	-				
DASS.str	.541**	.569**	-			
IT	-.097	-.070	-.112	-		
CD	.281*	.097	.031	-.116	-	
FastaReada	-.139	.067	-.002	-.209	-.191	-

Older Adults

Measure	DASS.dep	DASS.anx	DASS-str	IT	CD	FastaReada
DASS.dep	-					
DASS.anx	.599**	-				
DASS.str	.546**	.616**	-			
IT	.007	.025	-.090	-		
CD	. 233	-.062	.106	.054	-	
FastaReada	-.117	.083	.216	.089	-.279	-

Note: DASS.dep = DASS-21 depression score, DASS.anx = DASS-21 anxiety score, DASS.str = DASS-21 stress score, IT = Inspection Time, CD = Change Detection.

** p = <.01, * p = < .05

5.4.2 Backward digit-span (DSB) as a correlative measure of intellectual functioning

Table 1 provides descriptive data of DSB scores for young and older adults. Normative data as indicated by the WAIS manual (Wechsler, 2008) has been provided for healthy older adults between the ages of 20-24 years, 25-29 years, 65-69, and 70-74 and are mean DSB scores of 5.1, 4.9, 4.5, 4.3, and 4.4 respectively. Similar normative scores were noted in a recent study conducted by Monaco et al. (2013) aimed at providing standardization and normative data for the digit span tasks in a large healthy sample, which suggested the following norms for the DSB for healthy adults between 20-30. *M* = 5.07, between 61 – 70, *M* = 4.15, between 71-80 = 3.92. Thus, as shown in Table 1, young and older adults from the current study obtained scores that exceeded these suggested normative scores.

5.4.3 Age-group differences in performance on the IT, CD, and FastaReada

Significant differences in performance between young and older adults were demonstrated on the IT, where younger adults performed significantly faster than older adults (*M*difference = -87.335ms, $t(74) = -7.214$, $p = <.001$, $\eta^2 = 0.413$) as well as on the CD, where task performance was significantly faster for younger adults than older adults (*M*difference = -258.488ms, $t(77) = -3.348$ $p = .001$, $\eta^2 = 0.127$). There were no significant differences in FastaReada scores between young and older adults $t(97) = 0.336$, $p = .738$, $\eta^2 = 0.001$. These results are presented in Table 3.

Table 3. Descriptive Statistics and Independent Samples T-Test for Mean Difference for Scores on the IT, CD, and FastaReada in Younger and Older Adults

	Younger Adults				Older Adults				Age-Group Differences	
Measure	*N*	Range	*M*	SD	*N*	Range	*M*	SD	*p*	η^2
IT (ms)	46	20.00-130.00	49.30	169.06	30	34.90 – 343.00	136.64	74.93	<.001	0.413
CD (ms)	47	110.00-1288.00	636.36	338.52	33	175.80-1798.00	894.84	363.20	.001	0.127
Fasta Reada	67	105.30-848.80	375.82	161.73	33	128.50-721.50	364.53	145.92	.738	0.001

Note: IT = Inspection Time, CD = Change Detection

5.4.4 Relationships among age and performance on the IT, CD, and FastaReada

As our age distribution was not normally distributed and included two distinct age groups, correlational analyses using Spearman's Rank-Order Correlation were performed to investigate the strength, direction and significance of associations between age and dependent measures. Results revealed significant weak-moderate positive correlations between increasing age and threshold performance on IT (r_s = .569, p < .001) as well as age and threshold performance on CD (r_s = .382, p < .001). No significant correlations were revealed between age and performance on the FastaReada task. A full correlation table of all dependent measures is shown in Table 4.

Table 4. Spearman's Rank-Order Correlations between Age, and scores on IT, CD, and FastaReada

Variable	Age	IT	CD	FastaReada
Age	-			
IT	.569**	-		
CD	.382**	.143	-	
FastaReada	-.014	-.063	-.205	-

Note: IT=Inspection Time, CD = Change Detection,
** *p* = <.01

5.5 Discussion

The primary objective of this study was to investigate rate of visual attention and information processing on computerised perceptual speed tasks varying in complexity and familiarity, in similarly educated young and older adults while also accounting for affective factors. All tasks required rapid activation of transient attention, rapid visual processing and conscious perception of the object(s), which can be conceptually related to Posner’s three attentional networks (Posner & Petersen, 1990; Petersen & Posner, 2012). Collectively, the results of the IT and CD tasks indicated that the threshold exposure duration required by older adults to make a correct perceptual judgement was longer than that of younger adults even when the task demands were simple and predominantly requiring alerting and orientation for object recognition, as in the IT task, and even more so when the task was novel, as in the CD task that required new learning, short term memory, a less familiar task strategy and decision making i.e., executive control of attention. By comparison on the semantically more complex FastaReada task that utilized more familiar and regularly practiced skills, older adults demonstrated statistically comparable performance to younger adults, despite requiring complex cognitive skills. Overall, the results from the current study are in line with the *Cattell-Horn Theory of Fluid and Crystallized Intelligence* (Cattell, 1963; Horn & Cattell, 1966), Salthouse' (1991) *disuse perspective*, the *Processing Speed Theory of Adult Age Differences in Cognition* (Salthouse, 1996) and findings from Madden (2007).

5.5.1 Age and Performance on Inspection Time (IT) task

Contrary to hypotheses and our previous work (Ebaid et al., 2017), our older adults (60-81 years) required a significantly longer (i.e., slower) estimated threshold exposure time to discriminate and identify simple visual stimuli than did younger adults (18-30 years). Furthermore in this study, a small but significant correlation was exhibited between age and threshold exposure time on the IT task, implying that as age increases, threshold exposure time also increase (i.e., become slower), supporting past research using a similar IT task (Ritchie, Tucker-Drob & Deary, 2014) and theories of generalized slowing across the healthy lifespan (i.e., Salthouse, 1996). It is important to note that the sample in Ebaid et al. (2017) included a wider age range, with several participants between the ages of 30-50 years in the older group which may be a factor contributing to the discrepancy in findings.

From the viewpoint of the categories of attentional control proposed by Posner and Peterson (1990), the results of the IT task, that required rapid activation and orientation of attention to a visual stimulus, with minimal demands on executive control of attention, are in line with those that suggest that older adults demonstrate reduced alerting during ANT tasks, even when controlling for generalized cognitive slowing (Kaufman et al., 2016; Jennings, et al., 2007). However, when considering the demands of the IT tasks beyond the main requirement of object recognition, the IT task requires orientation to relevant local stimuli which globally represented a fish, truck or butterfly, and then executive control of attention when deciding which of the three images were presented. Although theoretically the control of attention can be conceptualized as three different networks that carry out functions of alerting, orienting, and executive control, it may not be ideal to dichotomise them when assessing the networks using behavioural measures even if the task is seemingly simple, as in the IT task. Instead, it may be more appropriate to consider the degree to which the attentional networks are required for performance on certain cognitive tasks.

When considering the demands of the IT task and its predominant reliance on bottom-up control of attention, our findings are consistent with those that suggest that older adults are slower and less accurate on task performance reliant on bottom-up processing (Madden, 2007). Although the visual stimuli used in the current study consisted of familiar objects i.e., a fish, truck or butterfly, the figures were made up of many small shapes contributing to the *globally* represented objects (See Figure 1). Thus, it is possible that older participants may have been more distracted by the local figures and hence had more difficulty processing the global image (Oken, Kishiyama, Kaye & Jones, 1999). Differences in global-local processing between healthy young and older adults has previously been explored in a study conducted by Oken, Kishiyama, Kaye, and Jones (1999) who reported a significant impairment in the ability of older adults to process global figures compared to local figures. More recent research has also demonstrated that healthy older adults between 65-86 years show a significant local-processing bias compared to young and middle-aged adults (Insch, Bull, Phillips, Allen, & Slessor, 2012). Other studies however, have reported that older adults are more biased to global processing, and in fact demonstrate global interference compared to young adults when trying to process local figures of small alphabetical letters which globally represent a large incongruent alphabetic letter (Roux & Ceccaldi, 2001).

5.5.2 Age and Performance on the Change Detection (CD) Task

Consistent with predictions, performance on the Change Detection (CD) task was significantly different between age groups, with younger adults detecting change between two visual arrays significantly faster than older adults. Furthermore, moderate significant correlations were also exhibited between age and threshold exposure duration on the CD, implicating that as age increases, exposure time required to detect change also increase. Again considering the categories of attentional control (Posner & Peterson, 1990), it may also be the case that deficits in the alerting system demonstrated with aging are associated with more extensive difficulties in orienting and executive control of attention that are required for the CD task: a suggestion put forward by Kaufman et al (2016). However, as alluded to above, it may be more appropriate to consider the extent or load of task demands on each of the attentional networks, as opposed to explicitly differentiating them when using behavioral measures. More specifically, the task demands for the CD are undoubtedly more complex than those of the IT and have a greater load on executive control of attention, however, both measures still require alerting, orienting, and executive control for accurate task performance, though to different degrees.

Results from the current study are also in line with the underlying presumptions of the Cattell-Horn theory (Cattell, 1963; Horn and Cattell, 1966) which suggests that cognitive abilities that involve inductive and deductive reasoning, problem solving, and manipulation of new information, are most susceptible to age related decline. These findings are also consistent with accuracy-based past studies exploring change detection and aging (Costello et al., 2010) and those that report positive relationships between increased age and reaction times in detecting change (i.e, Rizzo et al., 2009). With reference to bottom-up and top-down control of attention, the CD task is heavily reliant on bottom-up processing, and so findings from the current study are also in agreement with those that suggest that bottom-up processing is more susceptible to age-related decline compared to top-down control of attention (Madden. 2007). Furthermore, when there are several components to a visual scene such as hash symbols surrounding each letter in the array (i.e., #A#), and presentation time of stimuli is limited (as in the current study), this often exceeds visual-short term memory capacity (i.e., 4-items; Cowan 2001), which in turn increases task difficulty due to dual-task demands, whereby healthy older adults are often reported to show declines in performance relative to younger adults (Vaportzis, Georgiou-Karistianis, & Stout, 2013). However, when healthy older adults are given adequate time for encoding visual stimuli during dual-task working memory measures such as *N*-back tasks, age-group differences are not observed (See Ebaid & Crewther, 2018). From the perspective of the *Inhibitory Deficit Hypothesis* (Hasher & Zacks, 1988) it is also plausible that the hash symbols surrounding each letter in the array served as distractors to older participants who may not have been as efficient at inhibiting the irrelevant information, therefore impeding overall task performance.

5.5.3 Age and Performance on the FastaReada

Contrary to predictions, there were no significant differences in performance on the FastaReada task between young and older adults, and thus, results are not in line with findings from past research that report an age-related slowing in reading speed (Kliegl, Granmer, Rolfs, Engbert, 2004; McGowan, White, Jordan & Paterson, 2014). Past researchers have also suggested that compared to silent reading, reading aloud is slower given that readers are required to articulate each word and thus, visual fixations remain in the same place for longer (Rayner, 1998, 2009). This suggestion is also persuant to data indicating that talking speed or orofacial movement decline with normal aging (Bilodeau-Mercure et al., 2015). Results from the current study also reject such inferences, however it is important to note that although in the current study older adults were required to read sentences aloud, we did not measure speed of verbal articulation, given that the task itself varied in presentation time for each sentence. Specifically, after articulation of a sentence, a button press triggered the exposure of the next 6 words which became faster or slower depending on each participants' accuracy performance.

Reading is considered a unique neurobiocultural task (Meyer & Pollard, 2006) which is heavily reliant on rapid processing of visual information and complex cognitive skills including visual attention, continuous inhibition of distractors, continuous access to lexical storage, integration of sublexical, orthographic, phonological, and lexico-semantic information as well as working memory (Crewther & Cotton, 2009;Froehlich, et al., 2018) to achieve fast semantic understanding of the text (Daneman & Hannon, 2001; Elhassan et al., 2015, Sereno & Rayner, 2003; Kinsey, Rose, Hansen, Richardson, & Stein, 2004; Breznitz & Misra, 2003; Blaiklock, 2004). Indeed, fluent reading of text requires alerting, orienting, and executive control of attention for fast and accurate performance, with excess demands on working memory, continuous and rapid access to lexical storage, given that the text was progressively presented for shorter durations. Although the FastaReada is a complex cognitive task reliant on both bottom-up control of visual attention, as well as top-down semantic processing, reading can be considered a familiar and well-practiced task amongst highly educated individuals (Meyer & Pollard, 2006; Albert & Teresi, 1999), which in turn may have had a compensatory effect that enabled older adults to perform as fast as younger participants. When considering that many of the fundamental skills required for fluent reading entail skills such as verbal fluency and vocabulary, results from the current study are consistent with the notion that these skills which comprise *Crystallized Intelligence* remain relatively stable or even improve across the lifespan (Cattell, 1963; Horn & Cattell, 1966, Elgamal, Roy & Sharratt, 2011; Baltes, Staudinger, & Smith, 1995; Shimamura, Berry, Mangels & Rusting & Jurica, 1995; Hedden, Lautenschlager & Park, 2005). Furthermore, as participants vision was screened to ensure normal or corrected-to-normal acuity, this to some extent, ensured that sensory deficits in the visual domain were not impeding task performance, especially as stimuli were presented at same distance each time even though for varying temporal durations.

5.5.4 Negative Affect and Performance on the IT, CD, and FastaReada in Young and Older Adults

Findings from the current study surprisingly demonstrated that our older adult group reported lower levels of anxiety, depression, and stress symptoms compared to younger adults. Furthermore, there were also no significant correlations between performance on the IT, CD or FastaReada and any category of negative affect for the older adult group. This finding differs from previous research which suggests that older adults typically above 60 years have increased levels of negative affect which in turn is related to performance on cognitive tasks (Beaudreau & O'Hara, 2008; Beaudreau & O'Hara, 2009). It is important to note however, that our sample of older adults were actively engaged in vocational education, and generally active members of their communities, and thus such attributes are likely to contribute to lower levels of negative affect. Supporting this presumption, a study conducted by Glass, De Leon, Bassuk and Berkman (2006) found that healthy older adults above 65 who were socially engaged in activities including unpaid community or volunteer work had lower levels of depressive symptoms as measured with the Centre for Epidemiologic Studies Depression Scale. In addition, findings from the current study demonstrating that the younger sample had higher levels of depression, anxiety, and stress levels (though still in the ‘mild’ range) compared to older adults is in line with research suggesting that first and second year university students have higher levels of negative affect as measured with the DASS compared to students in more advanced years (Bayram &Bilgel, 2008).

5.5.5 Limitations

A limitation on the generalizability of findings is the similar education level of the two samples, both of which reported significant tertiary training. Education is a particularly relevant factor, especially for older adults, given that individuals with higher levels of education are often reported to be less susceptible to cognitive decline and forms of dementia later in life (Armstrong et al., 2012; Zhang et al., 1990). Thus, the older adults from the current study who have continued to engage in vocational study post-retirement, may not be representative of the general population of healthy older adults over 60. Future research should aim to include both young and older samples with more diverse levels of education. A further limitation of the current study was the sizeable discrepancy between the numbers of participants in the young adult group compared to the older adults. Indeed, the small sample size in the older adult group may have compromised the statistical power of group- based findings, and so future research should aim to include equal sizes samples. Although the overarching aim of our experiment was not to assess differences in cognitive performance between genders, male participants were under-represented in both age-groups. However, there is currently very little robust evidence to suggest gender-differences in cognitive performance in any age-group psychophysically and in neuroimaging (see Hill et al 2014; Reed et al., 2017; Ritchie et al., 2018). Thus, future research may benefit from including an even spread of genders within their study when assessing cognitive performance. In terms of the CD task, more ecologically appropriate stimuli might be better for translational validity using visual scenes of roads or traffic scenarios which may be more familiar to participants, and more applicable to the broader context of biomarkers for safety in driving given that visual deterioration due to presbyopia, glaucoma and age-related maculopathies are common in adults over 60 years of age (Goertz, Stewart, Burns, Stewart, & Nelson, 2014; Patel & West, 2007; Spierer, Fischer, Barak, & Belkin, 2016). Clinical assessment of vision and hearing in future studies may enable more rigorous dissociation of sensory receptor decline and cognitive performance if threshold contrast or sound levels are examined, rather than suprathreshold contrasts as used in the current study. Furthermore, in relation to theories which postulate an association between sensory and cognitive decline (Lindenberger & Baltes, 1994; Baltes & Lindenberger, 1997; Schneider & Pichora-Fuller, 2000), normal age-related deficits in vision and hearing may have indirectly affected cognitive performance. Given that both age groups in the current study had very low i.e., less than ‘mild’ levels of depression, anxiety, and stress when measured with the DASS, it may also be useful for future research into visual information processing to include a sample of participants with more variable levels of negative affect in order to more accurately explore its potential impact on cognitive performance.

5.5.6 Conclusions and Future Directions

The current study demonstrated that threshold rates of visual attention and processing speed is significantly slower for older adults even on perceptual tasks that simply require identification of a familiar visual stimulus, i.e., the IT task. Furthermore, when task demands were increased to measure exposure time required to detect change, older adults were also significantly slower. Interestingly, on the cognitively complex FastaReada which measured rate of fluent reading, older participants performed comparably to younger adults. Thus, the most obvious temporal difference affecting rate of visual information processing between the three tasks was the bottom-up requirement of the IT and CD tasks for participants to rapidly attend, learn and embed information in short term memory prior to making decisions on visual stimuli identification, or of ‘change’ or ‘no-change’ between two visual arrays. It was also interesting to note that lower levels of depression, anxiety, and stress symptoms were reported for our older adults compared to our younger sample, making it unlikely that negative affect impaired cognitive task performance.

To add further understanding to such findings and the attentional networks proposed by Posner and colleagues (1990), future research should aim to examine underlying biobehavioural mediators of visual attention and rapid perceptual processing, such as eye movements. As eye movements play a significant role in guiding and directing attention (Fernandez-Ruiz et al., 2018; McDowell, Dyckman, Austin, & Clementz, 2008), it may be valuable to explore these patterns between young and older adults during similar psychophysical tasks particularly given previous suggestions that current tasks used to assess the attentional networks such as the ANT (Fan et al., 2002) may not be reliable in disassociating the networks of attention in aging (MacLeod et al., 2010). Results from the current study are potentially important clinically, in regard to translational clinical tools able to provide rapid non-invasive measures of information processing and visual attention, and should inform theoretical areas of aging research relating to visual attention and processing

5.6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

5.7 Author Contributions

SGC initiated the project, designed the outline and content, contributed to the writing and data analysis. DE recruited participants, collected and analysed the data. DE has also contributed to most of the writing and developed the first and final draft of the manuscript along with SGC.

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5.10 References

Albert, S. M., & Teresi, J. A. (1999). Reading ability, education, and cognitive status assessment among older adults in Harlem, New York City. *American Journal of Public Health, 89,* 95–97. doi: 10.2105/ajph.89.1.95

Archer, J. A., Lee, A., Qiu, A., and Chen, S. A. (2018). Working memory, age and education: a lifespan fMRI study. *PLoS One* 13:e0194878. doi: 10.1371/journal.pone.0194878

Armstrong, M. J., Naglie, G., Duff-Canning, S., Meaney, C., Gill, D., Eslinger, P. J., et al. (2012). Roles of education and IQ in cognitive reserve in Parkinson's disease-mild cognitive impairment. *Dementia & Geriatric Cognitive Disorders Extra, 2,* 343–352. doi: 10.1159/000341782

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychology & Aging, 12,* 12–21. doi: 10.1037/0882-7974.12.1.12

Baltes, P. B., Staudinger, U. M., Maercker, A., and Smith, J. (1995). People nominated as wise: a comparative study of wisdom-related knowledge. *Psychology & Aging, 10,* 155–156. doi: 10.1037/0882-7974.10.2.155

Bashore, T. R., Ridderinkhof, K. R., & van der Molen, M. W. (1997). The decline of cognitive processing speed in old age. *Current Directions in Psychological Science, 6,* 163–169. doi: 10.1111/1467-8721.ep10772944

Bayram, N., & Bilgel, N. (2008). The prevalence and socio-demographic correlations of depression, anxiety and stress among a group of university students. *Social Psychiatry and Psychiatric Epidemiology, 43,* 667–672. doi: 10.1007/s00127-008-0345-x

Beaudreau, S. A., & O'Hara, R. (2008). Late-life anxiety and cognitive impairment: A review. *The American Journal of Geriatric Psychiatry, 16,* 790–803. doi: 10.1097/JGP.0b013e31817945c3

Beaudreau, S. A., & O'Hara, R. (2009). The association of anxiety and depressive symptoms with cognitive performance in community-dwelling older adults. *Psychology & Aging* 24, 507–512. doi: 10.1037/a0016035

Becker, M. W., Pashler, H., & Anstis, S. M. (2000). The role of iconic memory in change-detection tasks. *Perception, 29,* 273–286. doi: 10.1068/p3035

Bilodeau-Mercure, M., Kirouac, V., Langlois, N., Ouellet, C., Gasse, I., & Tremblay, P. (2015). Movement sequencing in normal aging: speech, oro-facial and finger movements. *Age, 37*, 9813. doi: 10.1007/s11357-015-9813-x

Blaiklock, K. E. (2004). The importance of letter knowledge in the relationship between phonological awareness and reading. *Journal of Research in Reading, 27,* 36–57. doi: 10.1111/j.1467-9817.2004.00213.x

Bowl, M. R., & Dawson, S. J. (2015). The mouse as a model for age-related hearing loss-a mini-review. *Gerontology, 61,* 149–157. doi: 10.1159/000368399

Breznitz, Z., & Misra, M. (2003). Speed of processing of the visual-orthographic and auditory-phonological systems in adult dyslexics: the contribution of "asynchrony" to word recognition deficits. *Brain & Language, 85,* 486–502. doi: 10.1016/s0093-934x(03)00071-3

Brown, A., Corner, M., Crewther, D. P., & Crewther, S. G. (2018). Human flicker fusion correlates with physiological measures of magnocellular neural efficiency. *Frontiers in Human Neuroscience, 12*, 176. doi: 10.3389/fnhum.2018.00176

Brown, A., & Crewther, D. (2012). Autistic children show more efficient parvocellular visual processing. *Front. Hum. Neurosci.* doi: 10.3389/conf.fnhum.2012.208.00021 [Epub ahead of print].

Cattell, R. B. (1941). Some theoretical issues in adult intelligence testing. *Psychological Bulletin.* 38, 592.

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: a critical experiment. *Journal of Educational Psychology, 54,* 1–22. doi: 10.1037/h0046743

Cona, G., Bisiacchi, P. S., Amodio, P., & Schiff, S. (2013). Age-related decline in attentional shifting: evidence from ERPs. *Neuroscience Letters*, 556, 129–134. doi: 10.1016/j.neulet.2013.10.008

Costello, M. C., Madden, D. J., Mitroff, S. R., & Whiting, W. L. (2010). Age-related decline of visual processing components in change detection. *Psychology & Aging, 25*, 356–368. doi: 10.1037/a0017625

Cotton, S. M., & Crewther, S. G. (2009). "Developmental dyslexia: a conceptual and measurement quandary," in *Reading: Assessment, Comprehension and Teaching*, eds N. H. Salas and D. D. Peyton (Hauppauge, NY: Nova Science Publishers).

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *Behavioural & Brain Sciences 24,* 87–114. doi: 10.1017/s0140525x01003922

Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology, 51*(1), 42-100.

Crewther, S. G., Goharpey, N., Carey, L., & Crewther, D. P. (2013). "Goal-driven attention and working memory," in *Stroke Rehabilitation; Insights from Neuroscience and Imaging*, ed. L. Carey (New York, NY: Oxford University Press), 191–2017.

Daneman, M., & Hannon, B. (2001). Using working memory theory to investigate the construct validity of multiple-choice reading comprehension tests such as the SAT. *Journal of Experimental Psychology: General*, *130,* 208–223. doi: 10.1037/0096-3445.130.2.208

Deary, I. J., Corley, J., Gow, A. J., Harris, S. E., Houlihan, L. M., Marioni, R. E., ... & Starr, J. M. (2009). Age-associated cognitive decline. *British Medical Bulletin*, *92*(1), 135-152.

Ebaid, D. & Crewther, S. G. (2018). Temporal aspects of memory: a comparison of memory performance, processing speed and time estimation between young and older adults. *Frontiers in Aging Neuroscience, 10*, 352. doi: 10.3389/fnagi.2018.00352

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A., & Crewther, D. P. (2017). Cognitive processing speed across the lifespan: beyond the influence of motor speed. *Frontiers in Aging Neuroscience*, 9, 62. doi: 10.3389/fnagi.2017.00062

Eckert, M. (2011). Slowing down: age-related neurobiological predictors of processing speed. *Frontiers in Aging Neuroscience*, 5, 25. doi: 10.3389/fnins.2011.00025

Elgamal, S. A., Roy, E. A., & Sharratt, M. T. (2011). Age and verbal fluency: the mediating effect of speed of processing. *The Canadian Geriatrics Journal, 14*, 66–72. doi: 10.5770/cgj.v14i3.17

Elhassan, Z., Crewther, S., Bavin, E., & Crewther, D. (2015). Preliminary validation of FastaReada as a measure of reading fluency. *Frontiers in Psychology, 6*, 1634. doi: 10.3389/fpsyg.2015.01634

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14*, 340–347. doi: 10.1162/089892902317361886

Fernandez-Ruiz, J., Peltsch, A., Alahyane, N., Brien, D. C., Coe, B. C., Garcia, A., & Munoz, D. P. (2018). Age related prefrontal compensatory mechanisms for inhibitory control in the antisaccade task. *Neuroimage, 165*, 92-101.

Finkel, D., Reynolds, C. A., McArdle, J. J., & Pedersen, N. L. (2007). Age changes in processing speed as a leading indicator of cognitive aging. *Psychology & Aging, 22*, 558–568. doi: 10.1037/0882-7974.22.3.558

Froehlich, E., Liebig, J., Morawetz, C., Ziegler, J. C., Braun, M., Heekeren, H. R., & Jacobs, A. M. (2018). Same same but different: processing words in the aging brain. *Neuroscience, 371*, 75-95.

Fukuda, K., Vogel, E., Mayr, U. & Awh, E. (2010). Quantity, not quality: the relationship between fluid intelligence and working memory capacity. *Psychonomic Bulletin & Review, 17*, 673–679. doi: 10.3758/17.5.673

Füllgrabe, C., Moore, B. C., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience, 6*, 347. doi: 10.3389/fnagi.2014.00347

Gamboz, N., Zamarian, S., & Cavallero, C. (2010). Age-related differences in the attention network test (ANT). *Experimental Aging Research, 36*, 287–305. doi: 10.1080/0361073X.2010.484729

Glass, T. A., De Leon, C. F. M., Bassuk, S. S., & Berkman, L. F. (2006). Social engagement and depressive symptoms in late life: longitudinal findings. *Journal of Aging & Health, 18*, 604–628. doi: 10.1177/0898264306291017

Godefroy, O., Roussel, M., Despretz, P., Quaglino, V., & Boucart, M. (2010). Age-related slowing: perceptuomotor, decision, or attention decline? *Experimental. Aging Research*, 36, 169–189. doi: 10.1080/03610731003613615

Goertz, A. D., Stewart, W. C., Burns, W. R., Stewart, J. A., & Nelson, L. A. (2014). Review of the impact of presbyopia on quality of life in the developing and developed world. *Acta Ophthalmology* 92, 497–500. doi: 10.1111/aos.12308

Griffin, P. T., & Heffernan, A. (1983). Digit span, forward and backward: separate and unequal components of the WAIS digit span. *Perceptual & Motor Skills* 56, 335–338. doi: 10.2466/pms.1983.56.1.335

Hammar, A., & Ardal, G. (2009). Cognitive functioning in major depression-a summary. *Frontiers in Human Neuroscience, 3*, 26. doi: 10.3389/neuro.09.026.2009

Harada, C. N., Natelson Love, M. C., & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in Geriatric Medicine, 29*, 737–752. doi: 10.1016/j.cger.2013.07.002

Hasher, L., & Zacks, R. T. (1988). "Working memory, comprehension and aging: a review and a new view," in *Psychology of Learning and Motivation*, (Vol. 22) ed. H. B. Gordon (San Diego, CA: Academic Press), 193–225.

