THE EFFECT OF HIGHER ORDER LISTENING FUNCTION AND HEARING LOSS ON COGNITION IN OLDER ADULTS

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ABSTRACT

Grace Kellee Nixon: The Effect of Higher Order Listening Function and Hearing Loss on Cognition in Older Adults

INTRODUCTION: Previous research has identified a relationship between hearing loss and cognitive impairment/dementia in older adults, however this research has primarily focused on measures of sensorineural hearing loss (SNHL). Central Auditory Processing (CAP), an ability which decreases with increasing age, is recognised as important for understanding speech in background noise, but is not routinely considered in audiological assessment or hearing-cognition research. Yet, some studies have provided evidence that poorer performance on some measures of CAP ability significantly relate to reduced cognitive function and/or increased likelihood of dementia diagnosis. Although there is no known treatment for cognitive impairment, hearing impairment is to some extent treatable with hearing aids (HAs).

OBJECTIVES: This study aimed to examine the relationship between hearing impairment and cognitive impairment by assessing both peripheral hearing loss and CAP ability. Additionally, this research aimed to investigate how hearing, cognition and personal factors influence HA outcomes (uptake/use/benefit) in older adults.

DESIGN: Experimental study design with 85 older adults between the ages of 60.33 and 80.08 (*m =70.23, SD = 5.17*). SNHL was assessed using Pure Tone Audiometry (PTA), the Listening in Spatialised noise-Sentences (LiSN-S) test and Dichotic Digits Test. Cognition was measured using the Cogstate Brief Battery. Personal factors were recorded from participant’s answers on a series of take-home questionnaires. Hearing aid benefit and use was subjectively reported at three- and six-months post HA fitting.

RESULTS: Results for three of the four LiSN-S conditions shared a significant correlation with at least one cognitive measure, and SNHL was also significantly related to two cognitive domains (attention and executive function) in this cohort. Those who decided to use HAs had significantly poorer hearing as measured by both PTA and the LiSN-S test, and those with poorer hearing reported greater HA benefit. Lastly, stronger psychomotor function was associated with greater reported use of HAs at three- and six-months post HA fitting. Greater family interaction and attention scores also were associated with greater HA use at three- and six-months post fitting respectively.

IMPLICATIONS: The older hearing-impaired patient may present with a combination of hearing loss, decreased auditory processing ability and impaired cognitive ability. It may be prudent to consider the presence and possible interactions of multiple health conditions as well as psychosocial factors when determining the appropriate management pathway for and expectations of the patient. Future research should investigate longitudinal cognitive implications for patients presenting with a SP deficit. Also, for older adults presenting with a SP deficit, the benefits of early referral for cognitive assessment should be considered. Moreover, a combination of hearing, cognitive and psychosocial factors impact HA outcomes in older Australians. These factors should be considered in audiological rehabilitation to best maximise patient HA outcomes, and further research should consider the long-term clinical implications HA fitting has on natural cognitive decline in the elderly.

Mum, your love of literature, and Dad, your scientific mind - was an inevitable catalyst for writing a thesis.

To my Parents, Julie and Stuart.

For your unwavering support, in every aspect of life.

For giving me the opportunities, you never had yourselves.

DECLARATION

(i) the thesis comprises only my original work towards the Doctor of Philosophy except where indicated in the preface;

(ii) due acknowledgement has been made in the text to all other material used;

(iii) the thesis is fewer than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

January 2020

Grace Kellee Nixon

PREFACE

This dissertation is my original, independent work and, to the best of my knowledge, contains no material written by another person, except where due acknowledgement has been made.

The PhD candidate, Grace Kellee Nixon, was responsible for the development, preparation, and execution of the dissertation. The contribution of others as co-authors on publications is as follows: Julia Sarant assisted with critical revisions for all four publications presented in Chapters: 2.2, 5, 6.2 and 7. Dani Tomlin assisted with revision for all four publications presented in Chapters: 2.2, 5, 6.2 and 7; and Richard Dowell provided assistance with statistical analysis and revision for three publications pertaining to experiments 1, 2 and 3 (Chapters 5, 6.2 and 7).