Hecht, R., Crewther, D., & Crewther, S. (2004). Rate of learning and asymptotic performance in an automatization task and the relation to reading. *Perceptual & Motor Skills, 99*, 1103–1121. doi: 10.2466/pms.99.3f.1103-1121

Hedden, T., & Gabrieli, J. D. (2004). Insights into the ageing mind: a view from cognitive neuroscience. *Nature Reviews Neuroscience, 5*, 87–96. doi: 10.1038/nrn1323

Hedden, T., Lautenschlager, G., & Park, D. C. (2005). Contributions of processing ability and knowledge to verbal memory tasks across the adult life-span. *The Quarterly Journal of Experimental Psychology, 58*, 169–190. doi: 10.1080/02724980443000179

Hill, A. C., Laird, A. R., & Robinson, J. L. (2014). Gender differences in working memory networks: a BrainMap meta-analysis. *Biological Psychology, 102*, 18–29. doi: 10.1016/j.biopsycho.2014.06.008

Horn, J. L., & Cattell, R. B. (1966). Refinement and test of the theory of fluid and crystallized general intelligences. *Journal of Education Psychology, 57,* 253–270. doi: 10.1037/h0023816

Insch, P. M., Bull, R., Phillips, L. H., Allen, R., & Slessor, G. (2012). Adult aging, processing style, and the perception of biological motion. *Experimental Aging Research, 38,* 169–185. doi: 10.1080/0361073x.2012.660030

Jayakody, D. M. P., Friedland, P. L., Martins, R. N., & Sohrabi, H. R. (2018). Impact of aging on the auditory system and related cognitive functions: a narrative review. *Frontiers in Neuroscience,* 12:125. doi: 10.3389/fnins.2018.00125

Jennings, J. M., Dagenbach, D., Engle, C. M., & Funke, L. J. (2007). Age-related changes and the attention network task: an examination of alerting, orienting, and executive function. *Aging, Neuropsychology & Cognition. 14*, 353–369. doi: 10.1080/13825580600788837

Kaufman, D. A., Sozda, C. N., Dotson, V. M., & Perlstein, W. M. (2016). An event-related potential investigation of the effects of age on alerting, orienting, and executive function. *Frontiers in Aging Neuroscience, 8,* 99. doi: 10.3389/fnagi.2016.00099

Kinsey, K., Rose, M., Hansen, P., Richardson, A., & Stein, J. (2004). Magnocellular mediated visual-spatial attention and reading ability. *Neuroreport, 15,* 2215–2218. doi: 10.1097/00001756-200410050-00014

Kliegl, R., Grabner, E., Rolfs, M., & Engbert, R. (2004). Length, frequency, and predictability effects of words on eye movements in reading. *European Journal of Cognitive Psychology, 16,* 262–284. doi: 10.1080/09541440340000213

Lemke, U., & Zimprich, D. (2005). Longitudinal changes in memory performance and processing speed in old age abstract keywords. *Aging Neuropsychology & Cognition, 12,* 57–77. doi: 10.1080/13825580590925116

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: a strong connection. *Psychology & Aging, 9,* 339–355. doi: 10.1037/0882-7974.9.3.339

Lichtenberger, E. O., and Kaufman, A. S. (2009). *Essentials of WAIS-IV Assessment (Vol. 50).* New York, NY: John Wiley and Sons.

Lovibond, S. H., & Lovibond, P. F. (1995). *Manual for the Depression Anxiety Stress Scale.* 2nd Edn. Sydney, NSW: Psychology Foundation of Australia.

Lu, P. H., Lee, G. J., Raven, E. P., Tingus, K., Khoo, T., Thompson, P. M., et al. (2011). Age-related slowing in cognitive processing speed is associated with myelin integrity in a very healthy elderly sample. *Journal of Clinical and Experimental Neuropsychology, 33*, 1059–1068. doi: 10.1080/13803395.2011.595397

MacLeod, J. W., Lawrence, M. A., McConnell, M. M., Eskes, G. A., Klein, R. M., & Shore, D. I. (2010). Appraising the ANT: psychometric and theoretical considerations of the attention network test. *Neuropsychology, 24*, 637–651. doi: 10.1037/a0019803

Madden, D. J. (2007). Aging and visual attention. *Current Directions in Psychological Science, 16*, 70–74. doi: 10.1111/j.1467-8721.2007.00478.x

Mahoney, J. R., Verghese, J., Goldin, Y., Lipton, R., & Holtzer, R. (2010). Alerting, orienting, and executive attention in older adults. *Journal of the International Neuropsychological Society, 16*, 877–889. doi: 10.1017/s1355617710000767

McDowell, J. E., Dyckman, K. A., Austin, B. P., & Clementz, B. A. (2008). Neurophysiology and neuroanatomy of reflexive and volitional saccades: evidence from studies of humans. *Brain & Cognition, 68*, 255–270. doi: 10.1016/j.bandc.2008.08.016

McGowan, V. A., White, S. J., Jordan, T. R., & Paterson, K. B. (2014). Aging and the use of interword spaces during reading: evidence from eye movements. *Psychonomic Bulletin & Review, 21*, 740–747. doi: 10.3758/s13423-013-0527-8

Meyer, B. J., & Pollard, C. K. (2006). "Applied learning and aging: a closer look at reading," in *Handbook of the Psychology of Aging*, 6th Edn. eds J. E. Birren and K. W. Schaie (San Diego, CA: Academic Press), 233–260.

Monaco, M., Costa, A., Caltagirone, C., & Carlesimo, G. A. (2013). Forward and backward span for verbal and visuo-spatial data: standardization and normative data from an Italian adult population. *Neurological Sciences,* 34, 749–754. doi: 10.1007/s10072-012-1130-x

Mundinano, I.-C., Fox, D. M., Kwan, W. C., Vidaurre, D., Teo, L., Homman-Ludiye, J., et al. (2018). Transient visual pathway critical for normal development of primate grasping behavior. *Proceedings of the National Academy of Sciences of the USA*, 115, 1364–1369. doi: 10.1073/pnas.1717016115

Oken, B. S., Kishiyama, S. S., Kaye, J. A., & Jones, D. E. (1999). Age-related differences in global-local processing: stability of laterality differences but disproportionate impairment in global processing. *Journal of Geriatric Psychiatry and Neurology*, *12*, 76–81. doi: 10.1177/089198879901200207

Patel, I., & West, S. K. (2007). Presbyopia: prevalence, impact, and interventions. *Community Eye Health* 20, 40–41.

Peelle, J. E., & Wingfield, A. (2016). The neural consequences of age-related hearing loss. *Trends in Neurosciences, 39*, 486–497. doi: 10.1016/j.tins.2016.05.001

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, *35*, 73–89. doi: 10.1146/annurev-neuro-062111-150525

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience. 13,* 25–42. doi: 10.1146/annurev.ne.13.030190.000325

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124,* 372–422. doi: 10.1037/0033-2909.124.3.372

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, *62*, 1457–1506. doi: 10.1080/17470210902816461

Reed, J. L., Gallagher, N. M., Sullivan, M., Callicott, J. H., & Green, A. E. (2017). Sex differences in verbal working memory performance emerge at very high loads of common neuroimaging tasks. *Brain & Cognition, 113*, 56–64. doi: 10.1016/j.bandc.2017.01.001

Ritchie, S. J., Cox, S. R., Shen, X., Lombardo, M. V., Reus, L. M., Alloza, C., et al. (2018). Sex differences in the adult human brain: evidence from 5216 UK Biobank participants. *Cerebral Cortex*, *28*, 2959–2975. doi: 10.1093/cercor/bhy109

Ritchie, S. J., Tucker-Drob, E. M., & Deary, I. J. (2014). A strong link between speed of visual discrimination and cognitive ageing. *Current Biology, 24*, R681–R683. doi: 10.1016/j.cub.2014.06.012

Rizzo, M., Sparks, J., McEvoy, S., Viamonte, S., Kellison, I., and Vecera, S. P. (2009). Change blindness, aging, and cognition. *Journal of Clinical and Experimental Neuropsychology, 31*, 245–256. doi: 10.1080/13803390802279668

Roberts, K. L., & Allen, H. A. (2016). Perception and cognition in the ageing brain: a brief review of the short- and long-term links between perceptual and cognitive decline. *Frontiers in Aging Neuroscience, 8,* 39. doi: 10.3389/fnagi.2016.00039

Roux, F., & Ceccaldi, M. (2001). Does aging affect the allocation of visual attention in global and local information processing? *Brain & Cognition, 46*, 383–396. doi: 10.1006/brcg.2001.1296

Rutkowski, J. S., Crewther, D. P., & Crewther, S. G. (2003). Change detection is impaired in children with dyslexia. *Journal of Vision, 3,* 95–105. doi: 10.1167/3.1.10

Salthouse, T. A. (1991). *Theoretical Perspectives on Cognitive Aging.* Hillsdale, NJ: Erlbaum Associates.

Salthouse, T. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review, 103*, 403–428. doi: 10.1037/0033-295x.103.3.403

Salthouse, T. A., & Ferrer-Caja, E. (2003). What needs to be explained to account for age-related effects on multiple cognitive variables? *Psychology & Aging, 18*, 91–110. doi: 10.1037/0882-7974.18.1.91

Salthouse, T. A., & Pink, J. E. (2008). Why is working memory related to fluid intelligence? *Psychonomic Bulletin & Review, 15,* 364–371. doi: 10.3758/pbr.15.2.364

Schneider, B. A., & Pichora-Fuller, M. K. (2000). "Implications of perceptual deterioration for cognitive aging research," in *The Handbook of Aging and Cognition* 2nd Edn. eds F. I. M. Craik and T. A. Salthouse (Mahwah, NJ: Lawrence Erlbaum Associates Publishers), 155–219.

Sereno, S. C., & Rayner, K. (2003). Measuring word recognition in reading: eye movements and event-related potentials. *Trends in Cognitive Sciences, 7*, 489–493. doi: 10.1016/j.tics.2003.09.010

Shimamura, A. P., Berry, J. M., Mangels, J. A., Rusting, C. L., & Jurica, P. J. (1995). Memory and cognitive abilities in university professors: evidence for successful aging. *Psychological Science, 6*, 271–277. doi: 10.1111/j.1467-9280.1995.tb00510.x

Sorenson, H. (1933). Mental ability over a wide range of adult ages. *Journal of Applied Psychology, 17*, 729–741. doi: 10.1037/h0072233

Spierer, O., Fischer, N., Barak, A., & Belkin, M. (2016). Correlation between vision and cognitive function in the elderly: a cross-sectional study. *Medicine 95*, 2423. doi: 10.1097/md.0000000000002423

Uchida, Y., Sugiura, S., Nishita, Y., Saji, N., Sone, M., & Ueda, H. (2019). Age-related hearing loss and cognitive decline-The potential mechanisms linking the two. *Auris Nasus Larynx 46*, 1–9. doi: 10.1016/j.anl.2018.08.010

Vaportzis, E., Georgiou-Karistianis, N., & Stout, J. C. (2013). Dual task performance in normal aging: a comparison of choice reaction time tasks. *PLoS One*, 8, e60265. doi: 10.1371/journal.pone.0060265

Vickers, D., Nettelbeck, T., and Willson, R. J. (1972). Perceptual indices of performance: the measurement of ‘inspection time’ and ‘noise’ in the visual system. *Perception, 1*, 263–295. doi: 10.1068/p010263

Wayne, R. V., & Johnsrude, I. S. (2015). A review of causal mechanisms underlying the link between age-related hearing loss and cognitive decline. *Ageing Research Reviews, 23*, 154–166. doi: 10.1016/j.arr.2015.06.002

Wechsler, D. (2008a). *Wechsler Adult Intelligence Scale-Fourth Edition (WAIS-IV) (Vol. 22).* San Antonio, TX: NCS Pearson. 498.

Wechsler, D. (2008b). *WAIS-IV Administration and Scoring Manual.* San Antonio, TX: The Psychological Corporation.

Whitney, D., & Levi, D. M. (2011). Visual crowding: a fundamental limit on conscious perception and object recognition. *Trends Cognitive Sciences*, *15*, 160–168. doi: 10.1016/j.tics.2011.02.005

Zhang, M. Y., Katzman, R., Salmon, D., Jin, H., Cai, G. J., Wang, Z. Y., et al. (1990). The prevalence of dementia and Alzheimers disease in Shanghai, China: impact of age, gender, and education. *Annals of Neurology, 27,* 428. doi: 10.1002/ana.410270412

Zimprich, D., & Martin, M. (2002). Can longitudinal changes in processing speed explain longitudinal changes in fluid intelligence? *Psychology & Aging*, *17*, 690–695. doi: 10.1037/0882-7974.17.4.690

chapter 6

06.

CHAPTER 6

The Contribution of Oculomotor Function to Visual Information Processing in Young and Older Adults

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6.1 Abstract

Although oculomotor functions are surrogate measures of visual attention shifting and information processing, the temporal characteristics of saccades and fixations have seldom been compared in healthy educated samples of younger and older adults. Thus, the current study aimed to compare duration of eye movement components in younger (18-25 years) and older (50-81 years) adults during text reading and during object/alphanumeric Rapid Automatic Naming (RAN) tasks. The current study also aimed to examine the contribution of oculomotor functions to threshold time needed for accurate performance on visually-driven cognitive tasks (Inspection Time [IT] and Change Detection [CD]). Results showed that younger adults fixated on individual stimuli for significantly longer than the older participants, while older adults demonstrated significantly longer saccade durations than the younger group. Results also demonstrated that older adults required longer threshold durations (i.e., performed slower) on the visually-driven cognitive tasks, however, the age-group difference on the CD task was eradicated when the effects of saccade duration were covaried. Thus, these results suggest that age-related cognitive decline is also related to increased duration of saccades and hence highlights the need to dissociate the temporal constraints of oculomotor function from visuo-cognitive speed of processing, particularly in the aged.

6.2 Introduction

Most human behaviour is visually driven (Mundinano et al., 2018) with visual attention considered the key driver of most perceptual, cognitive, and behavioural processes (Crewther, Goharpey, Carey, & Crewther, 2013; Forstmann et al., 2011; Godefroy, Roussel, Despretz, Quaglino, & Boucart, 2010). Vision and visual attention are known to undergo profound sensory and perceptual changes across the lifespan (Brown, Corner, Crewther, &. Crewther, 2018; Lindenberger & Baltes, 1994) and have been a focus of much experimental research in the last 25 years (Andersen, 2012; Deary et al., 2009; Govenlock, Taylor, Sekuler, & Bennett, 2010; Hutchinson, Arena, Allen, & Ledgeway, 2012). These changes parallel those seen in several cognitive domains including attention, speed of processing, working memory, and motor slowing across the lifespan (Braver et al., 2001; Deary et al., 2009; Ebaid, Crewther, MacCalman, Brown, & Crewther, 2017; Salthouse, 1996) though debate still exists as to which domains are most susceptible to decline across the lifespan (Cattell, 1963; Ebaid & Crewther, 2018; Ebaid & Crewther, 2019; Ebaid et al., 2017; Füllgrabe, Moore, & Stone, 2015; Hedden & Gabrieli, 2004; Madden, 2007).

Age related cognitive decline is commonly attributed to the anatomical and physiological impairments that occur in the eye and central nervous system with advancing years (Brown, Corner, Crewther, & Crewther, 2018; Govenlock, Taylor, Sekuler, & Bennett, 2009; Salvi, Akhtar, & Currie, 2006; Sekuler, 2000). Indeed, declines in normal age-related sensory function i.e., vision (Brown et al., 2018; Brown et al., 2018) and audition (Bowl & Dawson, 2015; Fortunato et al., 2016; Füllgrabe et al., 2015; Wayne & Johnsrude, 2015) have been shown to contribute significantly to the changes in cognitive ability seen across the lifespan. Such evidence underlies fundamental theories of cognitive aging including the Sensory Deprivation Hypothesis, the Common-Cause Hypothesis, and the Information Degradation Hypothesis, which collectively suggest a strong interaction between declines in sensory ability with age, and declines in cognitive abilities (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Schneider & Pichora-Fuller, 2000). Most recently, age related physiological and behavioural changes to the visual system have been demonstrated using both flicker fusion thresholds as a critical measure of the fastest conducting Magnocellular (M) pathway function, and multifocal Visually Evoked Potentials (mfVEPS) that have demonstrated M and Parvocellular (P) pathway latencies increase with age, though the M generated peak latency increases are greater than those associated with P pathway (Brown et al., 2018).The M pathway is known to drive attention (Leonard & Luck, 2011) and eye movements, and so increased age related conduction latency and age related motor decline would be expected to influence eye movements associated with activation and shifts in attention (Brown et al., 2018; Zhao, Gersch, Schnitzer, Dosher, & Kowler, 2012) in older individuals. Indeed, oculomotor functions including saccadic eye movements and fixations are surrogate measures of attention shifting (Mohler, Goldberg, & Wurtz, 1973; Wurtz & Goldberg, 1989) that can provide insight into other complex cognitive abilities such as time taken to process visual information (Chan, Chan, Lee, & Hsiao, 2018). The link between attention and saccadic eye movements has been well demonstrated both with single cell electrophysiological measures of arousal in primates (Wurtz & Goldberg, 1989) and in human fMRI and cortical stimulation research (Awh, Armstrong, & Moore, 2006; Bisley & Goldberg, 2006, 2010; Mohler et al., 1973; Sun & Goldberg, 2016; Wurtz & Goldberg, 1989). However, to date there has been little consideration of the contribution of temporal aspects of oculomotor functions to cognitive decline with age.

Oculomotor functions are known to undergo functional decline across the lifespan in the absence of neurological impairment, with older adults often showing increased saccade latencies, decreases in peak velocity, and in some cases decreases in accuracy, particularly for volitional saccades (Abel & Douglas, 2007; Irving, Steinbach, Lillakas, Babu, & Hutchings, 2006; Klein, Fischer, Hartnegg, Heiss, & Roth, 2000; Munoz, Broughton, Goldring, & Armstrong, 1998). Indeed, research has demonstrated a strong age-related effect on saccade reaction time (SRT), indicating that young children aged between 5-8 and elderly adults between 60-79 showed similar slower time to onset saccades than young adults aged between 20-30 (Munoz et al., 1998). Visual tracking performance (positional precision and smooth pursuit velocity gain of visual tracking) has shown similar age related effects (Maruta, Spielman, Rajashekar, & Ghajar, 2017), while anti-saccade paradigms (saccade in the opposite direction of a visual target) have demonstrated both reduced inhibitory control and reduced motor speed (Klein et al., 2000; Nieuwenhuis, Ridderinkhof, De Jong, Kok, & Van Der Molen, 2000) as predicted by theories of cognitive aging including the Inhibitory Deficit Hypothesis (Hasher & Zacks, 1988). This hypothesis suggests that older adults are more susceptible to task-irrelevant stimuli and have greater difficulty inhibiting distractions, resulting in heightened distractibility, reduced working memory capacity, and greater proactive interference (Hasher & Zacks, 1988). To date however, no single experimental study has examined the effects of oculomotor function and visual attention on visuo-cognitive reaction time performance (Barthelemy & Boulinguez, 2001; Kowler, 2011) using eye tracking in healthy younger and older populations. For example, it is still unknown whether longer saccade durations contribute to the slowing of cognitive processing during visuo-cognitive tasks between younger and older adults, and if so, whether these differences in cognitive speed will still be apparent after controlling for the effect of saccade latency.

Thus, the current study aimed to examine eye movement patterns while text reading and during a Rapid Automatic Naming (RAN) task (Lyytinen et al., 2006; Norton & Wolf, 2012; Peters, Taylor, Crewther, Cross, & Crewther, 2016) requiring participants to rapidly and accurately name a series of common objects or alphanumeric symbols. The current study also aimed to examine age-group differences in cognitive speed of processing on both simple and more complex visuo-cognitive tasks to determine whether older adults would again demonstrate a slowing of perceptual speed of processing as per our previous study (Ebaid & Crewther, 2019). We then aimed to explore whether oculomotor function contributes differentially to observed cognitive speed of both age groups, and whether visuo-cognitive speed can predict performance on the RAN and reading tasks. The RAN task was chosen as it allows for assessment of temporal and spatial ocular functions while individuals engage in a relatively simple/automatic task (i.e., the naming of familiar stimuli). In addition, the reading task was chosen as an ecologically valid task of visual perception and attentional processing (Ebaid & Crewther, 2019). The Inspection Time (IT; Vickers, Nettelbeck, & Willson, 1972) and Change Detection (CD; Rutkowski, Crewther, & Crewther, 2003) tasks were chosen as visuo-cognitive measures of threshold time required to process visual information and detect change between two visual arrays, respectively, with no reliance on hand motor-speed or affect (Ebaid & Crewther, 2019).

Based on our previous study (Ebaid & Crewther, 2019) it was hypothesized that older adults would read the passage as fast as younger adults, but that older adults would name less stimuli during the objects and alphanumeric conditions of the RAN. We also expected older adults to perform slower on the IT and CD tasks compared to younger adults and predicted that faster performance on these tasks would correlate with higher RAN scores, faster text-reading and better integrated oculomotor processing. Additionally, on the basis of confounding motor speed (Ebaid et al., 2017) and previous oculomotor research in aging (Abel & Douglas, 2007; Irving et al., 2006; Klein et al., 2000; Munoz et al., 1998), it was hypothesized that older adults would make more fixations, show increased fixation duration, and longer saccade durations during all the RAN and reading tasks compared to younger adults. In regard to controlling the effect of slower oculomotor function from performance on visuo-cognitive tasks, we predicted that doing so would decrease the age-group variance seen on both visuo-cognitive tasks. It was also hypothesised that performance on the visuo-cognitive tasks (IT and CD) would significantly predict RAN naming and reading scores given that they are widely accepted measures of visual processing speed and visual short-term memory capacity (Deary et al., 2009; Luck & Vogel, 1997).

6.3 Method

6.3.1 Participants

This study included 67 healthy educated participants, some of whom which participated in a previous study conducted by our lab (Ebaid & Crewther, 2019) and were divided into a young and older adult group. The young sample comprised of 45 adults aged between 18-25, and the older group included 22 healthy older adults aged between 50-81 years. The young adults were first year Psychology students from La Trobe University, Melbourne, and received course credit for their participation, whereas the older cohort were recruited from the University of the Third Age (U3A) Manningham, and received a $20 Coles-Myer voucher for their participation. U3A is an international volunteer organization where interested older individuals are able to come together and collaboratively learn, rather than for any qualifications (for more information please visit www.u3a.org.au). All participants had normal or corrected-to-normal visual acuity (6/6) and no history of ophthalmological disease. All experimental tasks were visually based and were all presented at suprathreshold visual contrast. A demographic questionnaire collected information on age, gender, and years of education. A measure of general negative affect: The Depression Anxiety and Stress Scale (DASS-21; Lovibond & Lovibond, 1995) was administered as a screening tool. Exclusion criteria included previous diagnoses of a neurological disorder or inability to speak or understand English with basic competence. No participant was excluded on this basis in the current study. The demographic information of the sample is summarised in Table 1.

This study was carried out in accordance with the recommendations of the National Statement on Ethical Conduct in Human Research, La Trobe University Human Ethics Committee (UHEC), with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by La Trobe University Human Ethics Committee, approval number S15/19.

Table 1. Means and Standard Deviations of Characteristics of Young and Older Adults

	Younger Adults *N = 45*		**Older Adults** *N = 22*	
	M	*SD*	*M*	*SD*
Age (years)	19.84	2.01	68.00	8.05
Gender (M/F)	6/39		8/14	
Education (Years)	7.78	1.09	10.45	2.84
Depression Score (DASS-21)	2.84	2.67	2.50	2.90
Anxiety Score (DASS-21)	3.22	3.13	1.91	2.37
Stress Score (DASS-21)	5.82	3.83	3.96	2.56

Note: Years of formal education was recorded from the first year of secondary school onwards, i.e., completion of secondary school was recorded as 6 years of completed formal education.

6.3.2 Materials

Oculomotor function using Gazepoint Eye Tracker

During the RAN and text-passage tasks (described below), eye movements were recorded using the Gazepoint (www.gazept.com) GP3 60Hz eye-gaze tracker which provided data on number of fixations, fixation duration, saccade duration in milliseconds per stimulus and per trial, recorded on the Open Gaze Application Programming Interface on the Gazepoint analysis software. Prior to each trial, participants' eye gaze was calibrated using the 9-point calibration.

Rapid Automatized Naming (RAN) Task

The RAN tests were administered on a 24-inch Dell computer monitor. Participants were seated approximately 57 cm away from the screen and used a chin rest to maintain position and minimize head movements. The RAN comprised three rapid naming tasks (i.e., numeric, alphabetic, and common objects) that included 30 items that were presented as a single-screen array of 6 rows of 5 items for the numbers and objects, and 5 rows of 6 items for the letters condition. In the numeric condition, participants were presented with single-syllable colored numbers ranging from 1-9 presented in Arial Black font, in 72 pt, and participants were required to sequentially name each number out loud from left to right to the bottom of the page, as fast and accurately as possible. Once they reached the last number on the page, they were required to continue naming the numbers until the task ceased after 60 seconds.

In the alphabetic condition, participants were presented with single-syllable colored letters ranging from A-Z and given the same instructions as in the numeric conditions were repeated. In the common objects condition, participants were presented with single-syllable cartoon images on a screen which comprised a *car, ball, cup, boy, girl, cat* and *chair*, presented in varying order across rows. Participants were given the same instructions as in the alphanumeric conditions. To ensure consistency in naming trials, researchers practiced the *correct* names of each object with participants, to ensure participants used the same names for objects across trials. The quantity of numbers, letters, and objects named in 60 seconds was recorded manually and via *Gazepoint,* with higher scores indicative of a faster rapid automatised naming speed. See Figure 1 a - c for examples of the task stimuli.

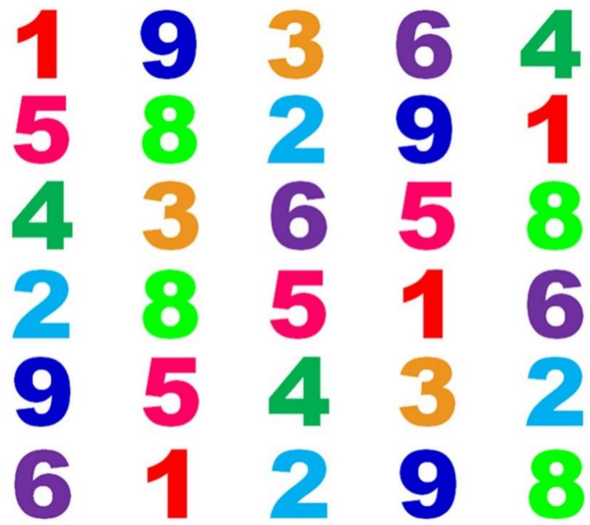


Figure 1a. Rapid Automatised Naming (RAN) task – Numbers condition

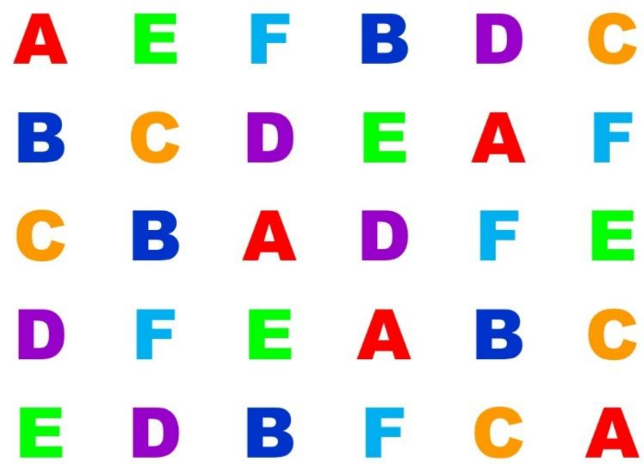
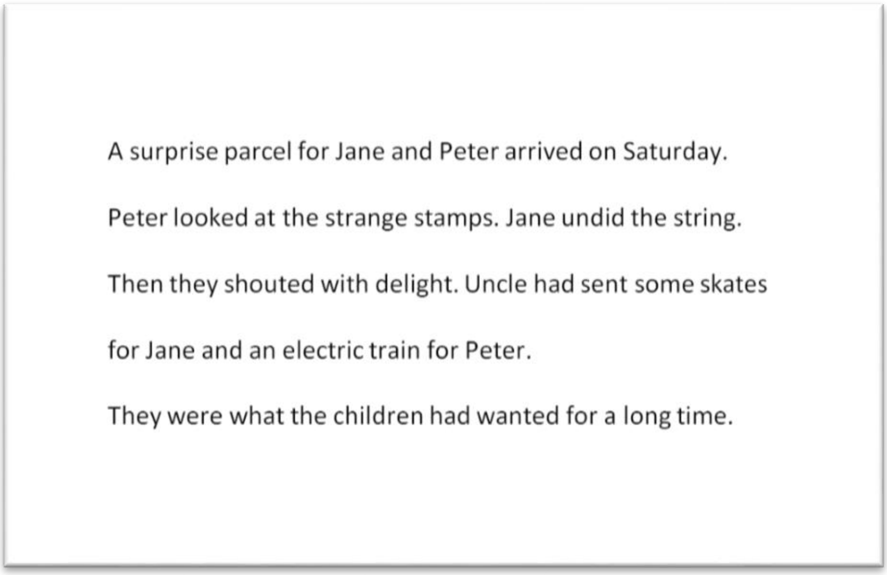


Figure 1b. Rapid Automatised Naming (RAN) task – Letters condition

Figure 1c. Rapid Automatised Naming (RAN) task – Objects condition

Rapid Text-Reading Task

The rapid reading task was administered via computer on a 24-inch Dell monitor and assessed word-and passage-reading fluency. The text-reading task consisted of a short 49-word passage presented in 18 pt Calibri font in narrative order. Participants were instructed to read the passage once, as quickly and as accurately as possible. Time taken to read the full story as well as each individual word was recorded in milliseconds manually and on *Gazepoint*. See Figure 2.