The publication status for each of the results chapters is outlined below:

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Chapter 7	Submitted for publication to Journal of Speech, Language and Hearing Research, January 2020

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I do not know where to begin with thanking my supervisors. Richard, for remaining calm during the repetitive emails and stats advice, I am incredibly grateful. Big Bear – where do I start? Julia, you have provided me with so many lessons that extend beyond an academic career. Your door was not only open to questions regarding my PhD, but to anything (big or small) that you were able to help with. Thank-you. Dani, this journey would never have begun without your initial guidance and encouragement. You helped me down this path that I would never have thought I was capable of following. Not only that, but you walked with me every step of the way.

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As published works were included as part of this thesis, a continuous numbering system for table and figures was not feasible. Tables and figures have been numbered for each chapter.

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Acronyms

4FA	Four-frequency average
AD	Alzheimer’s dementia
AP	auditory processing
APHAB	abbreviated profile of hearing aid benefit
ARHL	age related hearing loss
CAP	central auditory processing
CAPD	central auditory processing disorder
dB HL	decibel hearing level
DDT	dichotic digits test
DF	degrees of freedom
GiN	gaps in noise
HA	hearing aid
HADS	hospital anxiety and depression scale
HI	hearing impaired
HFA	high frequency average
HUI	health utilities index
Hz	Hertz
IRSAD	Index of Relative Socioeconomic Advantage and Disadvantage
LiSN-S	Listening in Spatialised Noise Sentence
LFA	low frequency average
LSNS	Lubben social network scale
MCI	mild cognitive impairment
MCQ	memory complaint questionnaire
MMSE	mini mental state examination
pAD	probable Alzheimer’s dementia
PGA	prescribed gain amplifier
PTA	pure tone audiometry
SD	standard deviation
SES	socio-economic status
SNHL	sensorineural hearing loss
SNR	signal-to-noise ratio
SP	spatial processing
SPD	spatial processing deficit
SRT	speech reception threshold

CHAPTER 1 INTRODUCTION

1.1 PURPOSE

Hearing impairment and cognitive impairment are two adverse conditions that are highly prevalent in an ever-growing older population (Cruickshanks et al., 1998; Gurgel et al., 2014a; Hofman et al., 1991)**.** Previous research has indicated that these two chronic diseases share a relationship (Loughrey, Kelly, Kelley, Brennan, & Lawlor, 2018; Taljaard, Olaithe, Brennan-Jones, Eikelboom, & Bucks, 2016). The purpose of this research is to try to understand this relationship better by looking beyond the previous focus on peripheral hearing alone, and consider other factors that may impact the rehabilitation of hearing loss.

1.2 BACKGROUND

There are parallels between cognitive impairment and hearing loss. Both place a great level of financial and support burden on individuals and their families, as well as on the community (Access Economics, 2006; Gurgel et al., 2014a). Moreover, they are two prevalent disabilities that affect the aging population, with advancing age increasing the likelihood of people experiencing one or both conditions (Cruickshanks et al., 1998; Gurgel et al., 2014a; Hofman et al., 1991).