A surprise parcel for Jane and Peter arrived on Saturday.

Peter looked at the strange stamps. Jane undid the string.

Then they shouted with delight. Uncle had sent some skates

for Jane and an electric train for Peter.

They were what the children had wanted for a long time.

Figure 2. Rapid text-reading task

Inspection Time

A modified Inspection Time (IT) task, based on the version of Vickers et al. (1972), was adapted using Vpixx (www.vpixx.com) by Brown and Crewther (2015) and was used as a non-motor visually driven cognitive task. The task employs an inbuilt Visual Parameter Estimation by Sequential Testing (VPEST) algorithm, designed to estimate the exposure threshold required to discriminate and identify which of the three possible stimuli consisting of either a *fish, truck* or *butterfly* was presented (See Figure 3). The task was presented at suprathreshold contrast on an Apple iMac (Retina 4K) computer with a 21.5-inch monitor running at 60 Hz screen refresh rate. Participants were required to identify the target stimulus from the 3 options (fish, truck or butterfly) by manually responding on a keyboard after the stimulus had disappeared. Prior to each trial, a fixation cross was presented for a random duration between 700-1000ms, followed by a blank screen for 50ms, after which the target stimulus was presented for variable exposure times for no greater than 1000ms. Presentation of target stimulus was immediately followed by a mask, presented for 500ms. The start of the next trial was triggered 100ms after the termination of the mask. Confidence intervals and estimations of exposure time were calculated as part of the Vpixx program, where the lowest reoccurring exposure time is used to estimate and indicate the threshold duration of each individual's perceptual time required to discriminate and accurately identify visual stimuli. See Figure 3 for example of task.

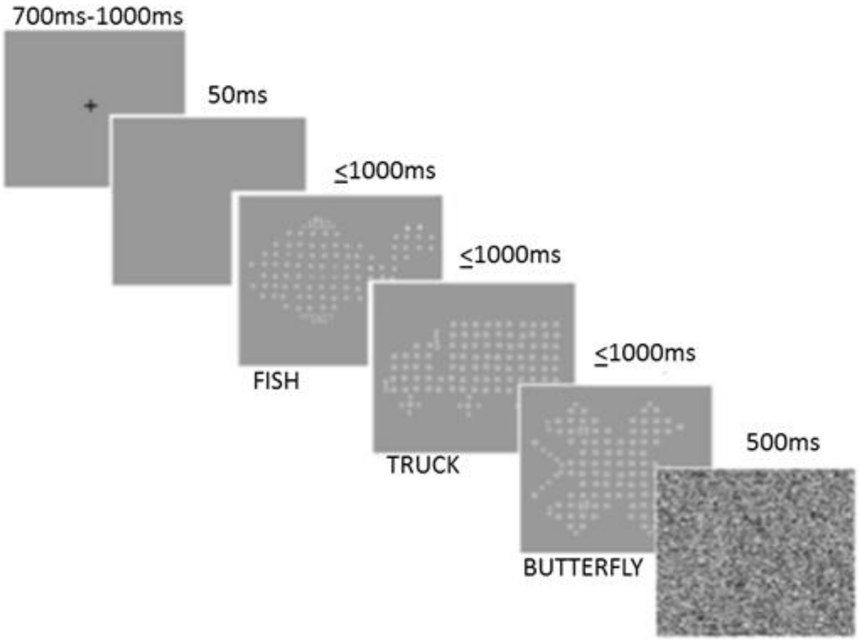


Figure 3. Modified Inspection Time task trial. *Note*. Only one target stimuli of fish, truck, or butterfly is presented per trial. From "Visual Information Processing in Young and Older Adults," by D. Ebaid and S.G. Crewther, 2019, Frontiers in Aging Neuroscience, 11, Copyright, 2019.

Change Detection

The Change Detection task (CD) was a visual cognitive non-motor task based on the Becker, Pashler, and Anstis (2000) version, as adapted by Rutkowski et al. (2003) and utilised the same software and VPEST technique as the IT task. The stimuli were four different alphabetic letters with a hash (#) symbol on either side of each letter, contained in a circle, presented on an Apple iMac (Retina 4K) computer with a 21.5-inch monitor running at 60 Hz screen refresh rate. The four circles were arranged into a square shape (See Figure 4). The addition of hash symbols around each letter were included to create visual crowding (Whitney & Levi, 2011) and used as non-alphabetic task-irrelevant stimuli, as the 4 alphabetic letters alone in a single array are well within the limit of visual-short term memory capacity (Cowan, 2010). A fixation cross was presented for 2 seconds at the start of each trial, followed by the first stimulus array of four letters for variable exposure times, and immediately followed by a 250ms delay, and then another array of four letters (presented for a period of 3000 ms). The conditions which were presented in random order were a *change* condition, whereby one of the four letters were changed in the final presentation, and a *no-change* condition, where the exact same letters were shown in both presentations. Participants were required to indicate whether there was a *change* or *no-change* after each set of visual arrays, and the estimated exposure time for detection of change between the two arrays was calculated. Confidence intervals and threshold estimations of exposure time were calculated by Vpixx where a lower estimated exposure time indicated a faster threshold response time required to detect change between visual stimuli. An example of the task is shown at Figure 4.

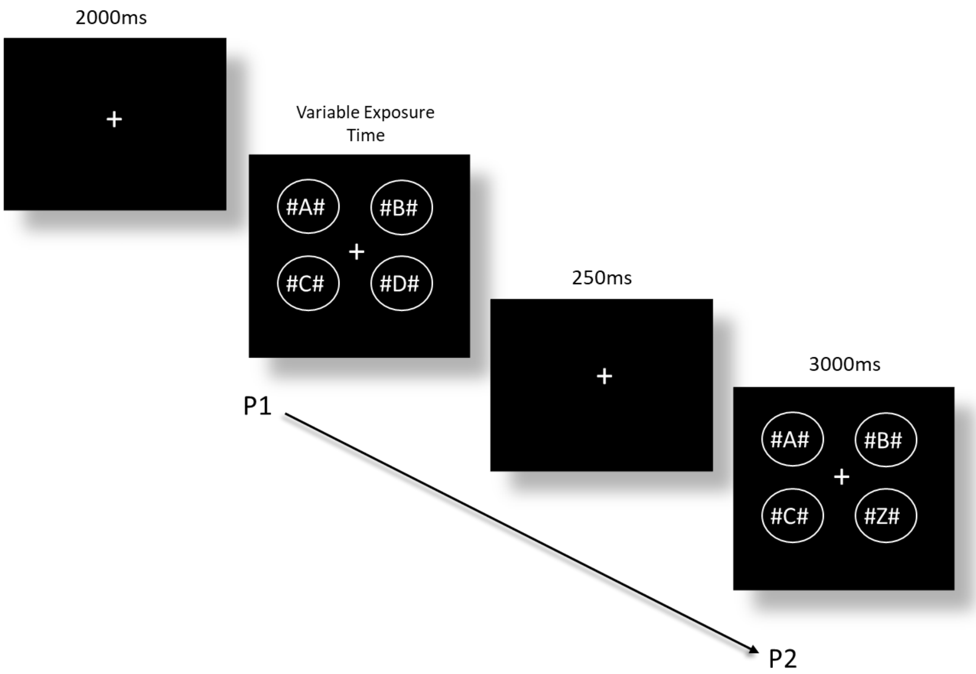


Figure 4. Modified Change Detection (CD) task where a change has occurred from presentation 1 (P1) to presentation 2 (P2). From “Visual Information Processing in Young

and Older Adults," by D. Ebaid and S.G. Crewther, 2019, Frontiers in Aging Neuroscience, 11, Copyright, 2019.

6.3.3 Procedure

Testing took place in a quiet room either at La Trobe University, Melbourne, or at U3A Manningham where only the participant and experimenter were present. All participants were guided through the experimental tasks and the order of administration of tasks were counterbalanced between participants. Total testing time took approximately 30 minutes.

6.3.4 Data Analysis and Screening

Variables collected included threshold exposure duration (ms) required to identify a visual stimulus during the IT task, and threshold exposure duration required to detect change between two visual arrays on the CD task. If confidence intervals were below 80% for the threshold estimations, the tasks were redone by participants. For the RAN tasks, naming score was collected, which represented the number of stimuli named by participants in 60 seconds per condition. For the reading task, reading score represented the duration (ms) participants took to read each word in the passage. Articulatory speed was measured using the FastaReada, which is a customized computer-generated task (Elhassan et al., 2015; Hecht, Crewther, & Crewther, 2004), designed to measure reading fluency by determining the number of words an individual can accurately read per minute. Preliminary analysis of age-group differences was conducted using an independent samples t-test to ensure that articulatory speed between age-groups was not contributing to age-group differences on the RAN tasks. Results demonstrated no significant differences on FastaReada scores between age-groups, (t (65) = 1.899, p =.346, $\eta 2$.=.009). Oculomotor measures were collected while participants completed the RAN and reading tasks. Oculomotor variables included number of visual fixations made during each RAN condition and during the text-passage, fixation duration (ms) during the

RAN and reading tasks, and saccade duration (ms) from one fixation point to the next during RAN and reading tasks. All analyses were performed using SPSS v. 25.0 (IBM Corp., Armonk, NY, USA). Data was screened for outliers on individual tasks and for any result indicating inconsistent performance across the different task conditions. None of these cases were found in the dataset.

6.4 Results

6.4.1 Means and standard deviations for IT, CD, RAN, text-reading and oculomotor function

Descriptive statistics for scores on the IT, CD, RAN (naming score), text-passage (reading score) and oculomotor measures (number of visual fixations, fixation duration and saccade duration) during the RAN and reading tasks for young and older adults are presented in Table 2

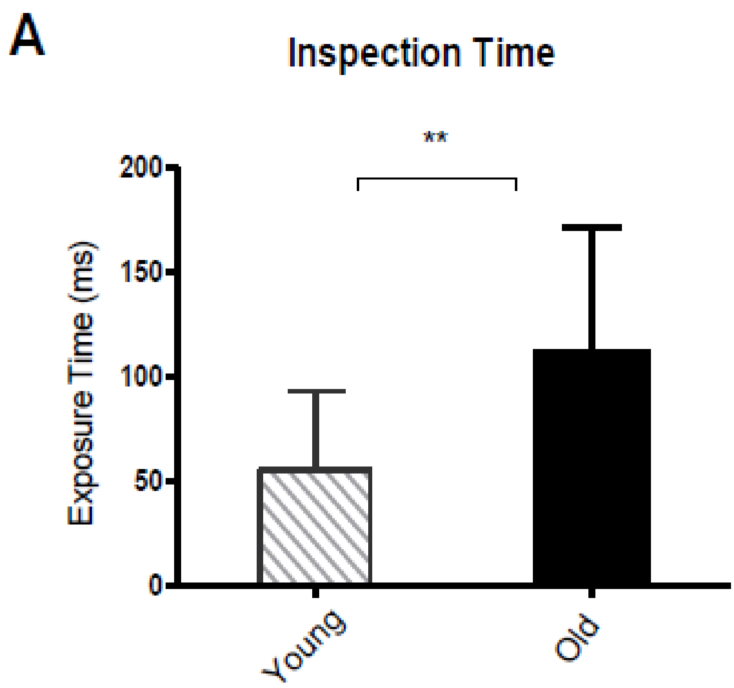
Table 2. Descriptive Statistics for Scores on the IT, CD, RAN, and Reading Tasks for Young and Older Adults

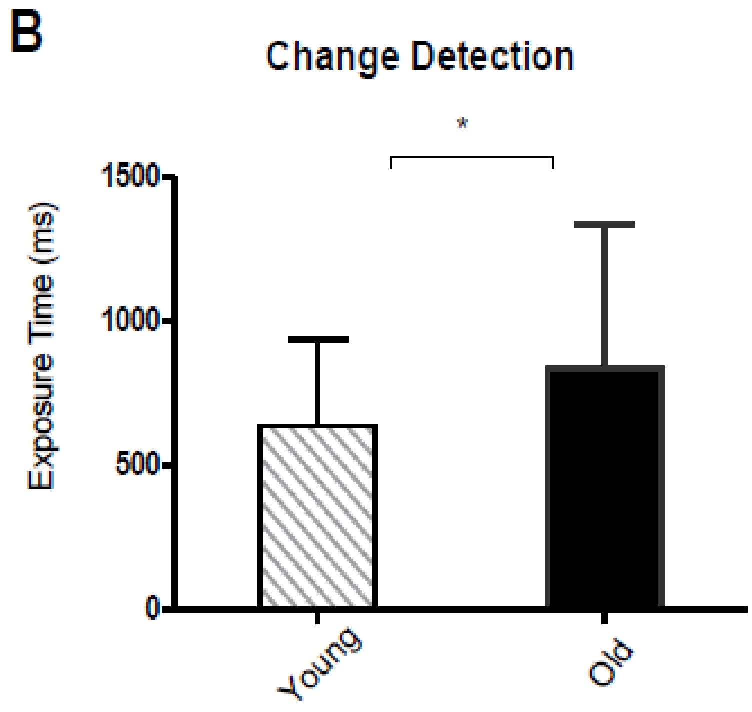
	Younger Adults				Older Adults				
Measure	N	Range	M	SD	N	Range	M	SD	*p*
IT (ms)	45	20.00 – 260.00	54.60	38.38	22	34.90-232.00	111.04	60.25	.000**
CD (ms)	45	110.00-1310.00	637.40	299.52	22	42.00-1798.00	839.64	494.39	.039*
RANObjects (naming score)	45	63.00-127.00	89.67	17.25	22	59.00-112.00	79.50	14.53	.020*
No. Fixations	45	88.0-150.0	120.47	14.012	22	113.0-152.0	127.00	10.52	.058
FixationDur (ms)	45	297.89 – 574.03	427.85	63.03	22	310.00-466.20	379.26	47.94	.002**
SaccadeDur (ms)	45	44.50-169.15	76.24	28.53	22	37.80-207.00	95.59	49.65	.043*
RANLetters (namingscore)	45	100.0-338.0	163.689	45.48	17	105.00-304.00	180.88	42.93	.183
No. Fixations	45	114.0-201.0	165.47	17.01	17	151.00-209.00	173.24	42.97	.099
FixationDur (ms)	45	251.00-454.00	314.94	39.74	17	233.30-350.00	283.88	31.76	.005**
SaccadeDur (ms)	45	29.00-134.00	49.24	17.98	17	37.00-112.00	62.92	22.27	.015*
RANNumbers (naming score)	45	90.00- 293.00	163.89	42.46	22	130.00-225.00	175.86	28.87	.237
No. Fixations	45	126.0 - 204.0	168.89	15.18	22	134.00-204.00	177.09	16.95	.050
FixationDur (ms)	45	240.40 – 399.00	301.61	33.86	22	237.00-329.00	277.40	23.45	.004**
SaccadeDur (ms)	45	33.00 – 150.00	55.56	22.39	22	36.00-395.00	81.76	79.69	.043*
Passage Reading Score (ms per word)	45	175.51 - 428.57	301.22	52.24	14	210.00-367.35	349.59	203.88	.148
No. Fixations	45	25.00 - 51.00	38.82	5.67	14	31.00-108.00	43.14	19.30	.183
FixationDur (ms)	45	264.20 – 390.80	329.77	27.63	14	279.30-427.90	325.64	41.61	.668
SaccadeDur (ms)	45	4.60 - 142.20	46.93	27.88	14	17.00-135.60	57.04	29.60	.248

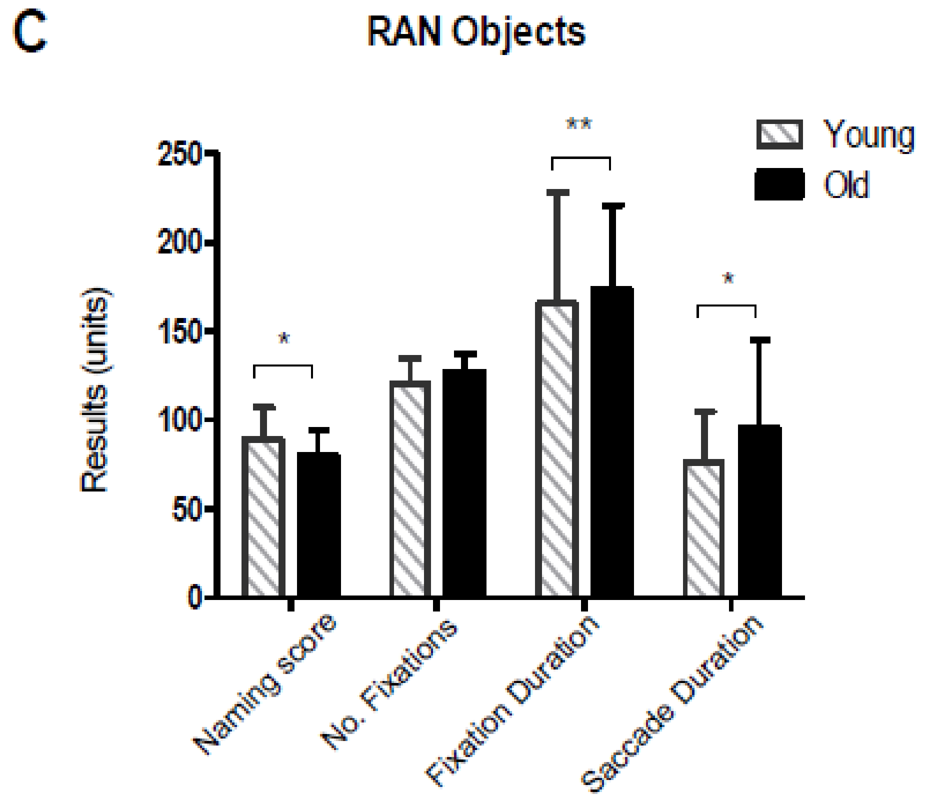
Note: Naming score = number of stimuli named on the RAN in 60 seconds, No. Fixations = number of fixations made during the RAN tasks and during the text-reading passage, Fixation Duration = Fixation time in milliseconds (ms) during the RAN and reading tasks, Saccade Duration = Saccade duration from one fixation point to the next during RAN and reading tasks, Passage Reading score = time taken (ms) to read each word in the text-passage.

6.4.2 Age-group differences in performance on the IT, CD, RAN, text-passage and oculomotor function

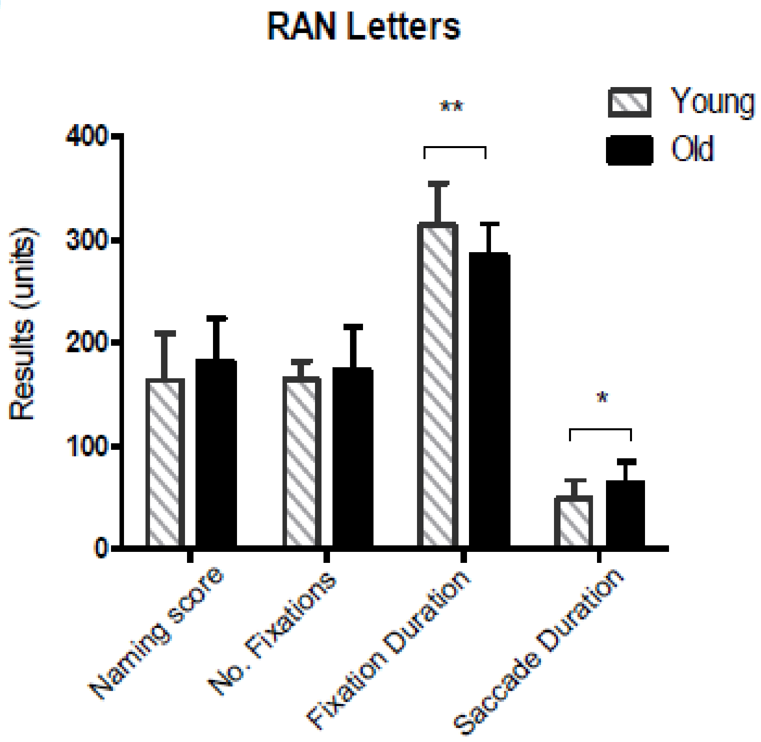
An independent samples t-test was performed to determine whether there were differences in RAN naming score, text-reading score, oculomotor function, or the IT and CD tasks between young and older adults. Significant age-group differences were demonstrated for the IT task (t (65) = -4.601, p < 0.05, η^{2}=.246), as well as for the CD task (t (65) = -2.080, p < .0.01, η^{2}=.064) where younger adults required a significantly shorter threshold exposure duration to identify a familiar visual stimulus or detect change between two visual arrays, respectively. With regard to ocular function, fixation and saccade duration during RAN tasks were the predominant differences between groups, where older adults had significantly longer saccade durations, though younger adults fixated on individual stimuli for significantly longer in the RAN objects and alphanumeric conditions, but not during the reading task. These results are depicted in Figures 5a – f.



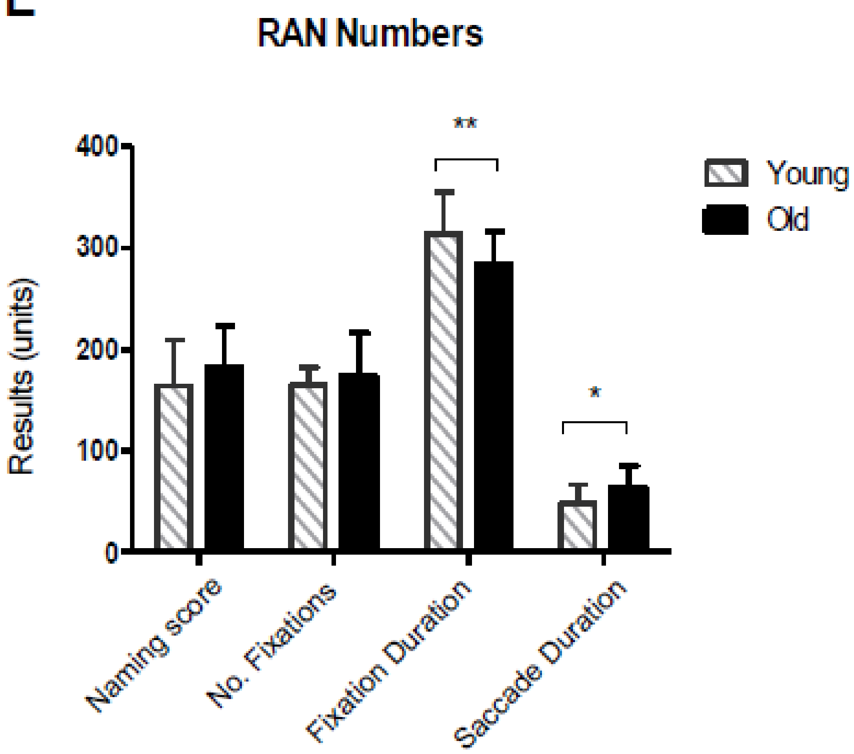

B
Change Detection
*
1500
1000
500
0
Exposure Time (ms)
Young
Old


C
RAN Objects
Young
Old
**
*
*
250
200
150
100
50
0
Results (units)
Naming score
No. Fixations
Fixation Duration
Saccade Duration

D


RAN Letters
Young
Old
**
*
400
300
200
100
0
Results (units)
Naming score
No. Fixations
Fixation Duration
Saccade Duration

E


RAN Numbers
Young
Old
**
*
400
300
200
100
0
Results (units)
Naming score
No. Fixations
Fixation Duration
Saccade Duration

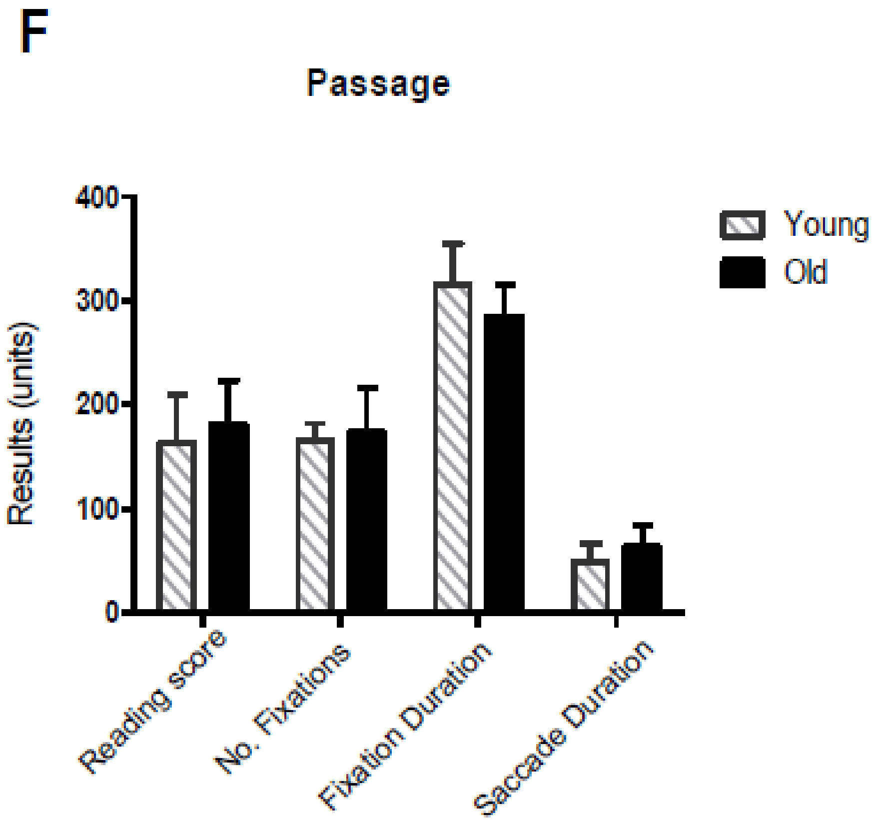


Figure 5a-f. Age-group differences in performance on the IT, CD, RAN objects/letters/numbers and text-passage. *Note*: Naming score = number of stimuli named on the RAN in 60 seconds, No. Fixations = number of fixations made during the RAN tasks and during the text-reading passage, Fixation Duration = Fixation time in milliseconds (ms) during the RAN and reading tasks, Saccade Duration = Saccade duration from one fixation point to the next during RAN and reading tasks, Passage Reading score = time taken (ms) to read each word in the text-passage

6.4.3 Age-group differences in performance on the IT, and CD while controlling for saccade duration

A Multivariate Analysis of Covariance (MANCOVA) was conducted to examine group differences in time required to process visual information and detect change between two visual arrays on the IT and CD, respectively, while controlling for saccade duration. Preliminary assumption testing was conducted to check for normality, linearity, homogeneity of variance and multicollinearity, with no violations noted. Saccade duration during the reading task was chosen as the covariate given that it can be considered the most automatic and ecologically valid cognitive task with the least cognitive load (Elhassan, Crewther, Bavin, & Crewther, 2015). After controlling for saccade duration, results still demonstrated a significant large effect of age- group on time required to process visual information on the IT, F (2, 57) = 17.314, p <0.001, η2 =.528. Further, after controlling for saccade duration, age-group explained 52.8% of the variance in IT scores. Results also indicated that after controlling for saccade duration, there was no longer a significant age group difference in time to detect change between two visual arrays on the CD, F (2, 57) = 1.303, p = .286, η2 =.078, whereby only 7.8% of the variance in CD scores were explained by age-group. Results of the MANCOVA are presented in Table 3.

Table 3. Multivariate Analysis of Covariance (MANCOVA) between Age-Groups and Performance on the IT and CD while Controlling for Saccade Duration (ms)

Variable	Sum of Squares	*df*	Mean Square	*F*	*p*	Partial η^2
IT	0.030	57	0.015	17.314	.000	.528
CD	0.274	57	0.137	1.303	.286	.078

6.4.4 Relationships among IT CD, RAN, reading and oculomotor function

Pearson's Correlation

To investigate the strength, direction and significance of associations between cognitive performance on the IT, CD, RAN, reading and oculomotor function, correlational analyses using Pearson's Correlation were performed separately for younger and older adults. For younger adults, results revealed a significant moderate positive correlation between IT and passage reading score ($r = .362$, $p < .05$) indicating that a shorter threshold exposure duration required to accurately identify a visual stimulus was associated with a shorter duration to read each word in the text-passage. For the older adults, results revealed a significant correlation between the CD and average saccade duration during the RAN Numbers task ($r = .840$, p < .05), indicating that a lower saccade duration was associated with shorter threshold exposure duration to correctly identify change between two visual arrays. A correlation table of IT and CD with RAN and reading tasks as well as oculomotor measures is shown in Table 4. Significant results are also depicted in Figures 6a-b.

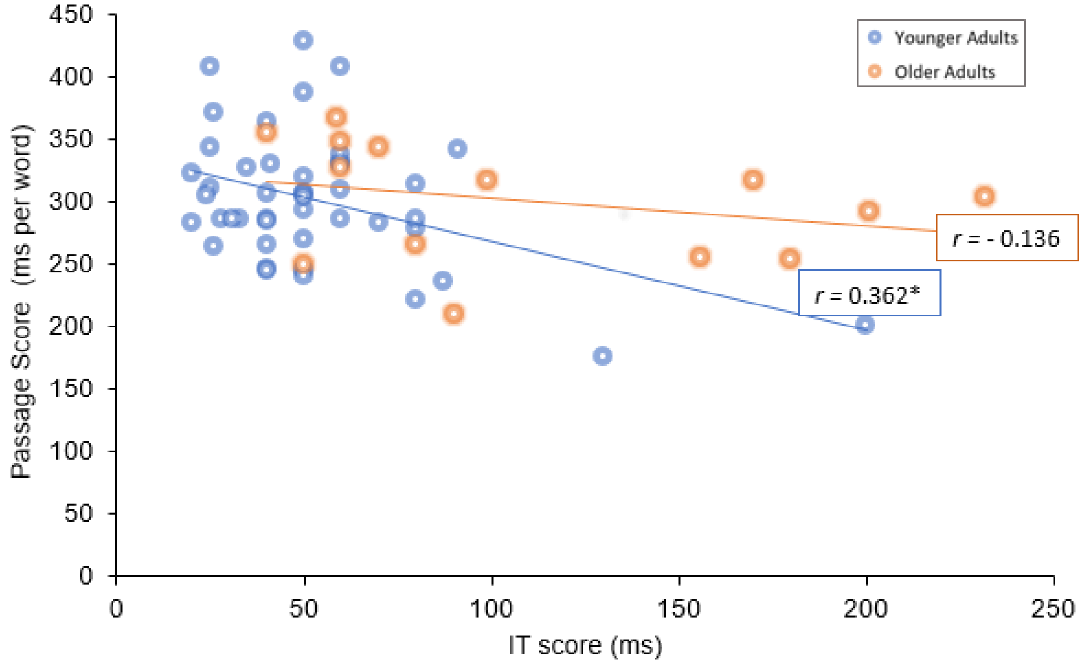
Table 4. Pearson's Correlations between Inspection Time (IT), Change Detection (CD), RAN, and three measures of ocular functions in younger and older adults

	Younger Adults		
	N	IT	CD
RANObjects	45	-0.025	-0.021
No. Fixations	45	0.16	-0.019
FixationDur	45	-0.123	0.051
SaccadeDur	45	-0.087	-0.101
RANLetters	45	-0.209	0.072
No. Fixations	45	0.007	-0.123
FixationDur	45	-0.115	0.191
SaccadeDur	45	0.02	-0.164
RANNum	45	-0.123	-0.122
No. Fixations	45	0.125	0.104
FixationDur	45	-0.065	-0.051
SaccadeDur	45	-0.109	-0.049
Passage	45	**0.362***	0.04
No. Fixations	45	0.259	0.143
FixationDur	45	0.089	0.00
SaccadeDur	45	0.091	-0.138
	Older Adults		
	N	IT	CD
RANObjects	22	-0.127	-0.407
No. Fixations	22	0.263	-0.353
FixationDur	22	-0.339	-0.676
SaccadeDur	22	0.21	0.794
RANLetters	17	0.361	-0.491
No. Fixations	17	0.829	-0.612
FixationDur	17	-0.68	0.893
SaccadeDur	17	-0.027	-0.882
RANNum	22	-0.267	-0.423

No. Fixations	22	0.442	-0.006
FixationDur	22	-0.528	0.489
SaccadeDur	22	0.053	**0.840***
Passage	14	-0.136	-0.059
No. Fixations	14	-0.223	-0.067
FixationDur	14	-0.51	0.074
SaccadeDur	14	-0.293	-0.156

Note. Significant values in bold

A



B

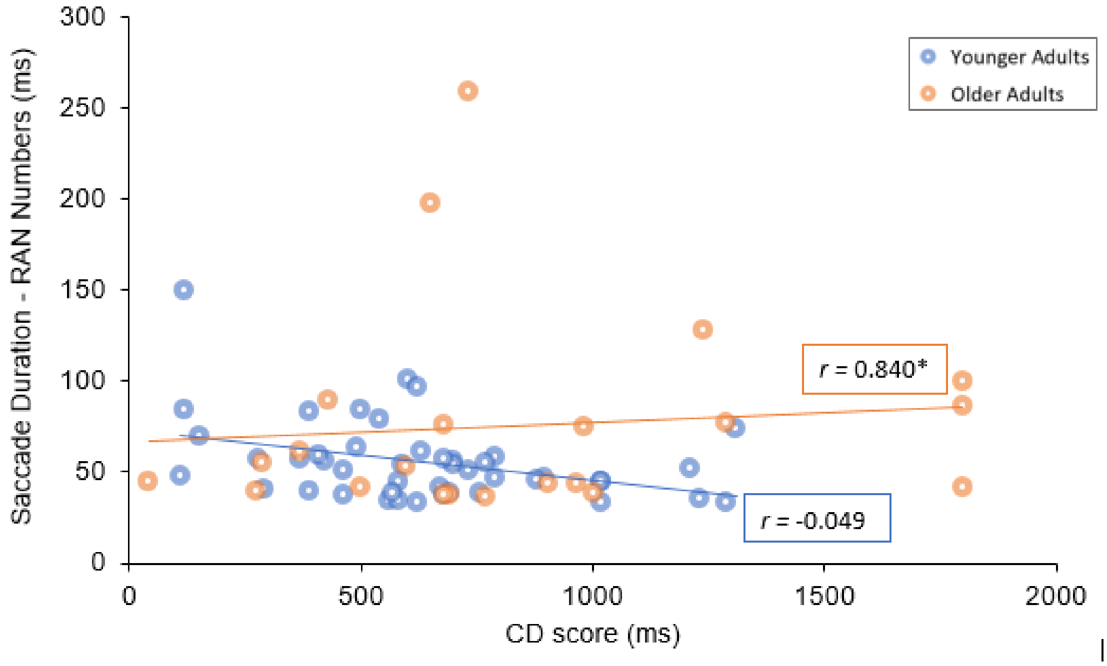


Figure 6a-b. Scatterplots depicting the correlation between the Inspection Time (IT), and the passage reading score (Figure A), and the correlation between the Change Detection (CD), and the average saccade duration during the RAN Numbers task (Figure B) for younger and older adults. *Note*. Only the correlation between IT score and the passage reading score for younger adults was statistically significant, and only the correlation between CD score and the average saccade duration during the RAN Numbers for older adults was statistically significant.

Hierarchical Multiple Regression

Hierarchical multiple regression was used to assess the ability of age and visual processing speed (using IT and CD scores) to predict naming scores for the three RAN tasks (Objects, Letters, Numbers) as well as the passage reading score after adjusting for age. Given that the IT and CD represent widely accepted measures of visual processing speed and visual short-term memory capacity (Deary et al., 2009; Luck & Vogel, 1997), they were chosen as the most appropriate measures to predict performance on the RAN and reading tasks. Preliminary analyses were conducted to ensure no violation of the assumptions of normality, linearity, multicollinearity and homoscedasticity, with no violations noted. For all analyses, age was entered at step 1, followed by IT and CD score at step 2.

RAN Objects

Age significantly explained 18.4% of the variance $R^2 = 0.184$, F (1, 67) = 15.06, *p <.001.* After the entry of IT and CD scores at step 2, IT and CD scores explained an additional 0.06% of the variance in RAN Objects naming score, and this was not a statistically significant contribution (*p* = .787). However, results demonstrated that the model as a whole was statistically significant and explained 19.00% of the variance in RAN Object naming scores, *F* (2, 67) = 5.246, *p* = .003.

RAN Letters

Age explained 0.3% of the variance in naming scores, and this was not statistically significant ($R^2 = 0.003$, *F* (1, 62) = 0.214, *p* =.645. At step 2, IT and CD scores significantly explained an additional 10.30% of the variance in naming scores ($R^2 = .106$, *F* (2, 62) = 2.681, *p* =.025. Results also demonstrated that the model as a whole which explained 10.60% of the variance in naming scores was not statistically significant (*p* = .054).

RAN Numbers

At step 1, age did not significantly explain the variance in naming scores ($R^2 = 0.00$, *F* (1, 67) = 0.280, *p* =.868. The entry of IT and CD scores at step 2 predicted an additional 5.9% of the variance, though this was not a statistically significant contribution ($R^2 = 0.059$, *F* (2, 67) = 1.421, *p* =.244). Results also showed that the model as a whole, which predicted 5.90% of the variance in RAN Numbers naming score was not statistically significant (*p* = .244).

Text-Passage

At step 1, age explained 0.3% of the variance in text-passage reading score, and this was not significant (R^2 = 0.003, F (1, 59) = 0.224, p =.638. The entry of IT and CD scores at step 2 predicted an additional 0.80% of the variance, though this also was not a statistically significant contribution (R^2 = 0.011, F (2, 59) = 0.259, p =.758). Results also showed that the model as a whole, which predicted 1.1% of the variance in text-passage reading scores, was not statistically significant (p = .855).

R^2 change (ΔR^{2}) and semi-partial correlation coefficients *(sr)* across all analyses are presented in Table 5.

Table 5. Hierarchical Multiple Regression of Age, IT, and CD predicting naming score on RAN tasks and text-passage reading score

	RAN Objects		**RAN Letters**		**RAN Numbers**		**Passage**	
Predictors	ΔR^2	***sr***	ΔR^2	***sr***	ΔR^2	***sr***	ΔR^2	***sr***
Step 1	.184	-.429	.003	0.055	.000	.020	.003	.056
Age								
Step 2	.006		.103		.059		.008	
Age		-.271		.217		.149		.040
IT score		-.050		-.153		-.117		-
CD score		-.061		-.288		-.216		.038
								.080

Note. Four separate hierarchical regressions were conducted for Age, IT and CD predicting naming score on the RAN Objects, Letters, Numbers and the text passage, respectively.

Factor Analysis

Given the number of variables in the current study, the factorability of all 19 variables was examined and subjected to Principal Components Analysis (PCA) as a means of data reduction. The suitability of the data for factor analysis was assessed prior to performing PCA. Inspection of the correlation matrix revealed the presence of several coefficients of .3 and above. The Kaiser-Meyer-Olkin value was slightly below (i.e., .50) the recommended value of .60 (Kaiser, 1970), though the Bartlett's Test of Sphericity (Bartlett, 1954) reached statistical significance, supporting the factorability of the correlation matrix.

PCA revealed the presence of five components with eigenvalues exceeding 1, explaining 39.83%, 16.74%, 10.48%, 7.50%, 6.27% of the variance, respectively. An inspection of the scree plot revealed a clear break after the third component, and thus it was decided to retain three components for further analysis.

The three-component solution explained a total of 67.05% of variance, with component 1 contributing 39.83%, component 2 explaining 16.74%, and component 3 explaining 10.48% of the variance. Oblimin rotation was performed to aid the interpretation of these three components. The rotated solution revealed the presence of simple structure (Thurstone, 1947), with all three components showing several strong loadings and all variables loading substantially on only one component. Table 6 depicts these results.

Table 6. Pattern and Structure Matrix for PCA with Oblimin Rotation for the 19 Dependent Variables

Item	Pattern Coefficients			Structure Coefficients			Communalities
	1	**2**	**3**	**1**	**2**	**3**	
FixationDur (RAN Letters)	.924			-.914			.841
No. Fixations (RAN Letters)	-.922			.893		-.324	.880
Naming score (RAN Letters)	.907			.866			.824
No.Fixations (RAN Numbers)	.858			.865			.823
Naming score (RAN Numbers)	-.849			.864			.765
FixationDur (RAN Numbers)	.848			-.852			.777
Naming score (RAN.Objects)	.785			.798			.662
No.Fixations (RAN Objects)	.756		.369	.743			.716
FixationDur (RAN Passage)	-.623	-.432		-.683	-.507	-.329	.657
FixationDur (RAN Objects)	-.616	-.527	-.391	-.642	-.597		.839
Age	.456			.453			.230
CD score							.009
SaccadeDur (RAN Numbers)		.941			.915		.888
Saccade Dur (RAN Letters)		.877			.885		.792
Saccade Dur (RAN Objects)		.868			.830		.789

SaccadeDur (Passage)	.343			.361	.845	.172
No. Fixation (Passage)		.814	-.410		.760	.847
Passage		.715	-.557		.581	.851
IT score		.600			-.324	.377

Note. Factor loadings <. 3 are suppressed

6.5 Discussion

The aim of the current study was to examine the temporal characteristics of ocular functions (saccades and fixations) during rapid automatized naming and text reading to investigate whether such functions contribute significantly to threshold times on visuo-cognitive tasks varying in complexity i.e., the IT and CD, in a healthy educated sample of younger and older adults. We also aimed to explore the predictive validity of the IT and CD for rapid automatized naming and reading scores. The key finding was that cognitive speed on the visuo-cognitive tasks was slower for older adults, and saccade duration during the RAN conditions was longer for older adults, though the age-group effects on the visuo-cognitive tasks were reduced when saccade duration was controlled. Specifically, after controlling for the effects of saccade duration, age-group differences in performance on the CD task were no longer present, though age-group differences on the IT task remained significant. Furthermore, older adults showed a slower naming speed for the objects condition of the RAN which can be deemed a less automatic condition compared to the alphanumeric tasks, thus partially supporting hypotheses that older adults would name less stimuli during the objects and alphanumeric conditions of the RAN.

Again, supporting hypotheses, older adults demonstrated comparable reading speed to younger adults during the text-passage task. The demonstration of some relationships between visuo-cognitive measures (IT and CD), RAN and reading tasks, as well as ocular measures partially supported the hypotheses, and demonstrated some predictive validity of the IT and CD for performance on the naming tasks. Indeed, the IT and CD represent widely accepted measures of visual processing speed and visual short-term memory capacity and have been considered predictors of other more complex cognitive tasks (Deary et al., 2009; Luck & Vogel, 1997). Threshold exposure times for the IT and CD tasks will first be discussed, followed by an examination of gaze pattern results with reference to age-group differences in performance on the RAN, reading tasks and visual tracking measures. Following this, the correlations between variables and the predictive validity of the visuo-cognitive measures to performance on the naming tasks will be discussed. A discussion of the factorability of the variables will follow later.

6.5.1 Age Group Differences in Threshold Exposure Times on the IT and CD

In line with hypotheses, older adults performed significantly slower i.e., required longer threshold exposure duration to detect a familiar visual stimulus and to detect change between two visual arrays as indicated by performance times on the IT and CD, respectively. These results are consistent with the past research reporting on declines in visuo-cognitive processing in healthy aging (Brown et al., 2018; Gamboz, Zamarian, & Cavallero, 2010; Kaufman, Sozda, Dotson, & Perlstein, 2016; Mahoney, Verghese, Goldin, Lipton, & Holtzer, 2010; Salthouse, 1991, 1996). Findings from the current study are in line with theories of aging which postulate sensory decline has an indirect influence on cognitive performance i.e., the Sensory Deprivation Hypothesis, the Common-Cause Hypothesis, and the Information Degradation Hypothesis (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Schneider & Pichora-Fuller, 2000), and from theories of cognitive slowing with age, i.e., the Processing Speed Theory of Adult Age Differences in Cognition (Salthouse, 1996). More specifically, given the age of our older population, it may be the case for example, that a lack of adequate sensory input over a prolonged period of time (i.e., due to natural declines in vision and audition) has resulted in associated neural atrophy (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Schneider & Pichora-Fuller, 2000), in turn impeding cognitive performance as seen in the current study.

Interestingly, when saccade duration was accounted for prior to assessing age-group differences, there was no longer a significant difference in cognitive processing speed during the visuo-cognitive task between younger and older adults. Given that rapid sequential eye movements are required to perform well on the CD to a greater extent than the IT, it may be the case that increased saccade latencies durations are affecting efficient attentional processing of all the stimuli in the array, resulting in an increased threshold duration required to detect change between two visual arrays. This finding is also in line with those found by Brown et al. (2018) who tested both flicker fusion thresholds and latency of the two retinal pathways with mfVEPS and showed that the M generated peak latency increases are greater than associated P changes in healthy older adults. These findings also add new insight into influential theories of cognitive aging which typically suggest a generalized slowing and inhibition in cognitive processing i.e., Hasher and Zacks (1988); Salthouse (1996) without accounting for visual processing and oculomotor function.

6.5.2 Age Group Differences in Oculomotor Functions during RAN Conditions and Text-Reading

The number of visual fixations for the objects, alphanumeric and the text passage condition were not significantly different between age groups, though there was a trend for older adults to make more fixations than younger adults across all tasks. Furthermore, fixation duration was significantly longer in younger adults compared to older adults for the objects and alphanumeric conditions but not for the text- reading passage, which may suggest that younger adults required longer duration to encode and access the name of single discrete stimuli in these conditions. Alternatively, this may infer a more efficient oculomotor strategy used by younger adults, by fixating for a longer duration on the target stimuli while inhibiting distractors (i.e., the surrounding stimuli (Klein et al., 2000). This was contrary to our hypotheses, given that we have previously demonstrated that a different group of healthy younger adults required shorter presentation time (i.e., 49ms compared to 136ms for older adults) to identify a familiar single stationary visual stimulus requiring simple short-term memory (Ebaid & Crewther, 2019), though eye-tracking was not available or utilized in our previous study. The current findings also contradict previous research which have interpreted longer fixations as reflective of the individual requiring more time to acquire visual/orthographic information from the stimuli in preparation for the correct response (Dahhan et al., 2014; Dahhan, Kirby, Brien, & Munoz, 2017). More specifically, given that our older adults showed longer threshold exposure times to complete the IT and CD tasks, while their performance was still comparable to the younger adults on the RAN letters/numbers task, as well as for the text-passage reading, then it is also unlikely that the longer fixation durations shown by the younger adults are reflective of inefficient visual encoding/requiring longer to embed stimuli into memory as previously suggested (Dahhan et al., 2017). Thus, as alluded to earlier, it may be the case that a different cognitive strategy was used by the younger individuals during the naming tasks, which did not impact on their behavioral performance (Moezzi et al., 2019; i.e., naming/reading scores were comparable across both groups). However, the precise cognitive strategy used by the two groups remains a subject of debate.

Saccade duration for older adults was significantly longer in the alphanumeric conditions of the RAN compared to younger adults, which is in line with past research (Dowiasch, Marx, Einhäuser, & Bremmer, 2015) and presumably associated with slower motor movements even in healthy aging (Ebaid et al., 2017). Specifically, this finding was consistent with our predictions, given that neural control mechanisms for the direction and amplitude of movement of the saccade are in part controlled by the motor neurons of the oculomotor nuclei (Sparks & Barton, 1993), and the parietal cortex which is critical in the interface between attention and motor planning, including saccadic eye movements (Ptak & Müri, 2013). Such pathways and brain areas have previously been shown to be vulnerable to decline with healthy aging (Brown et al., 2018). Again, an alternative explanation for the different temporal trajectories of the different age-related gaze patterns in facilitating similar naming score in the alphanumeric conditions of the

RAN, could also point to different cognitive strategies used by the two age groups, though what specific strategy is unclear.

6.5.3 Age-Group Differences in Performance on the RAN and Text-Reading Tasks

Our prediction that older adults would name less stimuli on the common-objects and alphanumeric conditions of the RAN was partially supported, with older adults naming significantly fewer stimuli during the RAN-objects condition compared to younger adults. Interestingly however, in the letters and numbers conditions, older adults on average named more alphanumeric stimuli compared to younger adults in the same time, though these differences did not reach statistical significance. With reference to older adults performing slower on the RAN-Objects, this condition of the task requires greater attention to individual objects that are presumably more variable and less familiar or predictable, compared to numbers or letters, despite having practice during the experiment. Given this, it may be the case that naming these stimuli was less automatic than rapidly naming numbers and letters which have no alternative names (Babcock & Salthouse, 1990; Gazzaley, Sheridan, Cooney, & D'Esposito, 2007; Kato et al., 2016; Salthouse, 1996) and required bottom-up processing (Madden, 2007). Thus, object naming may require more conscious effort, especially if older adults were required to inhibit a name that they would preferentially use for a particular object instead of the experimenter prescribed name. The inhibition of an automatic response may have impaired overall task performance, as explained by the Inhibitory Deficit Hypothesis (Hasher & Zacks, 1988). These findings are also consistent with suggestions made by Madden (2007) who proposed that older adults perform as fast and as accurately on visual search tasks which require top-down processing (i.e., the alphanumeric conditions of the RAN), but perform slower in tasks that require inhibition of distracters i.e., potentially the case in the objects condition. It should also be noted that differences in naming speed between younger and older adults may be due to sex-differences within the two age-groups. More specifically, females represented approximately 87% of the younger adults, and 63% of the older adults and thus, the overrepresentation of females in the younger group may have contributed to faster naming speed in the RAN-objects condition. Indeed, in a review investigating gender differences in processing speed (Roivainen, 2011), it was reported that females demonstrate a faster processing speed on tasks involving digits, alphabets and rapid naming, while men are typically faster on finger-tap reaction time tests (Roivainen, 2011).

6.5.4 Relationships among IT, CD, RAN, Text-Reading and Oculomotor Function

Correlation analyses demonstrated a significant relationship between IT performance and passage reading score in the younger adult group, indicating that a shorter threshold exposure duration required to accurately identify a visual stimulus was associated with a shorter duration to read and verbalize each word in the semantically predictable passage. For the older adults, results demonstrated a significant correlation between the CD and average saccade duration during the RAN Numbers task, indicating that a lower saccade duration was associated with shorter threshold exposure duration required to correctly identify change between two visual arrays. These findings partially supported the hypothesis that faster visuo-cognitive speed would correlate with more efficient eye movements. Interestingly, the lack of any additional significant correlations between IT, CD and oculomotor measures in the current study is similar to findings reported by Garaas and Pomplun (2008) who also used an Inspection Time task alongside oculomotor measures (fixation duration and saccade latency) in a sample of young to middle-aged adults.

In the current study, regression analyses demonstrated some predictive validity of the IT and CD scores in predicting naming scores on the RAN and reading tasks. More specifically, the model which included age, the IT and CD scores significantly predicted 19.00% of the variance in RAN Objects scores. However, for this task, age was the main contributor to scores (18.4%). For the RAN Objects task, it may be the case that fast performance is more reliant on working memory and access to lexical storage when retrieving the names of various objects, as opposed to threshold time to identify a visual stimulus/detect change between two visual arrays, as in the IT and CD. IT and CD scores also significantly explained over 10% of the variance in naming scores for RAN letters. The model which included IT, and CD scores while accounting for the effect of age, did not significantly predict any other scores on the RAN numbers or the text-passage. This was an unexpected finding which contradicted hypotheses given that visual perceptual speed has been reported to predict reading speed (Lobier, Dubois, & Valdois, 2013).

The factor analysis enabled exploration of the factorability of the variables in the current study with the results revealing a three-component solution which explained a total of 67.05% of variance. The three factors appeared to be clusters of variables predominantly relating to visual fixations, saccades, and text-reading along with the IT, respectively. The first component which included a combination of fixation durations and number of fixations during the alphanumeric RAN conditions, explained almost 40% of the variance. It may be the case that these variables relating to fixations are reflective of specific cognitive aspects i.e., perceptual speed, time needed to encode a visual stimulus and embed into memory, thus accounting for most of the variance in the model (Al Dahhan et al., 2014; Al Dahhan et al., 2017; Jordan, Dixon, McGowan, Kurtev, & Paterson, 2016). The second component which only included saccade durations, is likely reflective of the motor component during visual perception, which explained ~16.00% of the variance. The third component explained an additional ~10% of the variance which comprised of the number of fixations during the passage as well as the passage reading and IT score which may be reflective of the shared cognitive processes (i.e., rapid visual information processing) between text-reading and the IT task.

6.5.5 Limitations

A strength and weakness of this study was the similarly educated individuals in our sample. This enabled robust comparison between groups but limits the generalisability of the study findings to a more general, less educated population. In particular, our sample of healthy older adults may not be representative of the general community of older adults who have not continued to enthusiastically engage in vocational education. Our study is also limited in terms of the rigor of health status, in that we used self-report rather than neuropsychological assessment for potential mild cognitive impairment (MCI) (Ahmed, Arnold, Thompson, Graham, & Hodges, 2008). Thus, it is unclear whether age-related differences in the RAN-objects condition may be due to factors such as mild cognitive impairment in the older group. Indeed, research has demonstrated that naming of objects is impaired amongst individuals with MCI compared to healthy controls (Ahmed et al., 2008). However, the comparable scores between age groups on the alphanumeric RAN tests may argue against MCI. Our uneven sample sizes between age groups and relatively small sample of older participants, presumably also decreased the power of some statistical analyses conducted, particularly those requiring a large sample size (i.e., factor analyses). Additionally, there were some discrepancies within in the total number of participants within the older adult group for individual tasks, and this was due to some complications with the eye tracker during recording. Given this, future studies and analyses are likely to benefit from use of a larger sample of older participants when exploring similar research questions. Though sex differences in cognitive ability was not a focus of this study, future studies may also benefit from having an even spread of genders within each age-group to examine whether gender may contribute to differences seen in cognitive and ocular ability. Furthermore, the GazePoint eye tracker used in the current study did not enable measurement of micro-saccades, which may aid analysis of eye-movements made during other visual tasks which do not require the same degree of visual scanning and eye movements as in the RAN task.

6.5.6 Conclusions and Future Directions

In conclusion, our study is among the first to measure and compare robust cognitive measures of perceptual speed, as well as spatial and temporal aspects of gaze patterns during RAN tasks and text reading in healthy educated samples of younger and older adults. Our results show that oculomotor functions become slower with age and suggest use of different strategies that may further contribute to the slower cognitive processing on complex visuo-cognitive tasks seen across the lifespan. Interestingly, after covariation of saccade durations, the threshold exposure time needed to detect change was not significantly different between younger and older groups. To our knowledge, this study has also been the first to examine the predictive validity of the IT and CD to performance on the naming and reading tasks. Our quantification of gaze patterns during performance on visual-tasks elucidates perspectives on the time taken to activate and deactivate saccades, demonstrating that older adults have longer saccade durations, though this does not always denote slower behavioral performance. Thus, we can conclude that the two age groups may utilise slightly different temporal strategies to achieve similar performance on tasks such as naming alphanumeric stimuli and reading. However, whether the differences reflect unique differences to activate attention and initiate saccades, motor speed of saccade, or cognitive aspects of the tasks, or whether the differences are reflective of all three components remains to be determined. Overall, our findings extend understanding of ocular function with age and demonstrate that eye movements are a non-invasive and insightful measure of cognitive function which should continue to be employed in cognitive aging research and potentially, as clinical measures of cognitive processing. Future research should aim to examine whether oculomotor function during visual tasks are predictive of cognitive performance on other robust measures of cognitive speed with different task demands, as literature in this area remains relatively rare.

6.7 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6.8 Author Contributions

SGC initiated the project, designed the outline and content, contributed to the writing and data analysis. DE collected and analysed the data. DE and SGC have also contributed to the writing, and developed the first and final draft of the manuscript.

6.9 Funding

The project has been approved by La Trobe University Human Ethics Committee (UHEC), approval number S15/19. All funding has been provided by La Trobe University, School of Psychology and Public Health, Department of Psychology and Counselling.

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6.11 References

Abel, L. A., & Douglas, J. (2007). Effects of age on latency and error generation in internally mediated saccades. *Neurobiology of Aging, 28*(4), 627-637.

Al Dahhan, N., Georgiou, G. K., Hung, R., Munoz, D., Parrila, R., & Kirby, J. R. (2014). Eye movements of university students with and without reading difficulties during naming speed tasks. *Annals of dyslexia, 64*(2), 137-150.

Al Dahhan, N. Z., Kirby, J. R., Brien, D. C., & Munoz, D. P. (2017). Eye movements and articulations during a letter naming speed task: Children with and without dyslexia. *Journal of Learning disabilities, 50*(3), 275-285.