The parallels between hearing loss and cognitive decline encouraged exploratory research that found an independent association between the two conditions (Granick, Kleban, & Weiss, 1976; Lin, 2011a; Uhlmann, Larson, Rees, Koepsell, & Duckert, 1989; Wayne & Johnsrude, 2015). What remains unclear however, is *how* they are associated, with many hypotheses that attempt to explain the connection. The “sensory deprivation hypothesis” suggests that because of the reduced sensory input that accompanies hearing loss, cognitive deterioration occurs (Baltes & Lindenberger, 1997; Desjardins, 2016a; Lindenberger & Baltes, 1994a; Valentijn et al., 2005). Similarly, describing a direct causal relationship between hearing loss and cognition is the “resource allocation” or “information degradation” hypothesis, which postulates that individuals with sensory impairment require more attention and cognitive resources in order to interpret the degraded auditory signal which in turn impacts other cognitive functions (Committee on Hearing Bioacoustics and Biomechanics, 1988; Desjardins, 2016a; Pichora-Fuller, 2003; Schneider & Pichora-Fuller, 2000). The “common cause” hypothesis however, suggests that there are common causal mechanisms such as the degeneration of the central nervous system (Baltes & Lindenberger, 1997; Christensen, Mackinnon, Korten, & Jorm, 2001; Committee on Hearing Bioacoustics and Biomechanics, 1988; Lindenberger & Baltes, 1994a; Valentijn et al., 2005). Lastly, an alternative theory suggests that cognition is related to hearing loss only because the tests that assess cognition require sensory skills to be successfully performed (Gussekloo, de Craen, Oduber, van Boxtel, & Westendorp, 2005). When reviewing these hypotheses, it is difficult to conclude which is more probable. This may be complicated by the fact that other factors such as depression and social isolation have been shown to potentially mediate the relationship between hearing and cognition, and have not been considered as a significant part of any aforementioned hypothesis (Amieva et al., 2015). Nevertheless, research has consistently demonstrated an association between hearing loss and cognition. Given the prevalence of both disabilities and a growing elderly population, more extensive investigations of how and what aspects of hearing impairment impact cognition need to be undertaken to fully understand this complex relationship. Furthermore, a greater understanding of this relationship may provide clinicians with a deeper awareness of the multitude of challenges experienced by older adults and may help to inform a patient-centred approach to clinical practice.

Hearing impairment can occur on a peripheral and/or central level (Parham, Lin, Coelho, Sataloff, & Gates, 2013; Schneider, Pichora-Fuller, & Daneman, 2010). Initial research that explored an association between hearing loss and cognition, measured hearing loss on a peripheral level only (e.g. Granick et al. 1976; Gurgel et al., 2014; Lin et al., 2011). Additionally, current clinical assessment of hearing loss focuses predominantly on measures of peripheral hearing impairment. Generally, those with age-related hearing losses report difficulties listening in complex situations such as when background noise is present (Besser, Festen, Goverts, Kramer, & Pichora-Fuller, 2015; Glyde, Cameron, Dillon, Hickson, & Seeto, 2013; Kortlang, Mauermann, & Ewert, 2016). If a person experiences difficulty understanding speech in noisy environments but can perform normally in quiet, central auditory dysfunction is suspected (Glyde, Hickson, Cameron, & Dillon, 2011). This issue, known as central presbycusis, is thought to affect auditory structures such as the eighth nerve, the auditory brainstem and the auditory cortex (Stach, Spretnjak, & Jerger, 1990). In order to effectively communicate, cognitive systems and both peripheral and central auditory pathways need to be functioning effectively (Parham et al., 2013; Schneider et al., 2010). As such, if the relationship between hearing impairment and cognition is to be fully understood, how and which aspects of hearing impairment impact cognition need to be considered.

Central Auditory Processing (CAP) consists of the ability to use temporal and frequency discrimination, as well as binaural integration and interaction skills (Nelson & Soli, 2000; Picard & Bradley, 2001). Similar to cognitive and peripheral auditory ability, central auditory skills decline with age (Parham et al., 2013). Furthermore, like cognitive skills, CAP ability develops throughout childhood (Tomlin & Rance, 2016), contrasting with peripheral hearing which is mature by three-to-six months of age. Research has therefore considered the effect of central auditory dysfunction on cognition. As early as 1995, central auditory function was found to be significantly associated with dementia diagnosis (Gates et al., 1995). Since then, more specific areas of central processing such as temporal resolution and binaural integration have been examined and have been shown to predict the onset of Alzheimer's dementia (Gates, Anderson, McCurry, Feeney, & Larson, 2011; Iliadou et al., 2017). Knowing which aspects of central auditory processing are associated with cognitive decline will further provide a greater understanding of how hearing loss and cognition interact. It may also provide detail of the lived experiences of older adults presenting to audiology appointments, encouraging a change in clinical approach to extend beyond that of an audiogram when providing counselling and rehabilitation to hearing impaired individuals.

Understanding speech requires a multitude of brain functions beyond peripheral hearing (Gates, 2012; Royall et al., 2002). The ability to separate acoustic information into distinct streams is a major aspect of central auditory processing that allows us to interpret speech (Bregman, 1994; Glyde et al., 2013). The reduced ability to separate acoustic information into distinct streams is known as spatial processing dysfunction. Spatial processing ability has been shown to be affected by age to some degree, however its relationship to hearing impairment and cognition remains ambiguous (Glyde et al., 2011). Specifically, considering the Listening in Spatialised Noise-Sentences (LiSN-S) test as an assessment tool of spatial processing ability, there are no clear findings in available research on how spatial processing performance relates to factors that may influence cognition, such as age and other auditory processing skills (Besser et al., 2015; Cameron & Dillon, 2011; Glyde et al., 2013). Furthermore, there is little understanding of how to interpret results from the LiSN-S test battery with those for tests of cognitive function to determine how these may be related (Besser et al., 2015; Glyde et al., 2013), and whether in fact central auditory processing can be examined independently of the effects of SNHL and cognition.

Whilst there is no known cure for cognitive decline, hearing impairment to a certain extent can be addressed through the use of hearing aids or other amplification (Desjardins, 2016a; Kochkin & Rogin, 2000; Meister, Rählmann, Walger, Margolf-Hackl, & Kießling, 2015b). However, research on how hearing aid use is related to slowing cognitive decline and auditory processing skills is limited and contradictory. It appears however that hearing aid use does positively impact short term cognitive skills (Dawes et al., 2015; Desjardins, 2016a; Doherty & Desjardins, 2015; Kalluri & Humes, 2012). The same studies suggest that cognitive improvement from hearing aid use is not sustained in the longer term. Conversely, one recent longitudinal study discovered that hearing aid users' cognitive performance was similar to that of normally-hearing participants (Amieva et al., 2015). Whether those with poorer cognitive function use hearing aids differently has not yet been explored. Early studies concluded that central processing deficits may impact the effectiveness of hearing aid use (Chmiel & Jerger, 1996). Additionally, cognition has been shown to be connected to how hearing aid users listen in complex situations (Henkin, Waldman, & Kishon-Rabin, 2007; Neher et al., 2009; Rudner, Foo, Rönnberg, & Lunner, 2009). Uncertainty remains regarding how peripheral and central hearing impairment, cognition and hearing aid use are related.

1.3 OVERVIEW OF THIS RESEARCH

The overall objective of this thesis was to investigate the relations between different domains of cognition and hearing impairment as measured both peripherally (using PTA) and centrally (using tests of auditory processing) in addition to assessing how these factors influenced hearing aid use, benefit and/or uptake. As such, the following objectives were defined:

1. To assess the relationship between peripheral hearing, auditory processing skills and cognition in an older population.
2. To investigate whether those with impaired auditory processing ability in addition to peripheral hearing impairment had poorer cognitive skills than did those with peripheral hearing impairment alone.
3. To evaluate the impacts of the three outcome variables (cognition, peripheral hearing and central auditory processing ability) in addition to personal factors (e.g. psychosocial differences), on use, perceived benefit and/or uptake of hearing aids.

1.3.1 Study 1: The Relationship between Peripheral Hearing Loss, Higher Order Listening Function and Cognition in Older Australians.