Andersen, G. J. (2012). Aging and vision: changes in function and performance from optics to perception. *Wiley Interdisciplinary Reviews: Cognitive Sciences*, *3*(3), 403-410. doi:10.1002/wcs.1167

Awh, E., Armstrong, K. M., & Moore, T. (2006). Visual and oculomotor selection: links, causes and implications for spatial attention. *Trends in Cognitive Sciences*, *10*(3), 124-130. doi:10.1016/j.tics.2006.01.001

Babcock, R. L., & Salthouse, T. A. (1990). Effects of increased processing demands on age differences in working memory. *Psychology & Aging, 5*(3), 421-428.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychology & Aging*, *12*(1), 12.

Barthelemy, S., & Boulinguez, P. (2001). Manual reaction time asymmetries in human subjects: the role of movement planning and attention. *Neuroscience Letters, 315*(1-2), 41-44.

Becker, M. W., Pashler, H., & Anstis, S. M. (2000). The role of iconic memory in change-detection tasks. *Perception, 29*(3), 273.

Bisley, J. W., & Goldberg, M. E. (2006). Neural correlates of attention and distractibility in the lateral intraparietal area. *Journal of Neurophysiology, 95*(3), 1696-1717.

Bisley, J. W., & Goldberg, M. E. (2010). Attention, intention, and priority in the parietal lobe. *Annual Review of Neuroscience, 33,* 1-21.

Bowl, M. R., & Dawson, S. J. (2015). The mouse as a model for age-related hearing loss-a mini-review. *Gerontology, 61*(2), 149-157.

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., . . . Reed, B. R. (2001). Context processing in older adults: evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General*, 130(4), 746-763.

Brown, A. C., Corner, M., Crewther, D. P., & Crewther, S. G. (2018). Age related decline in cortical multifocal flash VEP: Latency increases shown to be predominately magnocellular. *Frontiers in Aging Neuroscience, 10*, 430.

Brown, A., & Crewther, D. (2012). Autistic children show more efficient parvocellular visual processing. *Frontiers in Human Neuroscience*, doi: 10.3389/conf.fnhum.2012.208.00021 [Epub ahead of print].

Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology, 54*(1), 1.

Chan, C. Y. H., Chan, A. B., Lee, T. M. C., & Hsiao, J. H. (2018). Eye-movement patterns in face recognition are associated with cognitive decline in older adults. *Psychonomic Bulletin Reviews*. doi:10.3758/s13423-017-1419-0

Cowan, N. (2010). The magical mystery four: How is working memory capacity limited, and why? *Current Directions in Psychological Science, 19*(1), 51-57.

Crewther, S. G., Goharpey, N., Carey, L., & Crewther, D. P. (2013). Goal-driven attention and working memory. In L. Carey (Ed.), *Stroke Rehabilitation; Insights from Neuroscience and Imaging* (pp. 191-2017). New York: Oxford University Press.

Deary, I. J., Corley, J., Gow, A. J., Harris, S. E., Houlihan, L. M., Marioni, R. E., . . . Starr, J. M. (2009). Age-associated cognitive decline. *British Medical Bulletin, 92*, 135-152. doi:10.1093/bmb/ldp033

Dowiasch, S., Marx, S., Einhäuser, W., & Bremmer, F. (2015). Effects of aging on eye movements in the real world. *Frontiers in Human Neuroscience, 9*, 46.

Ebaid, D., & Crewther, S. G. (2018). Temporal aspects of memory: A comparison of memory performance, processing speed and time estimation between young and older adults. *Frontiers in Aging Neuroscience, 10*.

Ebaid, D., & Crewther, S. G. (2019). Visual Information Processing in Young and Older Adults. *Frontiers in Aging Neuroscience, 11*, 116.

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A., & Crewther, D. P. (2017). Cognitive processing speed across the lifespan: Beyond the influence of motor speed. *Frontiers in Aging Neuroscience*, *9*, 62. doi:10.3389/fnagi.2017.00062

Fernandez-Ruiz, J., Peltsch, A., Alahyane, N., Brien, D. C., Coe, B. C., Garcia, A., & Munoz, D. P. (2018). Age related prefrontal compensatory mechanisms for inhibitory control in the antisaccade task. *NeuroImage*, *165*, 92-101.

Forstmann, B. U., Tittgemeyer, M., Wagenmakers, E. J., Derrfuss, J., Imperati, D., & Brown, S. (2011). The speed-accuracy tradeoff in the elderly brain: a structural model-based approach. *Journal of Neuroscience, 31*(47), 17242-17249. doi:10.1523/JNEUROSCI.0309-11.2011

Fortunato, S., Forli, F., Guglielmi, V., De Corso, E., Paludetti, G., Berrettini, S., & Fetoni, A. (2016). A review of new insights on the association between hearing loss and cognitive decline in ageing. *Acta Otorhinolaryngologica Italica, 36*(3), 155.

Füllgrabe, C., Moore, B. C., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience, 6*, 347.

Gamboz, N., Zamarian, S., & Cavallero, C. (2010). Age-related differences in the attention network test (ANT). *Experimental Aging Research, 36*(3), 287-305.

Garaas, T. W., & Pomplun, M. (2008). Inspection time and visual–perceptual processing. *Vision Research, 48*(4), 523-537.

Gazzaley, A., Sheridan, M. A., Cooney, J. W., & D'Esposito, M. (2007). Age-related deficits in component processes of working memory. *Neuropsychology, 21*(5), 532-539. doi:10.1037/0894-4105.21.5.532

Godefroy, O., Roussel, M., Despretz, P., Quaglino, V., & Boucart, M. (2010). Age-related slowing: perceptuomotor, decision, or attention decline? *Experimental Aging Research, 36*(2), 169-189. doi:10.1080/03610731003613615

Govenlock, S. W., Taylor, C. P., Sekuler, A. B., & Bennett, P. J. (2009). The effect of aging on the orientational selectivity of the human visual system. *Vision Research, 49*(1), 164-172. doi:10.1016/j.visres.2008.10.004

Govenlock, S. W., Taylor, C. P., Sekuler, A. B., & Bennett, P. J. (2010). The effect of aging on the spatial frequency selectivity of the human visual system. *Vision Research, 50*(17), 1712-1719. doi:10.1016/j.visres.2010.05.025

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In *Psychology of Learning and Motivation* (Vol. 22, pp. 193-225): Elsevier.

Hedden, T., & Gabrieli, J. D. (2004). Insights into the ageing mind: a view from cognitive neuroscience. *Nature Reviews Neuroscience, 5*(2), 87.

Hutchinson, C. V., Arena, A., Allen, H. A., & Ledgeway, T. (2012). Psychophysical correlates of global motion processing in the aging visual system: A critical review. *Neuroscience & Biobehavioural Reviews, 36*(4), 1266-1272. doi:10.1016/j.neubiorev.2012.02.009

Irving, E. L., Steinbach, M. J., Lillakas, L., Babu, R. J., & Hutchings, N. (2006). Horizontal saccade dynamics across the human life span. *Investigative Ophthalmology & Visual Science, 47*(6), 2478-2484.

Kato, K., Nakamura, A., Kato, T., Kuratsubo, I., Yamagishi, M., Iwata, K., & Ito, K. (2016). Age-related changes in attentional control using an n-back working memory paradigm. *Experimental Aging Research, 42*(4), 390-402.

Kaufman, D. A., Sozda, C. N., Dotson, V. M., & Perlstein, W. M. (2016). An event-related potential investigation of the effects of age on alerting, orienting, and executive function. *Frontiers in Aging Neuroscience, 8*, 99.

Klein, C., Fischer, B., Hartnegg, K., Heiss, W., & Roth, M. (2000). Optomotor and neuropsychological performance in old age. *Experimental Brain Research, 135*(2), 141-154.

Kowler, E. (2011). Eye movements: The past 25 years. *Vision Research, 51*(13), 1457-1483.

Leonard, C. J., & Luck, S. J. (2011). The role of magnocellular signals in oculomotor attentional capture. *Journal of Vision, 11*(13), 11-11.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: a strong connection. *Psychology & Aging, 9*(3), 339.

Lyytinen, H., Erskine, J., Tolvanen, A., Torppa, M., Poikkeus, A.-M., & Lyytinen, P. (2006). Trajectories of reading development: A follow-up from birth to school age of children with and without risk for dyslexia. *Merrill-Palmer Quarterly (1982-)*, 514-546.

Madden, D. J. (2007). Aging and visual attention. *Current Directions in Psychological Science, 16*(2), 70-74. doi:10.1111/j.1467-8721.2007.00478.x

Mahoney, J. R., Verghese, J., Goldin, Y., Lipton, R., & Holtzer, R. (2010). Alerting, orienting, and executive attention in older adults. *Journal of the International Neuropsychological Society, 16*(5), 877-889.

Maruta, J., Spielman, L. A., Rajashekar, U., & Ghajar, J. (2017). Visual tracking in development and aging. *Frontiers in Neurology, 8*, 640.

Meyer, B. J., & Pollard, C. K. (2006). Applied learning and aging: A closer look at reading. In *Handbook of the Psychology of Aging (Sixth Edition)* (pp. 233-260): Elsevier.

Mohler, C. W., Goldberg, M. E., & Wurtz, R. H. (1973). Visual receptive fields of frontal eye field neurons. *Brain Research, 61*(3), 85-83.

Mundinano, I.-C., Fox, D. M., Kwan, W. C., Vidaurre, D., Teo, L., Homman-Ludiye, J., . . . Bourne, J. A. (2018). Transient visual pathway critical for normal development of primate grasping behavior. *Proceedings of the National Academy of Sciences*, 201717016.

Munoz, D., Broughton, J., Goldring, J., & Armstrong, I. (1998). Age-related performance of human subjects on saccadic eye movement tasks. *Experimental Brain Research, 121*(4), 391-400.

Nieuwenhuis, S., Ridderinkhof, K. R., De Jong, R., Kok, A., & Van Der Molen, M. W. (2000). Inhibitory inefficiency and failures of intention activation: Age-related decline in the control of saccadic eye movements. *Psychology and Aging, 15*(4), 635.

Norton, E. S., & Wolf, M. (2012). Rapid automatized naming (RAN) and reading fluency: Implications for understanding and treatment of reading disabilities. *Annual Review of Psychology, 63*, 427-452.

Peters, J., Taylor, J., Crewther, D., Cross, A., & Crewther, S. G. (2016). *Relation of Rapid Automatized Naming (RAN) and Eye Movements in Young Learner Readers*. Paper presented at the Asia Pacific Conference on Vision Fremantle WA.

Ptak, R., & Müri, R. (2013). The parietal cortex and saccade planning: lessons from human lesion studies. *Frontiers in Human Neuroscience, 7*, 254.

Rutkowski, J. S., Crewther, D. P., & Crewther, S. G. (2003). Change detection is impaired in children with dyslexia. *Journal of Vision, 3*(1), 10-10.

Salthouse, T. A. (1991). Age and experience effects on the interpretation of orthographic drawings of three-dimensional objects. *Psychology & Aging, 6*(3), 426-433.

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

Salvi, S. M., Akhtar, S., & Currie, Z. (2006). Ageing changes in the eye. *Postgraduate Medical Journal, 82*(971), 581-587. doi:10.1136/pgmj.2005.040857

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (p. 155–219). Lawrence Erlbaum Associates Publishers.

Sekuler, B. P. J. B., Mortimer Mamelak, Allison. (2000). Effects of aging on the useful field of view. *Experimental Aging Research, 26*(2), 103-120.

Sparks, D. L., & Barton, E. J. (1993). Neural control of saccadic eye movements. *Current opinion in neurobiology, 3*(6), 966-972.

Sun, L. D., & Goldberg, M. E. (2016). Corollary discharge and oculomotor proprioception: Cortical mechanisms for spatially accurate vision. *Annual Review of Vision Science*, *2*, 61-84.

Vickers, D., Nettelbeck, T., & Willson, R. (1972). Perceptual indices of performance: the measurement of ‘inspection time’and ‘noise’in the visual system. *Perception*, *1*(3), 263-295.

Wayne, R. V., & Johnsrude, I. S. (2015). A review of causal mechanisms underlying the link between age-related hearing loss and cognitive decline. *Ageing Research Reviews*, *23*, 154-166.

Whitney, D., & Levi, D. M. (2011). Visual crowding: a fundamental limit on conscious perception and object recognition. *Trends in Cognitive Sciences, 15*(4), 160-168. doi:10.1016/j.tics.2011.02.005

Wurtz, R. H., & Goldberg, M. E. (1989). *The neurobiology of saccadic eye movements* (Vol. 3): Elsevier Science Limited.

Zhao, M., Gersch, T. M., Schnitzer, B. S., Dosher, B. A., & Kowler, E. (2012). Eye movements and attention: The role of pre-saccadic shifts of attention in perception, memory and the control of saccades. *Vision Research*, *74*, 40-60.

chapter 7

07.

CHAPTER 7

Temporal Aspects of Memory: A Comparison of Memory Performance, Processing Speed and Time Estimation between Young and Older Adults

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7.1 Abstract

Cognitive abilities are often reported to decline across the lifespan, particularly when assessed with working memory (WM) measures such as the auditory backward digit span and complex *N*-back tasks. However, some debate still exists regarding which aspects of cognition are most susceptible to the aging process and which may remain intact. Additionally, time estimation, though a complex psychological dimension, is often studied in relative isolation and is particularly neglected in traditional studies of WM, with little research from the viewpoint of retrospective temporal estimation. In particular, research seldom considers whether the ability to accurately estimate time retrospectively, is correlated with performance on traditional memory and processing speed measures in healthy populations. Thus, we chose to investigate performance of comparably educated young and older adult groups on both classical memory tasks including auditory and visual digit spans, *N*-back, WAIS-based measures of processing speed (i.e., Symbol Search [SS] and Coding [Cod]) and a temporal measure of WM with a focus on retrospective time estimation. Our sample included 66 university students (58 F, 8 M) between the ages of 18 – 29, and 33 university-educated healthy older adults (25 F, 8 M) between the ages of 60 – 81. Results indicated that older adults performed significantly worse on auditory but not the visual digit span tasks, as well as on both the SS and Cod, though performed equally well on the *N*=1 back task. Results also showed that retrospective time estimation was not significantly different between young and older adults, with both groups substantially underestimating duration of a simple task. Retrospective time estimation was not significantly correlated to any memory or processing speed measure, emphasizing the need for future research into the specific cognitive domains underlying the subjective estimation of a temporal interval.

7.2 Introduction

Aging is often associated with a decline in a range of cognitive abilities relating to measures of working memory (WM), dual tasks, and executive functioning (Gazzaley, Sheridan, Cooney, & D'Esposito, 2007; Kato et al., 2016; Kirova, Bays, & Lagalwar, 2015; Moore et al., 2005; Salthouse, 1990; Vellage et al., 2016; Wang et al., 2011). Traditionally, WM is defined as the memory system involved in actively maintaining current information for a period of time, allowing for on-line or later manipulation and access, and is suggested to underpin complex processes such as learning, reasoning, planning and problem solving (Baddeley, 1986, 2007; Baddeley, Eyesnck, & Anderson, 2009; Baddeley & Hitch, 1974). WM is also considered to be limited in the number of items that can be temporarily stored and manipulated simultaneously (Baddeley, 2007; Baddeley & Hitch, 1974; Salthouse, 1990) presumably due to limited attention span and capacity over a particular period of time (Cowan, 1998; Wiley & Jarosz, 2012). Interestingly, few reports have considered the aspects of WM that are optimum for the accurate perception of time in healthy older populations. Variables such as sensory (vision and hearing) receptor integrity (Lindenberger & Baltes, 1994; Baltes & Lindenberger, 1997; Füllgrabe, Moore, & Stone, 2015), education and affective factors have been suggested to contribute to the decline in WM seen with age (Hester et al., 2004; Puccioni & Vallesi, 2012; Vallesi, 2016; Hammar & Årdal, 2009; Beaudreau & O'hara, 2008; Beaudreau & O'Hara, 2009). Specifically, more years of formal education are suggested to mitigate cognitive decline seen in aging, while higher depressive and anxiety symptoms are consistently reported to impede on cognitive performance in all populations (Hammar & Årdal, 2009; Beaudreau & O'hara, 2008; Beaudreau & O'Hara, 2009).

Commonly used experimental measures of processing speed which often show decline across the lifespan are the Symbol Search (SS) and Coding (Cod) tasks from the

Information Processing Speed Index of the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 2008a, 2008b) i.e., Cornelis et al. (2014); Joy, Kaplan, and Fein (2004). In addition, one of the simplest and most commonly used WM measures is the *N*-back task, which involves presenting participants with a series of stimuli (predominantly visual) requiring a manual response to a nominated target stimulus that had been presented *N* items earlier (Kirchner, 1958). Research has commonly reported that older adults perform worse at this task when *N=2* or more and are more susceptible to distractors than younger adults (i.e., Kato et al., 2016). Neuroimaging data has linked good performance on the *N*-back task with activation in the frontal lobes (predominantly prefrontal cortex) parietal lobes, and more recently, the anterior cingulate, insula, cerebellum and thalamus (See Crewther, Lamp, Goodin, Laycock & Crewther, 2018). Furthermore, memory span measures including the auditory forward and backward digit span tests of the WAIS (Wechsler, 2008) are two of the most commonly used measures in the aging literature to examine short term and WM, respectively (Elliot, et al., 2011; Hester, Kinsella & Ong, 2004, Woods et al., 2011; Bopp & Verhaeghen, 2005; Hilbert, et al., 2014). Although age-related decreases in both the auditory forward and backward digit span have been reported (Babock & Salthouse. 1990; Hester, Kinsella & Ong, 2004) literature often reports that decreases in backward span are greater and more sensitive to age-related decline (Babock & Salthouse, 1990; Bopp & Verhaeghen, 2005; Elliot, et al., 2011). Interestingly, in the previous studies that examined age-related decline in auditory digit span tasks, seldom have explicitly measured hearing sensitivity and ensured it was matched to controls. However, the first study to do so was conducted by Füllgrabe, Moore and Stone (2015) who used a sample of audiometrically matched healthy young and older participants who were also matched on age-corrected performance IQ scores and years of education, where no significant differences were seen between older and younger participants in auditory digit span performance.

General declines in WM and cognitive processes across the lifespan are often explained by *the Processing Speed Theory of Adult Age Differences in Cognition* proposed by Salthouse (1996) which suggests that a slowing in the speed at which cognitive processing operations can be correctly executed, underlies the decline observed in higher cognitive abilities and general cognitive functions. Furthermore, decline in sensory function i.e., vision and audition that occurs in healthy aging, have been suggested to contribute to the decline in cognitive ability seen in healthy aging as suggested by theories including the *Sensory Deprivation Hypothesis*, the *Common-Cause Hypothesis*, and the *Information Degradation Hypothesis* (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Schneider and Pichora-Fuller, 2000). Age group differences in cognitive functions are also commonly discussed with reference to *the Inhibitory Deficit Hypothesis* (Hasher & Zacks, 1988) which suggests that age-related declines in WM tasks are a result of older adults being less efficient in concurrently attending selectively to task-relevant stimuli and inhibiting task-irrelevant information. Furthermore, research suggests that memory span also diminishes with age, and contributes to differences seen in WM processes between young and older adults (Gazzaley et al., 2007; Kato et al., 2016; Kirova et al., 2015; Mendelsohn & Larrick, 2011; Moore et al., 2006; Moore et al., 2005; Salthouse, 1990; Vellage et al., 2016; Wang et al., 2011).

To date, temporal aspects of WM have mainly been discussed from the viewpoint of temporary storage and encoding of temporal stimuli, but not from the viewpoint of the functional contribution to timing and time perception per se. Despite this, the ability to accurately perceive and estimate time is a ubiquitous psychological process, tightly embedded with cognitive skills including attention, memory, decision making and age (Polti, Martin, & van Wassenhove, 2018; Baudouin, et al., 2018; Rao, Mayer & Harrington, 2001; Lewis & Miall, 2003; Livesey, Wall & Smith, 2007; Perbal-Hatif, 2012; Bherer, Desjardins, & Fortin, 2007; Penney, Yim & Ng, 2014; Tse, Intriligator, Rivest, & Cavanagh, 2004; Turgeon, Lustig, & Meck, 2016; Block et al., 1998; Casini & Macar, 1997; Penney, Yim & Ng, 2014; Zakay et al., 1983; Carrasco et al., 2001). For example, research has suggested that older adults underestimate temporal interval durations both in the millisecond to second range and in the 1 minute to 8 minutes range (Carrasco et al. 2001, Feifel, 1957; Vanneste & Pouthas, 1995; Mc Grath & O'Hanlon Jr, 1968). However, age differences in reports of the subjective perception of time are not always consistently reported (see Friedman & Janssen, 2010). Insight from neuroimaging studies have suggested that different brain regions are reportedly responsible for time estimation in the millisecond range compared to estimating time in the seconds to minutes range (Coull, Cheng & Meck, 2011; Harrington, et al., 2004). Specifically, the basal ganglia, supplementary motor area, and cerebellum have been suggested to play a role in accurate time estimation in the millisecond range (Harrington, Haaland, & Hermanowitz, 1998; Harrington et al., 2004), whereas the prefrontal and parietal cortices, and the frontostriatal network have been suggested to underlie accurate time estimation in the second-to-minutes range (Smith et al. 2003; Wittmann, 2009). Furthermore, a recent review on the psychological and neurobiological processes associated with age-related distortions in the perception of time in the hundredths of milliseconds-to-minutes range has also suggested that age-related changes in the functioning of the cortico-thalamic-basal ganglia circuits are associated with distortions in time perception (Turgeon, Lustig, & Meck, 2015). However, Turgeon, Lustig, and Meck (2015) have noted that older adults can still accurately estimate time by recruiting additional neural networks and cognitive resources to partially compensate for age-related declines in time perception.

Literature relating to time estimation typically explains the perception of a temporal interval either within a modular framework which suggests a specialised mechanism that is representative of the temporal relationship between events (i.e., *the*

Internal Clock; Carrasco et al., 2001), or from a more general perspective, as a relationship that assumes that time perception is an intrinsic and ubiquitous property of neural activity (Ivry & Schlerf, 2008). For example, the Internal Clock Hypothesis (Carrasco et al., 2001) postulates that aging is associated with distortions to the speed of the internal clock (Craik & Hay, 1999), resulting in inaccurate time estimation for short intervals of time. Specifically, it has been suggested that compared to younger adults, the internal clock in older adults runs faster than objective time, leading to an underestimation of time intervals during experimental tasks (Carrasco et al., 2001; Craik & Hay, 1999; Licht, Morganti, Nehrke, & Heiman, 1986; Mc Grath & O'Hanlon Jr, 1968). Such findings support subjective reports from older adults that time seems to move more quickly compared to their younger years (Joubert, 1990). In healthy populations, debate still exists about the unifying principles that link aspects of time estimation to specific cognitive processes (Matthews & Meck, 2016). However, time estimation alongside WM tasks was recently studied with a clinical population of stroke and Transient Ischemic Attack (TIA) patients, where residual cognitive impairment was suggested to play a role in predicting the prognosis of perceptual timing abnormalities (See Low et al. 2016).

The first study to explore time estimation in a healthy population alongside WM tasks, including the Wisconsin Card Sorting Test (WCST; Nelson, 1976), the Verbal Fluency Test (Luszcz & Lane, 2008), the Number comparison test (Babcock, Laguna, & Roesch, 1997) and the Number Transformation Test (Babcock, Laguna, & Roesch, 1997), was conducted by Baudouin et al. (2018). Authors aimed to examine prospective time estimation in relation to general factors corresponding to executive decline and cognitive slowing which occurs in healthy aging. The study was conducted with a sample of young (mean age = 25.8 years), old (mean age=67.5 years), and very old adults (mean age = 82.5 years) who were required to *produce* or *reproduce* a time duration. In the production task, participants viewed a blue square on the screen, and were required to press a button when they estimated that the target duration of 5s, 14s or 38s had elapsed. Alternatively, in the reproduction task, participants were asked to reproduce the exposure time for which a blue square had previously been exposed. Results revealed that information processing speed was the most reliable predictor of time estimation in the duration production task, with faster processing speed related to more accurate duration productions, while executive function was the most reliable predictor of duration reproduction, which is reported to be more reliant on WM processes.

Research into retrospective time estimation in the seconds-to-minutes range using healthy older populations' remains relatively understudied. Thus, the current study aimed to investigate memory and processing speed performance between young and older adults of similar education, and its correlation to retrospective time estimation of a task lasting 85 seconds. We aimed to achieve this by using traditional measures of memory and processing speed such as visual and auditory digit span tasks, the WAIS SS and Cod, an *N*-back task using cartoon faces, a measure of retrospective time estimation, while considering affective factors (i.e., depression, anxiety and stress symptoms). The range of memory and processing speed tasks were chosen to ensure that aspects such as the requirement for rapid new learning, sustained attention, and ecological relevance of tasks were all considered. In terms of age group differences, it was hypothesized that older adults would demonstrate shorter forward and backward digit spans, in line with past research (Babcock & Salthouse, 1990; Hester et al., 2004; Bopp & Verhaeghen, 2005), and a slower processing speed on the SS and Cod based on our previous results (Ebaid, et al., 2017). It was also hypothesised that older adults would perform as well as younger adults on the simple *N*=1 back task as age-group differences are predominantly reported when *N*=2 or more (Kato, et al., 2016), but would underestimate task duration compared to younger adults. In regard to correlations, we hypothesised that retrospective time estimation would correlate to measures of memory and processing speed (Baudouin et al., 2018). However, given that there is little experimental research on retrospective time estimation of intervals in the seconds-to-minute range and its correlation to memory and processing speed tasks in healthy populations, this study is primarily exploratory in nature.

7.3 Method

7.3.1 Participants

Ninety-nine participants comprised the sample, which included 66 young first year Psychology students from La Trobe University, Melbourne, aged between 18-29 who received course credit for their participation. The study also included 33 healthy older adults aged between 60-81, recruited from the University of the Third Age (U3A) Manningham, and received a $20 Coles-Myer voucher for their participation. U3A is an international volunteer organization where interested older individuals are able to come together and collaboratively learn, rather than for any qualifications (for more information please visit www.u3a.org.au). All participants had normal visual acuity or corrected-to-normal visual acuity, and participants who wore hearing aids were able to keep them in during the study. Though researchers ensured that vision and hearing were adequate for participants to complete all suprathreshold contrast tasks, hearing sensitivity, i.e., pure-tone or speech audiometry was not explicitly assessed. A demographic questionnaire collected information on age, gender, and years of education. A measure of general negative affect: The Depression Anxiety and Stress Scale (DASS-21; Lovibond & Lovibond, 1995) was administered as a screening tool. Exclusion criteria included previous diagnoses of a neurological disorder or inability to speak or understand English with basic competence, though no participant was excluded on this basis. The demographic information of the sample is summarised in Table 1.

Table 1. Characteristics of Younger and Older Adults

	Younger Adults N = 66		Older Adults N = 33	
	M	**SD**	**M**	**SD**
Age (years)	19.60	2.26	70.30	5.62
Gender (M/F)	8/59		8/25	
Education (Years)	7.64	1.05	10.91	3.38
Depression Score (DASS-21)	3.09	2.51	1.79	1.93
Anxiety Score (DASS-21)	3.34	3.03	3.91	2.88
Stress Score (DASS-21)	5.89	3.49	1.79	1.93

7.3.2 Materials

Memory Measures:

Forward & Backward Digit Span (Auditory & Visual)

The forward and backward digit span tasks were adapted from the Auditory Digit Span subset of the WAIS 4th Edition (Wechsler, 2008). A customized digit span task made using Authorware Professional software was administered auditorally and visually on an Apple iMac (Retina 4K) computer with a 21.5-inch monitor. The forward digit span task reportedly measures attention in the context of immediate recall of information from short-term memory, while the backward span places demands on both attention and WM abilities in requiring manipulation (i.e., reordering) of the information (Lichtenberger & Kaufman, 2009). The forward digit span task involves presenting participants with a series of random digits (from 1-9) after which participants are required to repeat the list back in the same order either verbally, or by typing their response using a keyboard, as preferred. If successful, the participant is given a longer sequence. In the backwards digit span condition, participants are presented with a series of random digits (from 1-9), and are required to repeat the list backwards, again either verbally, or by typing their response using a keyboard, as preferred. The number sequence began at a span length of two, and increased by one after two correct trials, i.e., participants were given two trials per span length. Once two trials of the same span length were answered incorrectly, testing was discontinued, and the previously correct span length was recorded as the participants 'digit span capacity'.