The first study explored the relationship between peripheral hearing, central auditory processing and cognition. Previous results have indicated that peripheral hearing loss (typically defined by PTA measures) and cognitive impairment are associated (Taljaard et al., 2016). Furthermore, research has also consistently demonstrated that cognitive impairment is related to poorer central auditory processing ability as measured by tasks of binaural integration (Gates, Anderson, Feeney, McCurry, & Larson, 2008a; Gates et al., 2011). This study investigated whether central auditory processing ability as measured by tests of binaural integration (the Dichotic Digits Test) and/or binaural interaction/spatial processing (the Listening in Spatialised Noise-Sentences test), and/or peripheral hearing (measured by Pure Tone Audiometry and categorised into low, mid and high frequency averages) were related to any of the following domains of cognition: executive function, attention, psychomotor function, visual learning and working memory. The hypothesis was that there would be a positive relationship between poorer scores on the cognitive test battery and: 1) increased level of peripheral hearing impairment, and 2) decreased binaural integration and spatial processing performance measures.

1.3.2 Study 2: Spatial Processing Ability and Executive Function in Older Australians.

The second study investigated group differences in cognitive performance between those presenting with both a central auditory processing deficit and peripherally measured hearing impairment, and those presenting with a peripherally measured hearing impairment alone. Much of the research on the relationship between hearing and cognition has focused on peripheral hearing alone (Gussekloo et al., 2005; Lin, 2011a; Lindenberger & Baltes, 1994a). Additionally, current audiological assessment and rehabilitation in older adults maintains a primary focus on peripheral hearing impairment (Gates, Feeney, & Mills, 2008b). Patients presenting to audiologists may have multiple concerns contributing to communication difficulties beyond what is observed in the audiogram. These may include central auditory processing issues or impaired cognitive function. Furthermore, these additional factors may not be independent of each other, meaning that people presenting with one issue (e.g. a peripherally diagnosed hearing loss) may be more likely to be experiencing additional concurrent issues (e.g. central auditory processing difficulties). Current diagnostic approaches may not be revealing the full extent of a patient’s difficulties, and a rehabilitation focus on peripheral hearing deficits may not be addressing their needs. Understanding whether poor performance on different measurements of hearing (i.e. peripheral or central) increases the likelihood of other issues (i.e. cognitive dysfunction) will not only help us understand more about the relationship between hearing and cognition, but more about the patient experience. It was hypothesised that those with both a peripheral and central hearing impairment would perform more poorly on tests of cognition than those presenting with SNHL alone.

1.3.3 Study 3: Hearing Aid Uptake, Benefit and Use: The Impact of Hearing, Cognition and Personal Factors

Many factors have previously been shown to impact hearing aid outcomes including personal factors such as age and gender, as well as psychosocial factors such as the support of significant others (Meyer & Hickson, 2012; Vestergaard Knudsen, Öberg, Nielsen, Naylor, & Kramer, 2010). Self-perceived and measured hearing impairment is one of the greatest influencers of hearing aid use (Meyer & Hickson, 2012; Vestergaard Knudsen et al., 2010). The third study examines the impact of previously unexplored factors such as centrally measured hearing impairment (i.e. auditory processing skills) and/or cognition on hearing aid use. This study also examines how the aforementioned factors influence the rehabilitation of hearing impairment.

1.4 OVERALL AIM

The aim of this research was to examine the relationship between cognition, peripheral hearing loss and central auditory processing. Additionally, this research aimed to observe whether these factors influenced the rehabilitation of hearing impairment in relation to hearing aid uptake, use and perceived benefit.