The task always began with the forward digit span task followed by the backward digit span, and the order of presentation between the visual and auditory conditions were counterbalanced across participants (counterbalancing of tasks is later described). Prior to commencing the task, participants were seated approximately 60 cm away from the computer screen and the researcher verbally explained the instructions of each digit span task to participants. In the *visual* digit span condition, digits were presented in black Ariel 92pt font against a white background, at a rate of one digit per second, with no sound/voiceover reading the numbers. In the *auditory* condition, digits were read aloud i.e., verbally presented to participants via a voice over on loudspeaker on the Apple iMac computer as part of our custom modified computer task, with no visual representation of the numbers on the screen. After each number sequence, the following words appeared on the screen: "*Please type your response"* in black Ariel 48pt font, prompting participants to repeat the digit sequence. The next trial only commenced once the *Enter* key was pressed on the keyboard. As part of the computerized digit span task, verbal instructions were also provided to participants via voice-over iterating the task requirements for the forward and backwards digit span immediately before commencement. For example, for the visual forward digit span, the voice over script was as follows: "*You are going to see some numbers. After each trial, you will have to repeat these numbers in the same order. Ready?"* Participants were then required to press the space bar to begin the task or had the option to replay the instructions. The computerized instructions and the auditory presentation of numbers were played via loudspeaker on the Apple iMac computer in which the volume was set to a level preferred by the participant. This was adjusted during the computerized instructions phase, prior to formal commencement of the task.

***N*-Back task**

A modified version of the *N*-Back task originally developed by Kirchner (1958) was administered to participants on a computer, as a simple measure of sustained attention and WM, and took a total of 85 seconds. Participants were presented with a sequence of 34 cartoon faces that varied in shape (i.e., 9-star shaped faces, 9-round shaped faces, 8-sqaure shaped faces, and 8-oval shaped faces) at a rate of 1.5 second per stimulus, with a 1 second delay between stimuli. Participants were required to indicate by pressing the space bar, if the current image was the same as the image presented immediately prior (i.e., $N = 1$ back). This was the case on 7 occasions, and so the maximum correct score participants could obtain was 7. An N = 1 back was chosen on the basis of the task demands being relatively simple for both age groups as stimuli were presented for adequate time for participants to encode. In doing so, we aimed to ensure both groups of participants' sustained attention for the full duration of task in order to provide a true measure of time estimation at completion.

Processing Speed Measures

Symbol Search (SS) and Coding (Cod) (WAIS-IV)

As per the WAIS-IV kit instructions, the SS and Cod subtests from the WAIS-IV were administered for two minutes each. During SS, two target symbols appearing on the left of a row are sought among an array of five symbols on the right. The individual responds by marking with a pencil either the identical symbol, or a "no" box (if the matching symbol is not present in the array). Performance was measured as the number of symbols accurately identified in two minutes, with more symbols accurately completed indicative of faster processing speed. In healthy adults, raw scores on SS have been shown to decline by more than 50% between the ages of 25 and 65 (Wechsler, 2008b).

The Cod task requires an individual to copy the appropriate symbol in a box underneath a digit (one-to-nine), while referring to a key at the top of the page containing digits and their corresponding symbols. Performance is based on the number of pairs correctly copied in two minutes, with more pairs correctly copied indicative of a faster processing speed.

Time estimation

At the end of the *N*-back task participants were asked "*how long do you think that task took in seconds?"* and their estimation was recorded, in turn assessing retrospective time estimation. No prior warning was given to participants about having to estimate the task duration, in order to prevent any strategies of time-keeping or monitoring of temporal information and thus, simulating a more realistic example of 'on the spot' retrospective time estimation. Examining retrospective time estimation with no prior warning can only be done once in order to obtain a genuine estimate from participants. Though this may impede on the reliability of the data, if participants are asked to estimate time of several tasks, this data is unlikely to reflect a pure measure of retrospective time estimation without prior warning. This method of retrospective time estimation using the same *N*-back task has been used in recent research with a healthy and clinical sample of stroke and TIA patients (though task conditions were *N*=0; See Low et al., 2016).

7.3.3 Procedure

All participants were guided through the experimental tasks. To counterbalance the order of presentation of tasks between participants, Microsoft Excel was used to generate all the possible arrangements of the following number sequence (1,2,3,4,5) which represented the auditory digit span (forward and backward), the visual digit span (forward and backward), SS, Cod, and the *N*-back with time estimation, respectively. This generated a total of 120 arrangements in which the first 66 sequences were used for the young participants, and the first 33 sequences were used for the older participants. All testing was conducted in a quiet room either at La Trobe University or U3A, where only the participant and experimenter were present. All except the time estimation task were preceded by practice trials and total testing time took approximately 1 hour.

7.3.4 Data analysis

All analyses were performed using SPSS v. 25.0 (IBM Corp., Armonk, NY, USA). Data was screened for outliers on individual tasks and for any result indicating inconsistent performance across tasks. None were found. Bonferroni adjusted alpha levels of 0.0125 (.05/4) per digit span test and 0.025 (.05/2) per SS and Cod were applied to correct for multiple comparisons for the t-test and correlational analyses.

7.4 Results

Means and standard deviations were calculated for performance on all dependent measures for young and older adults. These results are presented in Table 2.

Table 2. Descriptive Statistics and Independent Samples T-Test for Mean Difference on Measures of Memory, Processing Speed, and Retrospective Time Estimation in Young and Older Adults

	Young Adults				Older Adults				Age-group Differences	
Measure	*N*	Range	*M*	*SD*	*N*	Range	*M*	*SD*	*p*	η^2
DS.Aud.FS	66	4-10	6.91	1.10	33	3-9	6.09	1.23	*0.001***	0.330
DS.Aud.BS	66	3-8	5.88	1.08	33	3-7	5.06	1.12	0.001**	0.279
DS.Vis.FS	66	4-9	6.56	1.15	31	4-11	5.87	1.45	0.013*	0.242
DS.Vis.BS	66	3-8	5.72	1.23	31	2-7	5.23	1.28	0.069	0.241
N-back	66	4-7	6.92	0.62	33	5-7	6.85	0.83	0.422	0.319
SS	66	24-60	39.54	7.69	33	16-48	28.42	7.05	<0.001**	0.549
Cod	66	37-121	78.73	13.09	33	31-91	53.55	12.59	<0.001**	0.575
Time Est (sec)	65	15.00-120.00	46.20	22.00	33	10.00-120.00	42.73	25.44	0.486	0.279

Note: DS.Aud.FS = Auditory Forward Digit Span, DS.Aud.BS = Auditory Backward Digit Span, DS.Vis.FS = Visual Forward Digit Span, DS.Vis.BS = Visual Backward Digit Span, SS=Symbol Search, Cod=Coding, Time.Est = Retrospective Time Estimation, i.e., Estimated duration of N-back task
** p <.01, *p <.05 (two-tailed, Bonferroni correction)

7.4.1 Relationships between measures of memory, processing speed, retrospective time estimation, and age

Correlational analyses on the entire sample were performed to investigate the strength, direction and significance of associations between measures of memory, processing speed, retrospective time estimation, and age. As our age distribution was not normally distributed and included two distinct age groups, correlational analyses using Spearman's Rank-Order Correlation was used to examine this.

Results revealed no significant correlation between retrospective time estimation and any measure of memory or processing speed. Furthermore, there were no significant correlations between age and time estimation (r_s = -.189). However, significant correlations were demonstrated between age, memory spans and speed performance, with shorter auditory and visual spans and slower speed performance associated with older age. Specifically, shorter auditory forward and backward span was weakly but significantly associated with older age (r_s = -.223, r_s = -.203, respectively). Furthermore, shorter visual forward span was weakly but significantly correlated with older age (r_s = -.213), and slower performance on the SS and Cod was significantly moderately correlated with older age (r_s = -.608, r_s = -.607, respectively). A full correlation table of age and all dependent measures is shown in Table 3.

Table 3. Spearman's Rank-Order Correlations between Measures of Memory, Processing Speed, and Retrospective Time Estimation

Measure	Age	DS.Aud FS	DS.Aud BS	DS.Vis FS	DS.Vis BS	*N*-back	SS	Cod	Time Est (Sec)
Age	-								
DS.Aud.FS	-.223*	-							
DS.Aud.BS	-.203*	.410*	-						
DS.Vis.FS	-.213*	.334**	.316**	-					
DS.Vis.BS	-.125	.250*	.361**	.347**	-				
N-Back	-.121	.205*	.239*	.156	.043	-			
SS	-.608**	.122	.171	.084	.213*	.041	-		
Cod	-.607**	.229*	.380**	.258*	.215*	.106	.657**	-	
Time Est (Sec)	-.189	.065	.070	.187	.144	-.018	.038	.124	-

Note: DS.Aud.FS = Auditory Forward Digit Span, DS.Aud.BS = Auditory Backward Digit Span, DS.Vis.FS = Visual Forward Digit Span, DS.Vis.BS = Visual Backward Digit Span, SS=Symbol Search, Cod=Coding, Time.Est = Retrospective Time Estimation, i.e., Estimated duration of N-back task in seconds

** *p* <.01, *p <.05 (two-tailed, Bonferroni correction)

7.4.2 Age-group differences in performance on measures of memory, processing speed, and retrospective time estimation

An independent-samples t-test was conducted to compare performance on measures of memory, processing speed, and retrospective time estimation between younger and older adults. Significant differences in performance between age groups were demonstrated on the auditory but not the visual digit span tasks, with younger adults demonstrating a significantly longer memory span compared to older adults on the auditory spans. Specifically, younger adults had a significantly larger auditory forward span compared to older adults ($p < .01$, $\eta^2 = .330$), but no significant differences were demonstrated in the visual forward span compared to older adults ($p < .05$, $\eta^2 = .013$). Furthermore, younger adults had a significantly larger auditory backward span compared to older adults ($p < .01$, $\eta^2 = .279$), though no significant difference between age groups was demonstrated on the visual backwards span ($p = .069$, $\eta^2 = .241$).

Results also revealed significant differences on the SS and Cod where younger adults demonstrated a faster processing speed compared to older adults ($p < .01$, $\eta^2 = .549$, $p < .01$, $\eta^2 = .575$, respectively). No significant differences between age groups were demonstrated on the *N*-back task in terms of accuracy ($p = .422$, $\eta^2 = .319$) or in retrospective time estimation ($p = .486$, $\eta^2 = .279$). These results are presented in Table 2.

7.5 Discussion

The aims of the current study were to assess performance on memory and processing speed measures in healthy young and older adults, and to investigate time estimation in a more novel way, from the viewpoint of retrospective time estimation of a short temporal interval of 85 seconds. The current study also aimed to explore how performance on memory and processing speed measures correlate to retrospective time estimation. Age group differences in performance on memory, processing speed and time estimation will first be discussed, followed by the relationship between memory and processing speed tasks with retrospective time estimation.

7.5.1 Age Group Differences in Memory, Processing Speed, and Time Estimation

Consistent with hypotheses and past research, memory span (forward and backward) as measured by the auditory digit span task was shorter in older adults compared to younger adults (Wechsler & De Lemos, 1981; Bopp & Verhaeghen, 2005; Elliot et al., 2011; Craik, Morris, & Gick, 1990; Foos & Wright, 1992). However, memory span as measured by the visual digit span, was not significantly different between young and older adults, which was not in line with hypotheses and past research (Craik, Morris, & Gick, 1990; Foos & Wright, 1992).Previous research often reports larger age-related effects for auditory backward memory span compared to forward memory spans (Bopp & Verhaeghen, 2005; Craik et al., 1990; Foos & Wright, 1992), which is not entirely reflective of results from the current study, with age differences seen in both the auditory forward and backward digit spans. It is important to note however, that although the older adults in the current study had normal or corrected-to-normal vision, they were not explicitly assessed for optimal hearing and auditory deficits. In addition, our older sample also had an average of three extra years of formal education compared to younger adults, and these two factors may provide an explanation for the comparable performance on the visual digit span task but the difference in performance on the auditory digit span. Indeed, higher levels of education have been suggested to ‘lower the load’ of cognitive tasks by conferring a greater ability to activate appropriate neural networks, and thus improve task performance (Archer, Lee, Qiu & Chen, 2018). Furthermore, from the viewpoint of theories which postulate an association between sensory and cognitive decline (Lindenberger & Baltes, 1994; Baltes & Lindenberger, 1997; Schneider & Pichora-Fuller, 2000), it is possible that sensory loss associated with the normal aging process contributed to the older adults having a shorter span on the auditory digit span tasks in the current study. More specifically, there may have been an indirect effect of uncorrected age-related hearing loss during the auditory digit span tasks which was not explicitly accounted for in the current study. Indeed, recent research reported no age group differences on the auditory forward and backward digit span tasks in a sample of healthy young and older participants who were matched on age-corrected performance IQ scores, years of education and were also audiometrically matched (Füllgrabe, Moore, & Stone, 2015).

Processing speed as measured with the WAIS SS and Cod was significantly different between groups, with older adults demonstrating a slower speed, in comparison to younger adults. This was in line with hypotheses and past research (Hoyer, et al., 2004; Gilmore, Spinks & Thomas, 2006) especially with regard to the SS and Cod which are WAIS clinical measures of processing speed, that are also heavily reliant on motor speed (Ebaid et al., 2017). In line with this, manual motor speed has been consistently reported to slow with increased age (Murata, et al., 2010; Ebaid et al. 2017). Elevated depression and anxiety symptoms are also often reported to impede cognitive performance in older populations (Beaudreau & O'hara, 2008; Beaudreau & O'Hara, 2009), however, it is interesting to note that our healthy older sample reported lower depression anxiety and stress scores than our younger adults, making negative affective issues unlikely to have impeded task performance in this case. As expected, scores on the *N*-back task were not significantly different between young and older adults, with both groups obtaining almost perfect total scores i.e., accurately detecting all 7 cases where the current image was the same as the image presented prior. As we have previously shown that threshold exposure time for healthy older adults to accurately identify visual stimuli is approximately 136ms (Ebaid et al., 2017) and 890ms to detect change between two visual arrays (Ebaid, Crewther, MacCalman, Brown, & Crewther, 2017), ceiling performance by both groups on the *N*-back was not a surprising finding.

Retrospective time estimation of the *N*-back task was not significantly different between young and older adults, with both groups underestimating the duration of the task, which was contrary to predictions. On average, older adults estimated that the task lasted 42 seconds, and younger adults estimated 46 seconds. As both groups substantially underestimated task duration, these results contradict past research which report that only older adults underestimate time (Carrasco et al., 2001; Craik & Hay, 1999) and as such, these results do not add credence to the *Internal Clock Hypothesis*. It is important to note that these earlier studies which explored age differences in interval time estimation made their participants aware prior to the task that they would have to estimate time. In doing so, these studies examined *prospective time estimation* and thus, participants could potentially consciously monitor time. In the current study, we examined *retrospective time estimation,* and participants were not given prior warning that they would have to estimate task duration, which may explain the discrepancy in findings between past and current research. In past research that reported younger adults demonstrating an overestimation or *lengthening effect* of reproduced temporal intervals, it has been attributed to the monotony of the task and decreased arousal due to boredom (Hicks & Allen, 1979; Treisman, 1963), and thus, the time interval was thought to be perceived as longer than objective time. The potential for mood and affective states such as boredom to influence the perception of time dates back to the early 1890's where William James wrote '*our feeling of time harmonizes with different mental moods'* (James, 1892), and is also implied in commonly understood phrases such as '*a watched pot never boils'*, or '*time flies when you're having fun*'. As participants in the current study obtained almost 100% accuracy on the *N*-back task, it is conceivable that they remained engaged, making it unlikely that their estimation of time was confounded by boredom or monotony of task. It may be the case that participants found the *N*-back task easy and/or rewarding, thus requiring less cognitive effort, and in turn perceiving the task as taking a shorter time. Indeed, the subjective duration of a task has been reported to be influenced by the amount of information processing resources required for accurate performance on the task (See Brown, 1997 for a review) with increased task complexity reported to lead to the increased perception of a temporal interval (Macar, Grondin, & Casini, 1994; Penney, Yim & Ng, 2014). Such reports may also be interpreted in the context of the *neural efficiency hypothesis* (Haier et al., 1988), in that if participants dedicated less neural resources to a task (suggesting more efficient processing), it is likely that estimates of task duration will be shorter than objective task duration. Interestingly, our time estimate results also contradict those found in Low et al. (2016), who measured retrospective time estimation of a similar, but easier *N*-back task, where *N*=0 i.e., participants were required to respond each time they saw a target stimulus instead of responding when the current image matched the one presented 1 stimulus earlier (as used in the current study). This was assessed in a clinical sample of stroke and TIA patients, and healthy controls (mean age = 55 years) in which the healthy controls were estimating that the task took an average of 86 seconds, which is strikingly close to actual task duration. However, the healthy participants in Low et al. (2016) may not be comparable to those from the current study, as requirement for participation was not comparable education to a university population nor were they continuing to engage in vocational education, as in the current study. Furthermore, participants in Low et al. (2016) were predominantly kin to the patients or recruited in response to flyers at the hospital from where the clinical sample was derived, and so it may be reasonable to assume that they were tested in circumstances that differed substantially from the current study, i.e., following their relative recently suffering a stroke or TIA. These factors may indicate that the two samples, though both neurologically healthy, are not comparable in other domains and thus, may play a part in the discrepancy in findings between studies.

7.5.2 The Relationship between Memory and Processing Speed with Retrospective Time Estimation.

Contrary to hypotheses, there were no significant relationships between memory and processing speed with retrospective time estimation. This also contradicts past research which demonstrated that a faster processing speed was correlated to more accurate ‘duration productions’ while more efficient executive function (in particular, set shifting and cognitive flexibility) as measured by the Wisconsin Card Sorting Test (WCST; Nelson, 1976) was the most reliable predictor of ‘duration reproduction’ (Baudouin et al., 2018). In the current study, we chose to use memory measures including the backward digit span and SS and Cod as correlative measures with retrospective time estimation, and thus, the difference in tasks may also explain the difference in findings between the current study and Baudouin et al. (2018). Further, it is important to note that the discrepancy between results from the current study and past research by Baudouin et al. (2018) is at least partly due to our study measuring retrospective time estimation, and not prospective time estimation. Indeed, it has been suggested that these two aspects of temporal estimation require different cognitive resources (Block & Zakay 1997; Pouthas & Perbal, 2004; Zakay & Block, 2004) with prospective time estimation suggested to rely on attentional resources and the ability to divide attention between the task and temporal information in order to keep track of time (Pouthas & Perbal, 2004), whereas retrospective time estimation or *remembered duration* is suggested to be a function of the amount of memory storage space available for events that occurred during a particular interval of time (Block, 2014). With this in mind, our results do not support the suggestion that accurate retrospective time estimation is reliant on implicit memory storage, with no significant correlation found between retrospective time estimation and any explicit memory span task. A recent study conducted by Polti, Martin and van Wassenhove (2018) with 24 healthy young adults also demonstrated the effect of attention and WM load during four *N*-back conditions (i.e., 0, 1,2 and 3 back) on prospective time estimation. Results showed that paying attention to time duration lengthens subjective duration and that dividing attention between monitoring time and concurrent WM task shortens perceived duration. However, these findings were not replicated in the current study.

7.5.3 Limitations

The generalizability of our study is limited in relation to other populations who may not have comparable education levels in both young and older samples. This is particularly the case for older adults where years of education is reported to potentially protect against cognitive decline and forms of dementia in later years in life (Armstrong et al., 2012; Zhang et al., 1990). Specifically, the older adults who were recruited from U3A have continued to engage in vocational study post-retirement, and thus, may not be representative of the general population of older adults over 60. In addition, given that we did not conduct explicit audiometric screens for our older participants, it may be the case that deficits in auditory processing impacted the results, given the prevelence of deficits in auditory processing that occurs with normal aging (Lindenberger & Baltes, 1994; Baltes & Lindenberger, 1997). Thus, future research should aim to include audiometric screening tests when conducting similar cognitive research. Furthermore, as retrospective time estimation of temporal intervals in the seconds to minutes range remains an understudied area of research with healthy older populations, it may be useful to further examine using several conditions where task demands and complexity are manipulated, and in more ecologically valid contexts.

7.5.4 Conclusions and Future Directions

The current study extended findings arising from cognitive aging literature, in that auditory memory span and processing speed tasks decline with age, but not in conditions with decreased cognitive load i.e., in our *N*-back condition where *N* was equal to 1 (Kato et al., 2016), and stimuli were presented for adequate durations to allow encoding and memory. These results should inform areas of cognitive aging research with a particular focus on the aspects of cognitive processing that may be susceptible to aging, and which aspects may remain intact in a healthy older population. Our study was novel in examining retrospective time estimation of a relatively short temporal duration (85 seconds), with educated healthy older adults, comparable to our younger sample of university students. Our participants were not pre-warned that they would be asked to reflect and estimate the duration of a recent time interval, and so our results are unique in providing preliminary insight into retrospective time estimation, bearing in mind that the task loses validity if participants are asked to estimate time on several occasions. We showed that both young and older populations substantially underestimated time when asked to estimate the duration of a simple task when no prior warning was given before commencement of the task. Our study revealed no significant correlations between memory and processing speed, and retrospective time estimation which differs substantially from previous research into estimation of a temporal interval and healthy aging. Future research is needed to uncover the memory processes that are unique to accurately estimating time in this manner, and the factors that may be contributing to such underestimations of time.

7.6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7.7 Author Contributions

The study was initiated by SGC who also designed the outline and content. DE recruited participants and collected the data. Both DE and SGC analyzed the data and contributed to the writing.

7.8 Ethical Statement

This study was carried out in accordance with the recommendations of the National Statement on Ethical Conduct in Human Research, La Trobe University Human Ethics Committee (UHEC), with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by La Trobe University Human Ethics Committee, approval number S15/19.

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7.11 References

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General, 135*(2), 298-313.

Archer, J. A., Lee, A., Qiu, A., & Chen, S. A. (2018). Working memory, age and education: A lifespan fMRI study. *PloS One, 13*(3), e0194878.

Armstrong, M. J., Naglie, G., Duff-Canning, S., Meaney, C., Gill, D., Eslinger, P. J., . . . Marras, C. (2012). Roles of education and IQ in cognitive reserve in Parkinson's Disease-Mild Cognitive Impairment. *Dementia & Geriatric Cognitive Disorders Extra*, *2*(1), 343-352. doi:10.1159/000341782

Babcock, R. L., Laguna, K. D., & Roesch, S. C. (1997). A comparison of the factor structure of processing speed for younger and older adults: Testing the assumption of measurement equivalence across age groups. *Psychology & Aging, 12*(2), 268–276. doi:10.1037/0882- 7974.12.2.268.

Babcock, R. L., & Salthouse, T. A. (1990). Effects of increased processing demands on age differences in working memory. *Psychology & Aging, 5*(3), 421-428.

Baddeley, A. (1986). *Working Memory*. Oxford, UK: Clarendon Press.

Baddeley, A. (2007). *Working memory, thought, and action*. Oxford: Oxford University Press.

Baddeley, A., Eyesnck, M. W., & Anderson, C. A. (2009). *Memory*. New York: Psychology Press.

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In H. B. Gordon (Ed.), *Psychology of Learning & Motivation* (Vol. Volume 8, pp. 47-89): Academic Press.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology & Aging, 12*(1), 12-21. doi:Doi 10.1037/0882-7974.12.1.12

Baudouin, A., Isingrini, M., & Vanneste, S. (2018). Executive functioning and processing speed in age-related differences in time estimation: a comparison of young, old, and very old adults. *Aging, Neuropsychology, & Cognition*, 1-18.

Bergmann, K., Schubert, A. L., Hagemann, D., & Schankin, A. (2016). Age-related differences in the P3 amplitude in change blindness. *Psychological Research, 80*(4), 660-676. doi:10.1007/s00426-015-0669-6

Beaudreau, S. A., & O'hara, R. (2008). Late-life anxiety and cognitive impairment: a review. *The American Journal of Geriatric Psychiatry, 16*(10), 790-803.

Beaudreau, S. A., & O'Hara, R. (2009). The association of anxiety and depressive symptoms with cognitive performance in community-dwelling older adults. *Psychology & Aging, 24*(2), 507-512. doi: 10.1037/a0016035

Block, R. A., Zakay, D., & Hancock, P. A. (1998). Human aging and duration judgments: A meta-analyticreview. *Psychology & Aging, 13*(4), 584–596. doi:10.1037/0882-7974.13.4.584

Block, R. A. (2014). *Cognitive Models of Psychological Time*: Psychology Press.

Bopp, K. L., & Verhaeghen, P. (2005). Aging and verbal memory span: a meta-analysis. *The Journals of Gerontology: Series B, 60*(5), P223-233. Brown, S. W. (1997). Attentional resources in timing: Interference effects in concurrent temporal and nontemporal working memory tasks. *Perception & psychophysics, 59*(7), 1118-1140.

Brown, L. A., & Brockmole, J. R. (2010). The role of attention in binding visual features in working memory: Evidence from cognitive ageing. *The Quarterly Journal of Experimental Psychology, 63*(10), 2067-2079. doi:10.1080/17470211003721675

Carrasco, M., Bernal, M., & Redolat, R. (2001). Time estimation and aging: a comparison between young and elderly adults. *The International Journal of Aging & Human Development, 52*(2), 91-101.

Casini, L., & Macar, F. (1997). Effects of attention manipulation on judgments of duration and of intensity in the visual modality. *Memory & Cognition, 25*(6), 812-818.

Cornelis, C., De Picker, L. J., Hulstijn, W., Dumont, G., Timmers, M., Janssens, L., . . . Morrens, M. (2014). Preserved Learning during the Symbol-Digit Substitution Test in Patients with Schizophrenia, Age-Matched Controls, and Elderly. *Frontiers in Psychiatry, 5*, 189. doi:10.3389/fpsyt.2014.00189

Coull, J. T., Cheng, R. K., & Meck, W. H. (2011). Neuroanatomical and neurochemical substrates of timing. *Neuropsychopharmacology, 36*(1), 3.

Cowan, N. (1998). Visual and auditory working memory capacity. *Trends in Cognitive Sciences, 2*(3), 77. doi:10.1016/S1364-6613(98)01144-9

Cowan, N., Kilb, A., Saults, J., & Naveh-Benjamin, M. (2006). Life-Span Development of Visual Working Memory: When Is Feature Bindinq Difficult? *Developmental Psychology, 42*(6), 1089.

Craik, F. I., & Hay, J. F. (1999). Aging and judgments of duration: Effects of task complexity and method of estimation. *Attention, Perception, & Psychophysics, 61*(3), 549-560.

Craik, F. I., Morris, R. G., & Gick, M. L. (1990). Adult age differences in working memory. *Neuropsychological Impairments of Short-Term Memory*, 247.

Crewther, S. G., Lamp, G., Goodin, P., Laycock, R., & Crewther, D. (2018, May). *Cerebellum added to working memory networks revealed by meta-analysis of activation likelihood estimation of fMRI sites in n-back tasks {abstract}. Poster presented at the Vision Science Society (VSS) 18th Annual Meeting,* St Pete Beach, Florida. Abstract retrieved from http://visionsciences1.org/vss_public/core_routines/view_abstract_no.php?show_close_window=yes&abstractno=1352

Ebaid, D. & Crewther, S.G., MacCalman, K., Brown, A., & Crewther, D. P. (2017, November) Speed of information processing for simple visual perceptual and salient cognitive tasks in young and older adults. Poster presented at *the 7th Australasian Cognitive Neuroscience Society Conference (ACNS),* Adelaide, South Australia. Abstract retrieved from http://www.acns.org.au/sites/default/files/2017ACNSConferenceProceedings_withISBN.pdf

Ebaid, D., Crewther, S. G., MacCalman, K., Brown, A., & Crewther, D. P. (2017). Cognitive processing speed across the lifespan: Beyond the influence of motor speed. *Frontiers in Aging Neuroscience, 9,* 62. doi:10.3389/fnagi.2017.00062

Elliott, E. M., Cherry, K. E., Brown, J. S., Smitherman, E. A., Jazwinski, S. M., Yu, Q., & Volaufova, J. (2011). Working memory in the oldest-old: evidence from output serial position curves. *Memory & Cognition, 39*(8), 1423-1434.

Enns, J. T. (2004). *The thinking eye, the seeing brain : explorations in visual cognition*. New York: New York : W.W. Norton.

Feifel, H. (1957). Judgment of time in younger and older persons. *Journal of Gerontologym 12*(1) 71-74.

Foos, P. W., & Wright, L. (1992). Adult age differences in the storage of information in working memory. *Experimental Aging Research, 18*(1-2), 51-57. doi:10.1080/03610739208253911

Friedman, W. J., & Janssen, S. M. J. (2010). Aging and the speed of time. *Acta Psychologica, 134*(2), 130-141. doi:https://doi.org/10.1016/j.actpsy.2010.01.004

Füllgrabe, C., Moore, B. C., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience, 6*, 347.

Gazzaley, A., Sheridan, M. A., Cooney, J. W., & D'Esposito, M. (2007). Age-related deficits in component processes of working memory. *Neuropsychology*, *21*(5), 532-539. doi:10.1037/0894-4105.21.5.532

Haier, R. J., Siegel, B. V., Nuechterlein, K. H., Hazlett, E., Wu, J. C., Paek, J., . . . Buchsbaum, M. S. (1988). Cortical Glucose Metabolic-Rate Correlates of Abstract Reasoning and Attention Studied with Positron Emission Tomography. *Intelligence, 12*(2), 199-217. doi:Doi 10.1016/0160-2896(88)90016-5

Hammar, Å., & Årdal, G. (2009). Cognitive functioning in major depression-a summary. *Frontiers in Human Neuroscience*, *3,* 26.

Harrington, D. L., Haaland, K. Y., & Hermanowitz, N. (1998). Temporal processing in the basal ganglia. *Neuropsychology*, *12*(1), 3.

Harrington, D. L., Lee, R. R., Boyd, L. A., Rapcsak, S. Z., & Knight, R. T. (2004). Does the representation of time depend on the cerebellum? Effect of cerebellar stroke. *Brain, 127*(3), 561-574.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *Psychology of Learning & Motivation, 22*, 193-225.

Hester, R. L., Kinsella, G. J., & Ong, B. (2004). Effect of age on forward and backward span tasks. *Journal of the International Neuropsychological Society, 10*(4), 475-481. doi:10.1017/S1355617704104037

Hicks, R. E., & Allen, D. A. (1979). The repetition effect in judgments of temporal duration across minutes, days, and months. *The American Journal of Psychology*, 323-333.

Hilbert, S., Nakagawa, T. T., Puci, P., Zech, A., & Bühner, M. (2014). The Digit Span Backwards task. *European Journal of Psychological Assessment, 31,* 174-180. https://doi.org/10.1027/1015-5759/a000223

Ivry, R. B., & Schlerf, J. E. (2008). Dedicated and intrinsic models of time perception. *Trends in cognitive sciences*, *12*(7), 273-280.

James, W. (1892). The stream of consciousness. *Psychology*.

Joubert, C. E. (1990). Subjective expectations of the acceleration of time with aging. *Perceptual and Motor Skills, 70*(1), 334.

Joy, S., Kaplan, E., & Fein, D. (2004). Speed and memory in the WAIS-III Digit Symbol--Coding subtest across the adult lifespan. *Archives of Clinical Neuropsychology, 19*(6), 759-767. doi:10.1016/j.acn.2003.09.009

Kato, K., Nakamura, A., Kato, T., Kuratsubo, I., Yamagishi, M., Iwata, K., & Ito, K. (2016). Age-related changes in attentional control using an N-Back working memory paradigm. *Experimental Aging Research, 42*(4), 390-402. doi:10.1080/0361073X.2016.1191867

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*(4), 352-358.

Kirova, A. M., Bays, R. B., & Lagalwar, S. (2015). Working memory and executive function decline across normal aging, mild cognitive impairment, and Alzheimer's disease. *Biomed Research International*, 748212. doi:10.1155/2015/748212

Lewis, P. A., & Miall, R. C. (2003). Brain activation patterns during measurement of sub- and supra-second intervals. *Neuropsychologia, 41*(12), 1583-1592.

Licht, D., Morganti, J. B., Nehrke, M. F., & Heiman, G. (1986). Mediators of estimates of brief time intervals in elderly domiciled males. *The International Journal of Aging and Human Development, 21*(3), 211-225.

Lichtenberger, E. O., & Kaufman, A. S. (2009). *Essentials of WAIS-IV assessment* (Vol. 50): John Wiley & Sons.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: a strong connection. *Psychology & Aging, 9*(3), 339-355

Lindenberger, U., Mariske, M., & Baltes, P. B. (2000). Memorizing while walking: Increase in dual-task costs from young adulthood to old age. *Psychology & Aging, 15*(3), 417. doi:10.1037//0882-7974.15.3.417

Livesey, A. C., Wall, M. B., & Smith, A. T. (2007). Time perception: manipulation of task difficulty dissociates clock functions from other cognitive demands. *Neuropsychologia, 45*(2), 321-331.

Low, E., Crewther, S. G., Perre, D. L., Ong, B., Laycock, R., Tu, H., & Wijeratne, T. (2016). Beyond neglect: preliminary evidence of retrospective time estimation abnormalities in non-neglect stroke and transient ischemic attack patients. *Scientific Reports, 6*, 22598.

Lovibond, S. H., & Lovibond, P. F. (1995). Manual for the depression anxiety stress scale (2nd ed.). Sydney: Psychology Foundation of Australia.

Luszcz, M. A., & Lane, A. P. (2008). Executive function in cognitive, neuropsychological, and clinical aging. In S. M. Hofer, D. F. Alwin, S. M. Hofer, & D. F. Alwin (Eds.), Handbook of cognitive aging: Interdisciplinary perspectives (pp. 193–206). Thousand Oaks, CA: Sage Publications, Inc. doi:10.4135/9781412976589.n12

Macar, F., Grondin, S., & Casini, L. (1994). Controlled attention sharing influences time estimation. *Memory & Cognition, 22*(6), 673-686.

Matthews, W. J., & Meck, W. H. (2016). Temporal cognition: Connecting subjective time to perception, attention, and memory. *Psychological Bulletin*, *142*(8), 865.

Mc Grath, J. J., & O'Hanlon Jr, J. F. (1968). Relationships among chronological age, intelligence, and rate of subjective time. *Perceptual & Motor Skills*, *26*(3_suppl), 1083-1088.

Mendelsohn, A. R., & Larrick, J. W. (2011). Reversing age-related decline in working memory. *Rejuvenation Research, 14*(5), 557-559. doi:10.1089/rej.2011.1247

Moore, T. L., Killiany, R. J., Herndon, J. G., Rosene, D. L., & Moss, M. B. (2006). Executive system dysfunction occurs as early as middle-age in the rhesus monkey. *Neurobiology of Aging, 27*(10), 1484-1493. doi:10.1016/j.neurobiolaging.2005.08.004

Moore, T. L., Schettler, S. P., Killiany, R. J., Herndon, J. G., Luebke, J. I., Moss, M. B., & Rosene, D. L. (2005). Cognitive impairment in aged rhesus monkeys associated with monoamine receptors in the prefrontal cortex. *Behavioural Brain Research, 160*(2), 208-221. doi:10.1016/j.bbr.2004.12.003

Murata, J., Murata, S., Hiroshige, J., Ohtao, H., Horie, J., & Kai, Y. (2010). The influence of age-related changes in tactile sensibility and muscular strength on hand function in older adult females. *International Journal of Gerontology, 4*(4), 180-183. doi:http://dx.doi.org/10.1016/j.ijge.2010.11.004

Nelson, H. E. (1976). A modified card sorting test sensitive to frontal lobe defects. *Cortex: A Journal Devoted To The Study Of The Nervous System And Behavior, 12*(4), 313–324. doi:10.1016/S0010- 9452(76)80035-4

Parra, M. A., Abrahams, S., Logie, R. H., & Sala, S. D. (2009). Age and binding within-dimension features in visual short-term memory. *Neuroscience Letters, 449*(1), 1-5. doi:10.1016/j.neulet.2008.10.069

Penney, T. B., Yim, E. N., & Ng, K. K. (2014). Distractor expectancy effects on interval timing. *Timing & Time Perception, 2*(1), 1-19.

Perbal-Hatif, S. (2012). A neuropsychological approach to time estimation. *Dialogues in Clinical Neuroscience*, *14*(4), 425.

Pouthas, V., & Perbal, S. (2004). Time perception depends on accurate clock mechanisms as well as unimpaired attention and memory processes. *Acta Neurobiologiae Experimentalis, 64*(3), 367-386.

Polti, I., Martin, B., & van Wassenhove, V. (2018). The effect of attention and working memory on the estimation of elapsed time. *Scientific Reports, 8*.

Puccioni, O., & Vallesi, A. (2012). Conflict resolution and adaptation in normal aging: the role of verbal intelligence and cognitive reserve. *Psychology & Aging, 27*(4), 1018-1026. doi:10.1037/a0029106

Rao, S. M., Mayer, A. R., & Harrington, D. L. (2001). The evolution of brain activation during temporal processing. *Nature Neuroscience, 4*(3), 317.

Read, C. A., Rogers, J. M., & Wilson, P. H. (2015). Working memory binding of visual object features in older adults. *Aging, Neuropsychology, & Cognition*, 1-19. doi:10.1080/13825585.2015.1083937

Rhodes, S., Parra, M. A., & Logie, R. H. (2015). Ageing and feature binding in visual working memory: The role of presentation time. *The Quarterly Journal of Experimental Psychology*, 1-15. doi:10.1080/17470218.2015.1038571

Salthouse, T. A. (1990). Working memory as a processing resource in cognitive aging. *Developmental Review, 10*(1), 101-124. doi:http://dx.doi.org/10.1016/0273-2297(90)90006-P

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

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. C. T. A. Salthouse (Ed.), The handbook of aging and cognition, 2nd ed (pp. 155-219). Mahwah, NJ, US: Lawrence Erlbaum Associates Publishers.

Smith, A., Taylor, E., Lidzba, K., & Rubia, K. (2003). A right hemispheric frontocerebellar network for time discrimination of several hundreds of milliseconds. *Neuroimage, 20*(1), 344-350.

Treisman, M. (1963). Temporal discrimination and the indifference interval: Implications for a model of the" internal clock". *Psychological Monographs: General and Applied, 77*(13), 1.

Tse, P. U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & Psychophysics*, *66*(7), 1171-1189.

Turgeon, M., Lustig, C., & Meck, W. H. (2016). Cognitive aging and time perception: Roles of bayesian optimization and degeneracy. *Frontiers in Aging Neuroscience, 8*, 102. doi:10.3389/fnagi.2016.00102

Vallesi, A. (2016). Dual-task costs in aging are predicted by formal education. *Aging Clinical and Experimental Research*, *28*(5), 959-964. doi:10.1007/s40520-015-0385-5

Vanneste, S., & Pouthas, V. (1995). Estimation temporelle prospective et rétrospective chez la personne âgée: comparaison avec le jeune adulte. *Bulletin de Psychologie*.

Vellage, A. K., Becke, A., Strumpf, H., Baier, B., Schonfeld, M. A., Hopf, J. M., & Muller, N. G. (2016). Filtering and storage working memory networks in younger and older age. *Brain & Behaviour, 6*(11), e00544. doi:10.1002/brb3.544

Wang, M., Gamo, N. J., Yang, Y., Jin, L. E., Wang, X. J., Laubach, M., . . . Arnsten, A. F. (2011). Neuronal basis of age-related working memory decline. *Nature, 476*(7359), 210-213. doi:10.1038/nature10243

Wearden, J. H., Wearden, A. J., & Rabbitt, P. M. (1997). Age and IQ effects on stimulus and response timing. *Journal of Experimental Psychology: Human Perception and Performance, 23*(4), 962.

Wechsler, D. (2008a). WAIS-IV administration and scoring manual. San Antonio, TX: The Psychological Corporation.

Wechsler, D. (2008b). WAIS-IV administration and scoring manual. San Antonio, TX: The Psychological Corporation.

Wechsler, D. (2008). Wechsler adult intelligence scale–Fourth Edition (WAIS–IV). *San Antonio, TX: NCS Pearson, 22*, 498.

Wechsler, D., & De Lemos, M. M. (1981). *Wechsler adult intelligence scale-revised*: Harcourt Brace Jovanovich.

Wiley, J., & Jarosz, A. F. (2012). Working Memory Capacity, Attentional Focus, and Problem Solving. *Current Directions in Psychological Science, 21*(4), 258-262. doi:doi:10.1177/0963721412447622

Wittmann, M. (2009). The inner experience of time. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1525), 1955-1967.

Woods, D. L., Kishiyama, M. M., Yund, E. W., Herron, T. J., Edwards, B., Poliva, O., ... & Reed, B. (2011). Improving digit span assessment of short-term verbal memory. *Journal of Clinical & Experimental Neuropsychology, 33*(1), 101-111.

Zakay, D., & Block, R. A. (2004). Prospective and retrospective duration judgments: an executive-control perspective. *Acta Neurobiologiae Experimentalis*, *64*(3), 319-328.

Zakay, D., Nitzan, D., & Glicksohn, J. (1983). The influence of task difficulty and external tempo on subjective time estimation. *Attention, Perception, & Psychophysics, 34*(5), 451-456.

Zhang, M., Katzman, R., Salmon, D., Jin, H., Cai, G., Wang, Z., . . . Levy, P. (1990). The prevalence of dementia and Alzheimer's disease in Shanghai, China: impact of age, gender, and education. *Annals of Neurology, 27*(4), 428-437.

chapter 8

08

CHAPTER 8

General Discussion

8.1 Summary of Objectives

The overall aim of the current thesis was to investigate cognitive processing in a healthy educated sample of older adults with a predominant focus on visual information processing from a systems neuroscience viewpoint. Accordingly, this thesis examined cognitive processing with a focus on visual attention, information processing speed, memory, and oculomotor function, in healthy educated samples of young and older adults, while accounting for sociodemographic factors and affective influences.

Although cognitive processing across the lifespan has received substantial consideration in the aging literature (Salthouse, 1996; Bergmann et al., 2016; Cona et al., 2013; Hedden & Gabrieli, 2004), with several theories put forward attempting to explain the decline seen in healthy aging, no single explanation can adequately and appropriately account for such declines. Furthermore, sociodemographic factors such as level of education and health status of apparently healthy populations, as well as biological markers of aging including changes to the sensory system i.e., vision and audition, changes to hypertension and immune responses including hypercortisolism associated with anxiety, are seldom considered or controlled for in previous cognitive aging research. There is however, vast biological literature associated with aging in the realm medical science, though this has not been adequately incorporated in cognitive aging research. Thus, the review chapter, along with the experimental segment of this thesis aimed to address the need for reconsideration and incorporation of the findings of biopsychosocial elements and psychoneuroimmunology to the construct of cognitive aging.

The participants in these studies were an educated population of adults aged between 18-81 years, recruited from a university population in Melbourne, Australia. To date, much of the research that examines cognitive performance between age groups has not considered time since completion of education, nor whether those older participants are currently engaged in ongoing education programs at the time of the experiment (Ball, et al., 2002; Baudouin, Isingrini & Vanneste, 2018). As the empirical chapters of this thesis considered such points, this enabled examination of cognitive performance of a healthy educated young and older population who were both enrolled in tertiary education at the time of participation in our experimental program. A clear and thorough understanding of the types of changes that occur in cognitive processing in healthy intellectually curious populations has important implications for (a) the types of cognitive assessments used with a clinical population, (b) the control groups used against clinical populations in neuroscientific research, and (c) will contribute to addressing the gaps in knowledge that exist within the aging neuroscience literature relating to the changes that occur to cognitive processing across the lifespan. Several objectives were raised to empirically address the principle aims of this thesis from a cognitive neuroscience viewpoint, as summarised below:

1. To compare cognitive processing speed in older adults to that in younger adults using traditional tests from the Processing Speed Index (PSI) of the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 2008) i.e., the Symbol Search (SS) and Coding (Cod), and on a computerised psychophysical task of perceptual speed independent of hand motor speed, i.e., the Inspection time (IT) task.

2. To examine whether performance on the SS and Cod is confounded by motor speed, and if so, how much of the variance in cognitive performance is motor driven?

3. To examine how age influences rate of visual information processing (specifically, threshold exposure time) when using computerised perceptual speed tasks varying in complexity and familiarity, while considering self-reported depression, anxiety, and stress symptoms.

4. To explore the contribution of oculomotor function (number of fixations, fixation durations, saccade durations) to visual information processing in young and older adults.

5. To investigate processing speed and memory performance when measured traditionally and as retrospective time estimation between young and older adults while considering self-reported depression, anxiety and stress symptoms.

6. To examine whether memory and processing speed correlated to retrospective time estimation in the seconds to minutes range.

8.2 Summary of Findings

8.2.1 Age and Cognitive Processing Speed

In Chapter 4, cognitive processing speed as measured with the SS and Cod subsets from the WAIS (Wechsler, 2008) was compared to that on a computerised psychophysical task, namely the Inspection Time (IT), in young adults (age range = 18 – 29 years) and older adults (age range = 40 – 81 years). Significant age-group differences were obtained for scores on the SS and Cod, where younger adults showed faster processing speed compared to the older adults. However, on the psychophysical IT task (Vickers, Nettelbeck & Willson, 1972), which is a measure of perceptual speed with no reliance on a speeded motor response, there was no significant difference in performance between young and older adults. This result implied that cognitive processing speed still declines in healthy aging when assessed with non-motor psychophysical tasks but not significantly or as rapidly as when assessed with paper-pencil measures such as tests from the WAIS.

8.2.2 Contribution of Motor Speed to WAIS Measures of Cognitive Speed

Chapter 4 also examined hand-motor speed and its correlation to performance on the SS, Cod, and the psychophysical IT task (Vickers, Nettelbeck & Willson, 1972) in young and older groups. Hand motor speed as measured with the Purdue Pegboard (Reddon, Gill, Gauk, & Maerz, 1988) demonstrated significant age-group differences, where the same group of older adults had a significantly slower motor speed compared to younger adults. Furthermore, when assessing the relationship between hand-motor speed to performance on the cognitive speed measures, significant moderate positive correlations were demonstrated between all Pegboard conditions and the SS and Cod, but not with the IT task. This result showed that faster hand-motor speed was significantly correlated to scores on the SS and Cod but not to performance on the IT. Taken together, these results demonstrated that hand motor speed contributes to the overall performance on WAIS-based measures of speed, even though these are seldom considered experimentally or clinically.

Chapter 4 also examined whether a significant difference in performance on the SS and Cod would remain after statistically controlling for motor speed. The significant differences between age-groups implies that although motor speed was significantly correlated to performance on the SS and Cod, it did not fully account for performance differences on the measures. Overall, the findings from Chapter 4 support the notion that cognitive processing speed declines with age, when assessed with WAIS measures (Salthouse, 1996), but also highlight the importance of accounting for motor speed when using such tools.

8.2.3 Age and Rate of Visual Information Processing

Chapter 5 investigated rates of visual attention and information processing on computerised perceptual speed tasks varying in complexity and familiarity, in similarly educated young and older adults (though with a more restricted age range compared to participants in Chapter 4) while also controlling for affective factors. Namely, tasks used included IT (Vickers, Nettelbeck & Willson, 1972), the CD (Becker, Pashler & Anstis, 2000; Rutkowski et al., 2003) and FastaReada (Elhassan, et al., 2015; Hecht et al., 2004). The IT task (Vickers, Nettelbeck & Willson, 1972) has long been considered a simple perceptual speed task with minimal requirements and demands on more complex cognitive abilities such as working memory, and executive function i.e., planning and problem solving (Vickers & Smith, 1986; Ritchie Tucker-Drob & Deary, 2014). The CD however, is considered a more complex perceptual speed task, with additional demands on working memory problem solving and decision making, in order to detect change between two rapidly presented visual arrays (Rutkowski et al., 2003). Chapter 5 demonstrated that older adults were slower, that is, required significantly longer threshold exposure time to discriminate and identify simple visual stimuli, and also required significantly longer to detect change between two visual arrays compared to younger adults. Interestingly, in the FastaReada measure of rapid reading, visual attention and processing speed, older adults performed as fast as younger adults despite the task requiring organized sequential shifts in attention via eye movements, continuous visual processing and access to working memory and semantic comprehension. These findings are line with those which suggest that when tasks require top-down processing i.e., based on observers expectations, older adults perform as fast and as accurately as younger adults, as opposed to when tasks require bottom-up processing i.e., requiring the inhibition of distractors and driven by salient differences among the features of the stimuli (Madden, 2007).

8.2.4 Age, Negative Affect, and Visual Information Processing

Chapter 5 also investigated self-reported depression, anxiety, and stress symptoms to determine whether they correlate with visual information processing in either age group. Findings from Chapter 5 demonstrated that negative affect was lower in the older adult sample compared to younger adults, which was in line with past literature indicating that older adults above 65 who are engaged in social activities have lower depressive symptoms (Glass et al., 2006), and that students in their first and second year of university report higher levels of negative affect compared to students in more advanced years (Bayram and Bilgel, 2008). Negative affect did not correlate with cognitive performance in the older sample, however, for the younger adults, correlation analyses revealed a small significant positive correlation between depression scores and performance on the CD task. This finding may be explained by a recent study conducted by Goodall et al. (2018) who found that currently depressed young adults aged between 12-25 years show poorer performance in the domains of visual memory, processing speed and reaction time. Though the cross-sectional nature of this study did not allow for inferences regarding causality of the relationship between negative affect and visual information processing in young adults, it was still an important finding.

8.2.5 Age and Oculomotor Function

Chapter 6 examined oculomotor functions including number of fixations, fixation duration, and saccade durations in young and older adults while text-reading and during a common objects/alphanumeric Rapid Automatic Naming (RAN) task. Chapter 6 also examined the contribution of oculomotor function to visuo-cognitive tasks i.e., the IT and CD. Again, Chapter 6 demonstrated that cognitive speed was slower in older adults compared to younger adults as indicated by the IT and CD. Findings from Chapter 6 also showed that there were no significant differences in number of visual fixations made during the reading task and alphanumeric conditions of the RAN, though younger adults fixated on the alphanumeric stimuli for significantly longer than the older adults. Further, findings demonstrated that older adults had a longer i.e., slower saccade latency in the objects and alphanumeric conditions of the RAN which contributes to knowledge relating to motor speed decline with age, particularly relating to the neural constructs that control motor movements in the parietal lobe which are also partly responsible for eye movements.

In Chapter 6, the effect of saccade duration was covaried to examine whether there would still be an age-group difference on the IT and CD tasks. Results showed that when subtracting the effect of saccade duration, this eradicated the age-group difference seen on the complex CD measure but not the simpler IT task. Findings from Chapter 6 provide further insight into oculomotor function with age, showing that oculomotor movements become slower as age increases, and this may underlie slowing in general cognitive processing on complex visuo-cognitive tasks seen in older age-groups.

8.2.6 Age, Processing Speed and Memory

Chapter 7 examined age-related differences in memory and processing speed using traditional speed measures from the PSI of the WAIS i.e., the SS and Cod, common measures of memory i.e., the forward and backward digit span (Wechsler, 2008), and an *N*-back task (Kirchener, 1958). Findings showed that older adults had a slower processing speed as indicated by the SS and Cod. Findings in Chapter 7 also demonstrated that forward and backward memory spans as measured by the auditory digit span task were shorter in older adults compared to younger adults. However, the difference between age-groups was not significantly different when assessed with the visual digit span. Further, performance on the *N*-back measure was not significantly different between age-groups. Collectively, these results suggest that speed of processing when measured with paper-pencil measures requiring a motor response is slower in healthy older adults, though memory and working memory performance do not always show age-group differences when assessed as a visual forward memory span and with a simple *N*-back measure.

8.2.7 Age and Retrospective Time Estimation

Chapter 7 also examined a more novel approach to memory by assessing retrospective time estimation of the duration of the *N*-back task between age groups, and explored whether it was associated with performance on processing speed and memory measures. Findings showed that duration of the *N*-back task was substantially underestimated in both young and older adults, with no significant differences in estimation between age-groups. Furthermore, Chapter 7 sought to determine whether retrospective time estimation was correlated to other cognitive measures of memory or processing speed. Findings showed that time estimation was not significantly correlated to any other measure of memory or processing speed, providing novel insight into retrospective time estimation between age groups and into the field of memory in general.

8.3 Theoretical and Clinical Implications of Findings

The current thesis has served to provide deeper knowledge of cognitive processing in healthy educated populations, as well as characterisations of factors that underlie cognitive slowing in healthy older adults. The studies within this thesis have also contributed to a newer systems neuroscience approach to cognitive aging. In addition, findings from this thesis have provided additional understanding of classical constructs of memory, which have implications for future research with healthy populations and individuals with neurological impairments. The findings summarised above also extend to current knowledge of the specific cognitive domains that show decline with age, as well as the way these areas of cognition are assessed in both clinical and healthy samples. Below are summaries of additional implications that were not documented in the experimental chapters.

8.3.1 Assessment of Cognition in Aging

Findings from this thesis demonstrated that when assessing cognitive speed in a healthy older population, motor speed is significantly correlated with scores when measured with WAIS-based speed tests (Wechsler, 2008). It is important to note the application of these findings to a clinical population i.e., in stroke populations where motor impairments are prominent (Langhorne, Coupar, & Pollock, 2009). Indeed, findings showed that psychophysical IT tasks can serve as effective tools in addition to paper-pencil measures of speed, whereby motor speed is not a confounding factor. Indeed, clinical measures to assess cognitive speed have shown little substantial change since the 1940's in which paper-pencil WAIS measures remain the most common clinical tool used in all populations (Wechsler, 2008). Many of the findings from this thesis have been deduced from psychophysical measures which vary in complexity and familiarity, and can serve as efficient, non-invasive and robust measures of visual-cognitive abilities and translate to any clinical population.

8.3.2 The Cognitive Dynamics of Information Processing in Aging

In examining particular elements of cognitive processing in an aged population, this thesis has employed novel psychophysical quantifications including measures of eye-gaze patterns in which traditional paper and pencil measures from the WAIS are not useful, given their reliance on gross cognitive abilities (Wechsler, 2008; Lichtenberger & Kaufman, 2012). Information processing remains a complex area of neuroscience particularly in an aging population. Moreover, even seemingly simple psychophysical tasks, such as the IT measure which was originally described as *"relatively immune from influence by higher cognitive activities or by motivational and social factors*" (Vickers & Smith, 1986, p. 609), requires many cognitive skills to ensure accurate performance. Indeed, the IT task requires rapid activation of transient attention, rapid visual processing and conscious perception of the object(s), access to lexical storage to recall the name of the object, and decision making when reporting which objects have been identified amongst the other possibilities. With consideration of this, the age-group differences in such measures found in Chapter 5 is not a surprising finding. Furthermore, it is likely that impairments in these so called *simple* cognitive processes, where correct performance requires embedding into visual short-term memory and conscious perception of what has been seen, contributes to decline in more complex tasks i.e., those seen on the CD measure.

8.3.3 A New Perspective of Cognitive Processing in Aging

This thesis has led to new perspectives of cognitive processing in healthy aging. Firstly, it is apparent that ‘cognitive task complexity’ is more appropriately conceptualised on a spectrum as *degrees of complexity*, instead of being dichotomised as distinctive categories (i.e., *simple,* or *complex tasks)*. As alluded to above, some of the ‘simplest’ psychophysical measures still require complex cognitive abilities especially ongoing working memory and decision making, though not to the same degree as other tasks i.e., the CD. However, these apparently simple cognitive abilities required during an IT task are still susceptible to neurological impairment and age-related decline (see Low, Crewther, Ong, Perre & Wijeratne, 2017). Furthermore, the brain as a number of interconnected functional networks lends support to the view that deficits in performance on such ‘simple’ IT tasks are likely linked to deficits in more complex tasks such as the CD (van den Heuvel & Sporns, 2013). These theoretical considerations are important in the context of cognitive assessment in both clinical and healthy populations.

8.3.4 The Role of Oculomotor Function in the Assessment of Cognition

Eye movements as non-invasive biobehavioral measures of cognition, can provide extensive understanding into (a) motor speed inferred by saccadic eye movements, and (b) attentional processing deduced from visual fixations. To date, no efficient neuropsychological measure of cognitive processing exists that can provide information relating to the application and deactivation of attention, speed of processing, and processing duration in the manner that eye movement patterns are able. Thus, utilisation of such measures in a clinical setting would likely serve as an efficient tool able to provide extensive insight into cognition in various clinical populations.

8.3.5 An Update to Theories of Cognitive Aging

With consideration of the findings from the critical review in Chapter 2 of this thesis and the conclusions from the experimental studies, this thesis highlights the need for a novel systems neuroscience approach to cognitive aging (see Figure 1). Specifically, the combined findings emphasise the need to encapsulate sensory changes, the biological markers of aging i.e., changes to hypertension, consideration of the unbalanced autonomic nervous system/immune responses to stress, as well as the cognitive changes deduced from behavioural task performance, thereby adding a novel psychoneuroimmunology perspective to cognitive aging. At present, no single theory has taken this approach to describe cognitive aging, and thus, doing so can enable holistic neurobiological conceptualisation of the changes that occur in information processing across the lifespan.