1.5 SUMMARY AND SIGNIFICANCE

Hearing loss and cognitive decline are two of the most prevalent health conditions affecting the geriatric population, and cause great socioeconomic and personal burden (Access Economics, 2006; Gurgel et al., 2014a). Research has consistently demonstrated that there is an association between peripheral hearing loss and cognitive function; although whether there is a causal relationship (or the direction of this causation) between the two remains unclear (Wayne & Johnsrude, 2015). However, hearing impairment does not only occur on a peripheral level (Parham et al., 2013; Schneider et al., 2010). Central hearing impairment is also common with aging, and impacts many different processes important for the interpretation of complex auditory signals (Gates et al., 2008b; Glyde et al., 2011; Ponton, Eggermont, Kwong, & Don, 2000). Central auditory dysfunction has also been shown to be associated with reduced cognitive functioning. Poor performance on tests of two of the skills necessary for successful auditory processing has also been shown to be significantly predictive of Alzheimer's dementia (Gates et al., 1996; Gates et al., 1995; Iliadou et al., 2017). However, little research has explored how tests of spatial processing are related to cognition. Moreover, although hearing aids are commonly used in rehabilitative practices to alleviate hearing impairment, how their use is impacted by auditory processing skills and/or cognition is unknown. If rehabilitative practices for both people with cognitive impairment and hearing impairment are to be optimised, a better understanding of this relationship is necessary. To do this, limitations in previous studies need to be addressed (for example, how hearing and cognition are assessed), other aspects of auditory processing need to be explored, and an examination of current rehabilitative practices should occur.

The literature review that follows this introductory chapter will present the relevant works and current understanding of this field, identifying gaps in knowledge. The general methodology used in the study will be described in Chapter 3. Results specific to each of the three studies will be presented in Chapters 4, 5, 6 and 7, with overall findings and general conclusions described in detail in Chapter 8.

CHAPTER 2 LITERATURE REVIEW

2.1 OUTLINE

This literature review begins with an overview of “The Aging Brain” which details both natural and pathological age-related changes (behavioural and anatomical) in brain and auditory system. This is then followed by a published peer reviewed narrative review detailing previous research into the relationship between hearing and cognitive function. The review explores how tests of both Auditory Processing (AP) and peripheral hearing have in past research been connected to cognitive performance/dementia. Additionally, it highlights current knowledge on how these processes (hearing and cognition) relate to common hearing rehabilitative practices (i.e. HAs). This chapter will then focus on additional research in this area that has since been published following the submission of the narrative review. Lastly, the focus of the forthcoming experimental chapters will be presented.

2.2 THE AGING BRAIN: The Hearing-Cognitive Link

2.2.1. Foreword

Childhood stories such as Peter Pan highlight an innate fear of growing older. Fortunately, due to advances in health care and increased longevity, growing older (or ‘aging’) is an inevitable fate for most people in the 21st century. The term ‘aging’ carries with it many negative connotations. Changes in structure and function are labelled as by-products of an aging system. The Working Group on Speech Understanding and Aging (1988) highlighted three separate processes that contribute to negative age-related change in structure and function. Firstly, there is intrinsic (‘natural’) time-related degeneration, which as the description implies, is unavoidable. Secondly there is extrinsic insult, and thirdly, age-related susceptibility to disease. The latter two changes are more likely in an older individual as they have lived more years of life, but are also potentially avoidable or remediable processes. These potentially remediable processes are a large focus of age-related research, and subsequently motivated the premise of this thesis, which was to understand the relationship between two common areas of decline with age (hearing and cognition). However, it is first important to understand age-related pathological changes in the hearing and cognitive systems. However, there is a caveat to the negative connotations of aging. Whilst there are age-related pathological declines (which will subsequently be described), there are also compensatory gains with age in the ability to use context, knowledge and past-experience (Pichora-Fuller, Alain, & Schneider, 2017). Additionally, whilst the following discussion details age-related changes in a general context, it is important to remember that there is great variance and heterogeneity within the older population, and that every person is an individual. Particularly, the clinical implications and future directions sections of this dissertation (8.4 and 8.6) highlight that future clinical audiology should individualize audiological care for the different needs an older adult may present with.