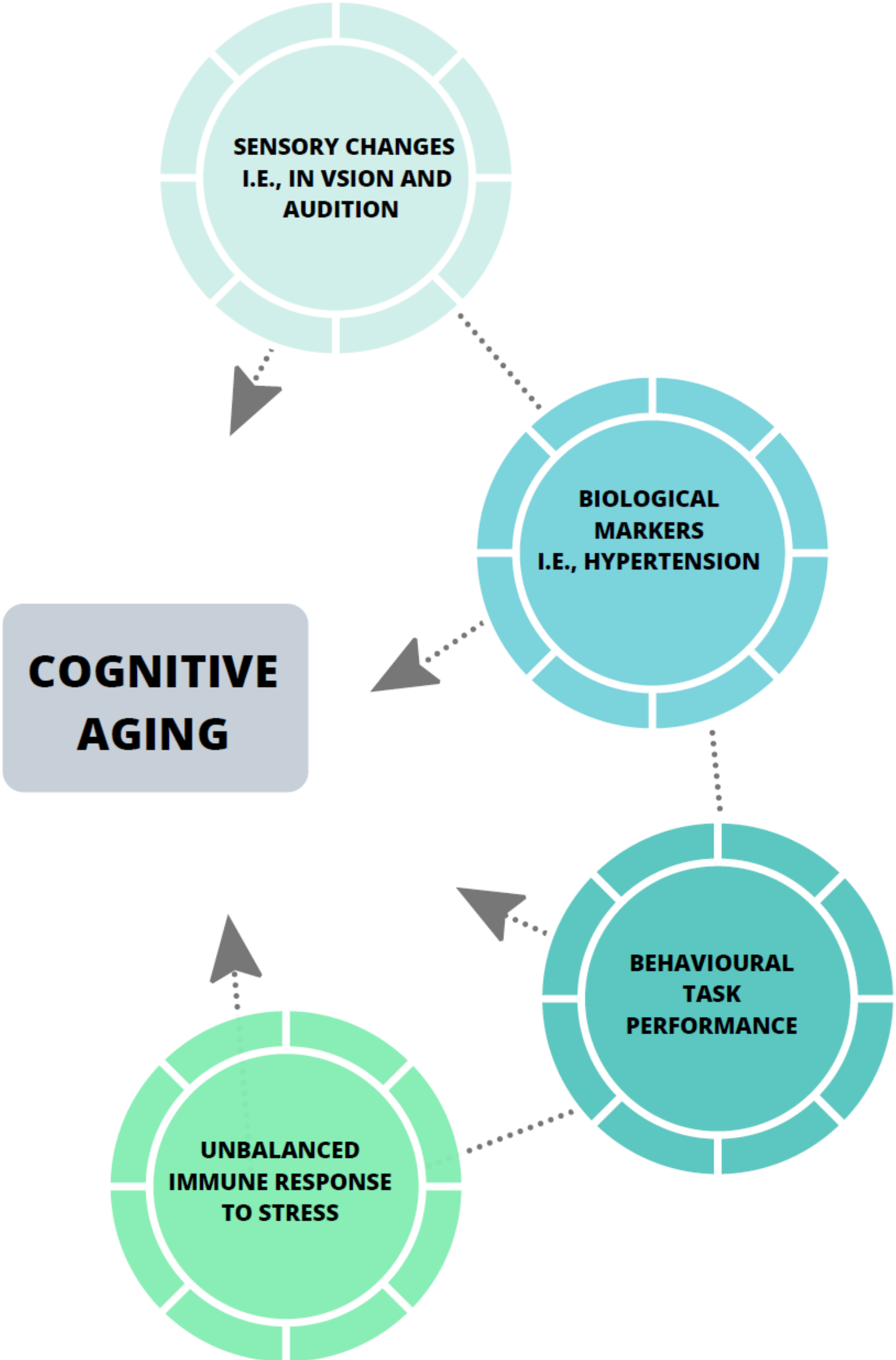

Figure 1. A psychoneuroimmunology viewpoint to cognitive aging.

8.4 General Limitations

8.4.1 Sample Size

The current study employed a large total sample of 107 participants, which were predominantly divided into two age groups, namely young adults (*N* = 67) and older adults (*N* = 40). In Chapters 5 and 7 however, participants aged between 30 and 59 were excluded from analyses in order to capture a *more representative* older adult participant pool. Though effective sizes were calculated for the validation of statistical results in all chapters (Tabachnick &Fidell, 2013), small sample sizes particularly in the older adult group may have compromised group-based findings. In addition, Chapter 6 which predominantly examined oculomotor function between age groups, included a smaller sample which were derived from the original full sample due to complications in the eye-gaze tracking device. Specifically, only 45 young participants and 22 older participants were included in Chapter 6, and this may have compromised the robustness of statistical findings.

8.4.2 Generalisability of Results

The study of cognitive processing in healthy aging broadly encapsulates any older participant aged 60 years and above (Salthouse, 2009), with no diagnosis of neuropathological disorder. Though the older participants utilised for the empirical chapters in this thesis fit such criteria, they were also highly educated, and still actively participating in vocational education. Given this, they may be considered an elite subset of older adults over 60 with high levels of motivation, and may not be representative of healthy older adults in the wider population. Likewise, the subset of younger adults were also undergraduate university students, and may not be representative of similar- aged young adults who are not enrolled in any tertiary education. Thus, caution should be taken when generalising results to other healthy populations who are not equally educated.

8.5 Future Research

While the studies within the current thesis have been important in identifying cognitive changes in relation to visual information processing, cognitive speed, memory and oculomotor function in an educated healthy young and older population, future research will be important in extending upon the current findings. Each empirical study includes suggestions for future research specific to their respective experiment in Chapter 4 to 7. This section includes some additional suggestions for future research and can be utilised in designing rapid and rigorous clinical measures for acute neurological assessment of patients.

8.5.1 Neurological Investigations

The utilisation of electrophysiology and brain imaging techniques would add additional confirmation to our understanding of the underlying neuroanatomical structures and neural mechanisms of information processing in a healthy educated sample. For example, Brown, Corner, Crewther, and Crewther (2018) used both flicker fusion thresholds as a critical measure of Magnocellular (M) pathway function and multifocal Visually Evoked Potentials (mfVEPS) to assess age related physiological and behavioural changes to the visual system. Brown et al. (2018) found that M and Parvocellular (P) pathway latencies increase with age, though the M generated peak latency increases are greater than associated P changes. Utilising such techniques with a healthy educated population may be beneficial for future research in understanding the role of the visual cortex in speed of information processing.

8.5.2 Sensory System Decline and Cognitive Performance

Previous literature has demonstrated that when sensory system integrity is matched between young and older adults, age-groups, differences in cognitive performance are no longer observed (Füllgrabe, Moore, & Stone, 2015). Specifically, Füllgrabe, Moore and Stone (2015) used a sample of audiometrically matched healthy young and older participants who were also matched on IQ scores and years of education and found no significant differences in auditory digit span performance between older and younger participants. Future research into cognitive performance between age-groups may benefit from utilizing such methods in relation to visual and auditory sensory integrity when matching their age groups.

8.5.3 Biological Measures of Anxiety and Cognitive Performance

Previous research has reported strong links between the biological response to anxiety and compromised cognitive performance (i.e., Gulpers et al., 2016). Though it was not within the scope of the studies within this thesis to utilise blood samples in order to investigate hormone levels alongside cognitive performance, future research may benefit from investigating such links to add further insight into the role of vascular anomalies in cognition across the lifespan. Interestingly, emerging research has suggested that human cortisol exposure can be measured by extracting cortisol from human hair (Raul, Cirimele, Ludes & Kintz, 2004; Staufenbiel, et al., 2013). The analysis requires a strand of hair cut from the scalp which is then extracted by methanol and further analysed by immunoassays or liquid chromatography (Gow, Koren, Rieder & Van Uum, 2011). Such methods may be a useful alternative to collecting and analysising blood, saliva or urine samples from participants when studying cortisol levels as a measure of anxiety in future cognitive aging research. Indeed, such data can provide further understanding into sympathetic and parasympathetic nervous system functioning and cellular and molecular mechanisms (McEwen, 2019) when assessing cognitive processing in a healthy population of older adults.

8.6 Conclusions

In summary, the research presented in this thesis investigated cognitive processing in healthy educated samples of young and older adults with a predominant focus on visual information processing from a systems neuroscience viewpoint of cognitive aging. The original research presented in the current thesis was designed to address six common limitations in the aging literature, which are:

1. No explicit consideration of the potential confounds of motor speed to paper-pencil tests of cognitive speed.
2. A dearth of robust tasks that are able to decipher specific aspects of cognitive processing.
3. A lack of comparable age-groups based on educational profiles
4. Limited investigation into affective influences on cognitive performance
5. Current cognitive aging research does not sufficiently incorporate biological markers of aging to explain their contribution to cognitive decline.
6. Eye movements as a surrogate measure of attention not being explored alongside robust cognitive tasks in older populations.

In addressing these limitations, the research has demonstrated that traditional WAIS-based measures of processing speed are contaminated by slowed motor speed in a healthy population. This research also demonstrated the usefulness and efficiency of psychophysical measures of varying complexity which provide insight into rates of visual attention, visual processing, and decision making without the confound of motor speed. In addition, findings from this thesis have provided new insight into adult age-differences in memory from a novel viewpoint by examining retrospective time estimation as a temporal measure of memory. Furthermore, oculomotor function alongside visuo-cognitive tasks were assessed as a surrogate measure of cognitive processing which provided new perspectives into factors that may be contributing to the general slowing of processing speed in a healthy population. Overall, the combined findings from this thesis have expanded understanding into cognitive processing in a healthy educated population and provided new perspectives in relation to assessment of cognition, and potential underlying contributors to areas of cognitive decline. Taken together, this thesis highlights the need for newer systems neuroscience approach to cognitive aging which considers the contribution of biological markers of aging to decrements in cognitive task performance. Such findings are important to consider experimentally and clinically, and can contribute to improving the accuracy and efficiency of experimental and clinical assessment of cognitive functions within the realm of neuroscientific research and neuropsychological healthcare.

8.7 References

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., ... & Unverzagt, F. W. (2002). Effects of cognitive training interventions with older adults: a randomized controlled trial. *The Journal of the American Medical Association*, *288*(18), 2271-2281.

Baudouin, A., Isingrini, M., & Vanneste, S. (2018). Executive functioning and processing speed in age-related differences in time estimation: a comparison of young, old, and very old adults. *Aging, Neuropsychology, & Cognition, 1*-18.

Bayram, N., & Bilgel, N. (2008). The prevalence and socio-demographic correlations of depression, anxiety and stress among a group of university students. *Social Psychiatry & Psychiatric Epidemiology*, *43*(8), 667-672.

Becker, M. W., Pashler, H., & Anstis, S. M. (2000). The role of iconic memory in change-detection tasks. *Perception, 29*(3), 273-286. doi: 10.1068/p3035

Bergmann, K., Schubert, A. L., Hagemann, D., & Schankin, A. (2016). Age-related differences in the P3 amplitude in change blindness. *Psychological Research, 80*(4), 660-676. doi:10.1007/s00426-015-0669-6

Brown, A. C., Corner, M., Crewther, D. P., & Crewther, S. G. (2018). Age related decline in cortical multifocal flash VEP: Latency increases shown to be predominately magnocellular. *Frontiers in Aging Neuroscience, 10*, 430.

Chan, C. Y. H., Chan, A. B., Lee, T. M. C., & Hsiao, J. H. (2018). Eye-movement patterns in face recognition are associated with cognitive decline in older adults. *Psychonomic Bulletin & Review*. doi:10.3758/s13423-017-1419-0

Cona, G., Bisiacchi, P. S., Amodio, P., & Schiff, S. (2013). Age-related decline in attentional shifting: Evidence from ERPs. *Neuroscience Letters, 556*, 129-134. doi:10.1016/j.neulet.2013.10.008

Elhassan, Z., Crewther, S., Bavin, E., & Crewther, D. (2015). Preliminary validation of FastaReada as a measure of reading fluency. *Frontiers in Psychology, 6*.

Füllgrabe, C., Moore, B. C., & Stone, M. A. (2015). Age-group differences in speech identification despite matched audiometrically normal hearing: contributions from auditory temporal processing and cognition. *Frontiers in Aging Neuroscience, 6*, 347.

Glass, T. A., De Leon, C. F. M., Bassuk, S. S., & Berkman, L. F. (2006). Social engagement and depressive symptoms in late life: longitudinal findings. *Journal of Aging & Health, 18*(4), 604-628.

Goodall, J., Fisher, C., Hetrick, S., Phillips, L., Parrish, E. M., & Allott, K. (2018). Neurocognitive functioning in depressed young people: A systematic review and meta-analysis. *Neuropsychology Review*, *28*(2), 216-231.

Gow, R., Koren, G., Rieder, M., & Van Uum, S. (2011). Hair cortisol content in patients with adrenal insufficiency on hydrocortisone replacement therapy. *Clinical Endocrinology*, *74*(6), 687-693.

Gulpers, B., Ramakers, I., Hamel, R., Köhler, S., Voshaar, R. O., & Verhey, F. (2016). Anxiety as a predictor for cognitive decline and dementia: a systematic review and meta-analysis. *The American Journal of Geriatric Psychiatry, 24*(10), 823-842.

Hecht, R., Crewther, D., & Crewther, S. (2004). Rate of learning and asymptotic performance in an automatization task and the relation to reading. *Perceptual & Motor Skills, 99*(2), 1103-1121. doi:10.2466/pms.99.3f.1103-1121

Hedden, T., & Gabrieli, J. D. (2004). Insights into the ageing mind: a view from cognitive neuroscience. *Nature Reviews Neuroscience, 5*(2), 87.

Langhorne, P., Coupar, F., & Pollock, A. (2009). Motor recovery after stroke: a systematic review. *The Lancet Neurology, 8*(8), 741-754.

Lichtenberger, E. O., & Kaufman, A. S. (2012). Essentials of WAIS-IV Assessment: Wiley.

Low, E., Crewther, S. G., Ong, B., Perre, D., & Wijeratne, T. (2017). Compromised motor dexterity confounds processing speed task outcomes in stroke patients. *Frontiers in Neurology*, *8*, 484.

Madden, D. J. (2007). Aging and visual attention. *Current Directions in Psychological Science, 16*(2), 70-74. doi:10.1111/j.1467-8721.2007.00478.x

McEwen, B. S. (2019). What Is the Confusion With Cortisol?. *Chronic Stress*, *3*, 2470547019833647.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*(4), 352-358.

Raul, J. S., Cirimele, V., Ludes, B., & Kintz, P. (2004). Detection of physiological concentrations of cortisol and cortisone in human hair. *Clinical Biochemistry, 37*(12), 1105-1111.

Reddon, J. R., Gill, D. M., Gauk, S. E., & Maerz, M. D. (1988). Purdue Pegboard: test-retest estimates. *Perceptual & Motor Skills, 66*(2), 503-506. doi:10.2466/pms.1988.66.2.503

Ritchie, S. J., Tucker-Drob, E. M., & Deary, I. J. (2014). A strong link between speed of visual discrimination and cognitive ageing. *Current Biology*, *24*(15), R681-R683.

Rutkowski, J. S., Crewther, D. P., & Crewther, S. G. (2003). Change detection is impaired in children with dyslexia. *Journal of Vision, 3*(1), 95.

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

Salthouse, T. A. (2009). When does age-related cognitive decline begin? *Neurobiology of Aging 30,* 507–514.

Staufenbiel, S. M., Penninx, B. W., Spijker, A. T., Elzinga, B. M., & van Rossum, E. F. (2013). Hair cortisol, stress exposure, and mental health in humans: a systematic review. *Psychoneuroendocrinology*, *38*(8), 1220-1235.

Tabachnick, B. G., & Fidell, L. S. (2013). *Using multivariate statistics* (6th ed.). Boston, MA: Pearson.

van den Heuvel, M. P., & Sporns, O. (2013). Network hubs in the human brain. *Trends in Cognitive Sciences*, *17*(12), 683-696.

Vickers, D., Nettelbeck, T., & Willson, RJ. (1972). Perceptual indices of performance: the measurement of ‘inspection time’and ‘noise’in the visual system. *Perception, 1*(3), 263-295.

Vickers, D., & Smith, P. L. (1986). The rationale for the inspection time index. *Personality and Individual Differences*, *7*(5), 609-623.

Wechsler, D. (2008). Wechsler Adult Intelligence Scale–Fourth Edition (WAIS–IV): San Antonio, TX: The Psychological Corporation.

APPENDICES

Appendix A – Research Ethics Approval

LA TROBE UNIVERSITY

COLLEGE OF SCIENCE, HEALTH & ENGINEERING

MEMORANDUM

To:	**Professor Sheila Crewther**
From:	**Secretariat, Human Ethics Sub Committee**
Subject:	**S15/19 - Review of Human Ethics Committee Application - Approved**
Title:	**Information Processing Across the Lifespan**
Date:	**10/04/2015**

Thank you for your recent correspondence in relation to the research project referred to above. The project has been assessed as complying with the *National Statement on Ethical Conduct in Human Research*. I am pleased to advise that your project has been granted ethics approval and you may commence the study now.

The project has been approved from the date of this letter until 31/12/2017.

Please note that your application has been reviewed by a sub-committee of the University Human Ethics Committee (UHEC) to facilitate a decision before the next Committee meeting. This decision will require ratification by the UHEC and it reserves the right to alter conditions of approval or withdraw approval at that time. You will be notified if the approval status of your project changes. The UHEC is a fully constituted Ethics Committee in accordance with the National Statement under Section 5.1.29.

The following standard conditions apply to your project:

- **Limit of Approval.** Approval is limited strictly to the research proposal as submitted in your application while taking into account any additional conditions advised by the Human Ethics Sub-committee (HESC) .

- **Variation to Project.** Any subsequent variations or modifications you wish to make to your project must be formally notified to the HESC for approval in advance of these modifications being introduced into the project. This can be done using the appropriate

- **Adverse Events.** If any unforeseen or adverse events occur, including adverse effects on participants, during the course of the project which may affect the ethical acceptability of the project, the Chief Investigator must immediately notify the HESC Secretary on at hesc.she@latrobe.edu.au. Any complaints about the project received by the researchers must also be referred immediately to the HESC Secretary.

- **Withdrawal of Project.** If you decide to discontinue your research before its planned completion, you must advise the HESC and clarify the circumstances.

- **Monitoring.** All projects are subject to monitoring at any time by the Human Ethics Sub- committee.

- **Annual Progress Reports.** If your project continues for more than 12 months, you are required to submit an *Ethics - Progress/Final Report Form* annually, **on or just prior to 12 February**. The form is available on the Research Services website (see above address). Failure to submit a Progress Report will mean approval for this project will lapse.

- **Auditing**. An audit of the project may be conducted by members of the HESC.

- **Final Report.** A Final Report (see above address) is required within six months of the completion of the project.

If you have any queries on the information above or require further clarification please contact me at hesc.she@latrobe.edu.au.

On behalf of the Faculty of Health Sciences Faculty Human Ethics Committee, best wishes with your research!

Ms Kate Ferris
Human Ethics
Officer
Secretariat – SHE College Human Ethics Sub-
Committee Ethics and Integrity / Research
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Appendix B – Research Study Participant Information Sheet

FHEC # S15/19____________

Participant ID______________

College of Science, Health and Engineering
SCHOOL OF PSYCHOLOGY AND PUBLIC HEALTH

INFORMATION PROCESSING ACROSS THE LIFESPAN

Participant Information Statement

Chief Investigators: Professor Sheila Crewther (Supervisor, s.crewther@latrobe.edu.au); Dr Ben Ong (Co-Supervisor, b.ong@latrobe.edu.au)

Co-Investigators: Miss Deena Ebaid (Doctor of Philosphy (PhD) candidate, debaid@students.latrobe.edu.au); Miss Taylah Suffredini (Honours Candidate, 16486565@students.latrobe.edu.au); Miss Kirsty MacCalman (Honours Candidate, kmmaccalman@students.latrobe.edu.au); Miss Molly Corner (Honours Candidate, mscorner@students.latrobe.edu.au); Miss Melanie Murphy (Associate Lecturer, m.murphy@latrobe.edu.au); Miss Essie Low (Doctor of Clinical Neuropsychology Candidate, s5low@students.latrobe.edu.au)

Past research has reported that attention, memory, and the way we process information is very different between age groups. The current study aims to examine how we process information across the lifespan by investigating temporal changes in behavioural responses and patterns of eye movements with age. Data gathered will provide new information on cognition across the lifespan, particularly whether changes occur in rapidity of cognitive responses as well as in motor responses and whether this also applied to eye movements. Slower less accurate patterns of eye movements may play a major role in the changes seen in attention with age.

How have you been identified and recruited? You may have responded to a flyer advertising this project or you may be part of the first year psychological science subject *History, Philosophy and Methodology of Psychological Science (HPM)* and chosen to participate in this study to meet a hurdle requirement for that subject. You may have also responded to an email or a phone call made by one of the investigators. You must be at least 17 years of age to participate in the study.

What will you be asked to do? If you agree to take part in this study, you will initially be asked to complete a simple questionnaire about yourself and a questionnaire about your mood. You will then be asked to participate in a range of simple memory and attention tasks such as puzzles and general knowledge quizzes. . At times, your eye-movements will be measured with an eye-gaze device, controlled by the investigator. The entire process will take approximately 50 minutes.
Please note that the current study is part of a larger study being conducted via Western Health (*Investigating Visual Attention Post-Stroke HREC /13/WH/105*), where stroke patients are recruited to investigate visual attention and processing using the same tasks. Therefore, the data collected from you may be used as a basis for comparison, to the data collected from the patients.

Are there any risks? There are no foreseeable risks associated with participation in the study. Your identity will remain anonymous, as your data and response sheets will be identified with a numeric ID. Short breaks will be encouraged and allowed at any time you like. If you have ever been diagnosed with a neurological disorder, you will be ineligible to participate. Given that cognitive abilities and attention shifting may be influenced by neurological disorders, these groups of patients will not be eligible to participate in the current study. Further, if you have a visual or hearing impairment that prohibits you from reading regular text, or listening to verbal instructions, it is not in your best interest to participate in the current study given that all of the tasks require reading and listening.

Will your information remain confidential and how will my data be used? Your identity will remain anonymous, as your data and response sheets will be identified with a numeric ID. Hard copies of the signed consent forms will be locked in a file cabinet in Biological Sciences Building 2, in a Neuropsychology Laboratory. Printed questionnaire data and consent forms will be kept in a file cabinet in the locked Neuropsychology Laboratory room for five years, which is required by law. After this period, they will be appropriately destroyed. Data arising from questionnaires will be de-identified prior to group analyse and will only be viewed by the project investigators and project Chief Investigator. Grouped data from the experiment however, will be written up as part of academic theses (PhD thesis, several Honours theses, and possibly an MPsych thesis). Furthermore, this data may be published as a journal paper. The de-identified SPSS data, may also be used in future similar experiments utilising different methodology and research conditions, however, this will only occur with your consent. The use of this data will hopefully add to the scientific literature in lifespan research and be used to increase future sample sizes of age groups.

How will the study benefit you? You may derive some benefit through this opportunity to see how psychological research is conducted. In general, this research will contribute to a wider body of knowledge about the variation in memory, attention, and information processing across the lifespan. Furthermore, as this study is part of the larger clinical study, data gathered from you will aid in comparing data gathered from the stroke population after performing the same tasks. Therefore, your participation will have significant contribution in informing better rehabilitation and recovery of stroke patients. As a reward for your participation, you may receive a $20 Coles-Myer gift voucher upon completion of the study. *Please note, if your participation is part of the requirement for first year psychology subject History, Philosophy and Methodology of Psychological*

Science (HPM) you will not be eligible for this reward, given that participation in research studies is a hurdle requirement.

Can I withdraw from the study? Your participation is completely voluntary and you have the right to withdraw from the study at any time. Within a period of four weeks, you may also request that the data collected from your participation not be used in the research project. In order to do this, you may complete the "Withdrawal of Consent Form" or directly contact the investigators by email or telephone, informing them that you wish to withdraw your consent for your data to be used in the study. The consent form will note your numerical ID which will allow for the easy findings of your data if you wish to withdraw it within the appropriate period after participating in the study. In doing this, there are no disadvantages, adverse consequences or penalties for prematurely withdrawing from the research study or not participating at all.

If you have any questions about this research study, you can contact any of the student investigators: (**Deena Ebaid:** debaid@students.latrobe.edu.au; **Taylah Suffredini** 16486565@students.latrobe.edu.au, **Molly Corner:** mscorner@students.latrobe.edu.au, **Kirsty MacCalman**: kmmaccalman@students.latrobe.edu.au) or our research supervisors (Professor Sheila Crewther, School of Psychological Science, Email: s.crewther@latrobe.edu.au, Tel: 9479 2290 or Dr. Ben Ong, School of Psychological Science, Email: b.ong@latrobe.edu.au; Tel: 9479 1119).

If you have any complaints or concerns about your participation in the study that the researcher has not been able to answer to your satisfaction, you may contact the Senior Human Ethics Officer, Ethics and Integrity, Research Office, La Trobe University, Victoria, 3086 (P: 03 9479 1443, E: humanethics@latrobe.edu.au) . Please quote the application reference number S15-19.

Appendix C – Participant Consent Form

LA TROBE UNIVERSITY

College of Science, Health and Engineering
SCHOOL OF PSYCHOLOGY AND PUBLIC HEALTH

INFORMATION PROCESSING ACROSS THE LIFESPAN

Consent Form

I (the participant) have read (or, where appropriate, have had read to me) and understood **the participant information statement and consent form,** and any questions I have asked have been answered to my satisfaction. I agree to participate in the project, realising that I may withdraw at any time. I agree that research data provided by me or with my permission during the project may be included in a thesis, presented at conferences and published in journals on the condition that neither my name nor any other identifying information is used.

☐ *Please check this box if you permit the data collected from you to be used in future similar studies or analyses.*

1. Name of Participant ____
   (block letters)

   Signature: ✗______________________________ Date: ____________

   Numerical ID: _________________________

2. Name of Investigator ____
   (block letters)

   Signature: ✗______________________________ Date: ___________

3. Name of Chief Investigator: Prof. SHEILA CREWTHER

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UNIVERSITY

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SCHOOL OF PSYCHOLOGY AND PUBLIC HEALTH

Consent for Eye Movement Tracker Data and Photography

I understand that eye-movement recordings are a crucial aspect to this study, and are being used as a measure of attention shifting, and speed of processing. I consent to have my eye-movements recorded and my eyes photographed for this purpose. I understand that these photographs and data will be reviewed by researchers at a later time for the purpose of data analysis. Stored data obtained by the eye-movement tracker will only be stored with participants' de-identified numeric ID and under no circumstance be stored with participants' name.

1. Name of Participant ____
(block letters)

Signature: ✗______________________________ Date: ____________

Numerical ID: _________________________

2. Name of Investigator ____
(block letters)

Signature: ✗______________________________ Date: ____________

3. Name of Chief Investigator: Prof. SHEILA CREWTHER

Appendix D – Participant Withdrawal of Consent Form

LA TROBE UNIVERSITY

College of Science, Health and Engineering
SCHOOL OF PSYCHOLOGY AND PUBLIC HEALTH

INFORMATION PROCESSING ACROSS THE LIFESPAN

Withdrawal of Consent

I, (the participant), wish to WITHDRAW my consent to the use of data arising from my participation. Data arising from my participation must NOT be used in this research project as described in the Information and Consent Form. I understand that data arising from my participation will be destroyed provided this request is received within four weeks of the completion of my participation in this project. I understand that this notification will be retained together with my consent form as evidence of the withdrawal of my consent to use the data I have provided specifically for this research project.

Name of Participant ____
(block letters)

Signature: ✘_____________________________

Date: ____________

Appendix E – FastaReada Script

It was night I was miles
from home in a lonely wrecker's
yard. Next to me was a
bus with the only remaining part
of my mother in it. Giant
slobbering worms were straining at the
battered yard gate, desperate to suck
out my bones. And what was
it that made me run blindly
into the darkness in terror? A
dog. Dawn the chicken, that's what
Rory would have called me. Well
he'd have been wrong. The dog
was a killer. It had a
savage snarl and huge teeth. Its
saliva had bubbles in it, not
from eating the soap, from being so
vicious. When it charged at me
with its huge jagged mouth wide
open. I ran to the Scary broken-down farm
equipment loomed out of the darkness
I crashed into something, scraping my
Arm on rusty metal. I kept
Running until I tripped and sprawled
Painfully in the dirt. I scrambled
Up, heart thumping. Expecting to see
Dog-food-stained teeth coming for my throat
At any second but the dog
was over by the gate, leaping
Up at the slithering tongues of
The giant worms. My heart slowed.
Down very fast the dog
Hadn't been going for me, it
Had been going for the slobberers.
There was enough moonlight for me
To see my hands trembling with
Relief, I felt scampering towards
Me.'rory? I tried to yell
But all that came out of
My throat was a parched croak.
I strained to see if it
Was rory, he was about as