2.2.2 The Aging Brain

A decrease in cognitive skills is commonly thought of as an inevitable part of the aging process. As noted in *The Handbook of Aging and Cognition* (Craik & Salthouse, 2011), behavioural evidence supports a general age-related decline across many cognitive functions. Whilst memory is anecdotally reported as a prominent area of age-related decline, there is also decreased performance in other cognitive functions such as executive function, attention, psychomotor function, learning, and speed of processing (Gurgel et al., 2014). There are well-documented differences in cognitive performance between older and younger adults. These differences are most likely attributed to physiological age-related changes in the brain, which will be discussed later in this chapter. However, when cognitive performance is poorer than expected for one’s age, cognitive impairment is suspected. Cognitive impairment has been labelled as one of the most prevalent and expensive health conditions that affects the older population (Access Economics, 2006; Gurgel et al., 2014b). A decline in cognition greater than expected for one’s age can be due to several cognitive disorders ranging from a Mild Cognitive Impairment (MCI) to the various forms of dementia. MCI is suspected when cognitive function (commonly memory) is outside age-expected limits, however the level of impairment does not significantly impact on one’s life. In comparison, a diagnosis of dementia is more likely to occur when the cognitive impairment an individual is experiencing is sufficiently great that it impacts daily function (Albert et al., 2011). An older individual may transition between MCI to dementia over a period of time, and this transition can be difficult to diagnose (see Albert et al. (2011) for a discussion on diagnostic guidelines). There are both behavioural and morphological differences between those with dementia and those without, and within the sub-types of dementia themselves. For instance, Alzheimer’s disease (the most prevalent form of dementia) characteristically presents with amnestic impairment, whereas in frontotemporal dementia and Lewy Body dementia amnestic impairment is less common (Gauthier et al., 2006). Vascular dementia is associated with blood circulation problems in the brain, and Lewy Body dementia presents with small protein deposits in neurons across the brain (Gauthier et al., 2006). Overall, cerebral atrophy (particularly in the hippocampus) is a common physiological symptom, in addition to ongoing atrophy and dead brain tissue across many cortical areas (Alzheimer's Society, 2017).

The neurological changes in those with cognitive impairment significantly relate to the behavioural presentation of the disease. However, there are also age-related changes that occur in the brain that are not necessarily associated with significant cognitive impairment or disorder. Differences in cognitive performance related to advancing age have been “intimately linked to age-related changes in the integrity of cerebral architecture and function” (Dennis & Cabeza, 2011 p. 10). That is, there are neural differences in the brain anatomy of older adults which are significantly correlated with performance on cognitive tasks. Age-related neurocognitive decline underwrites the inability of older adults to recruit brain regions during cognitive tasks that would be otherwise be employed by younger brains. Reductions in the volume of both white and grey brain matter are associated with increased age, most prominent in anterior regions of the cortex. The frontal lobe demonstrates the steepest rate of atrophy, followed by parietal, and then temporal lobes (Dennis & Cabeza, 2011). However, as hallmark birthday cards remind us, ‘with age comes wisdom’. Whilst certain brain regions are inactive in an older adult performing a cognitive task relative to a younger individual, there is evidence of additional neural recruitment in older adults that is not seen in the younger brain. Dennis and Cabeza (2011) refer to this as ‘functional compensation’, and argue that examining both types of neural activity (decreased and increased) is important in understanding the plasticity of the aging brain and cognitive aging. There are two patterns of age-related differences in brain activity that are commonly referred to in neuro-cognitive age-related research: the Hemispheric Asymmetry Reduction in OLDer Adults (HAROLD) and the Posterior-Anterior Shift in Activity in older Adults (PASA). The HAROLD pattern highlights that prefrontal activity during cognitive tasks is less lateralized in older adults than in younger adults (Cabeza, 2002). This reduction in hemispheric asymmetry may present with a compensatory function, such as increased activation of alternate pre-frontal regions during cognitive tasks to compensate for inactive contralateral pre-frontal regions. Likewise, the PASA pattern recognizes increased activation of pre-frontal cortex regions for tasks that would otherwise require posterior regions (such as reduction in occipital lobe activation for visual processing tasks (Grady et al., 1994)). Both theories highlight the rearrangement of neural networks that occurs in an older adult’s brain. There may also be alternate strategies employed by older adults when presented with cognitively demanding tasks (Dennis & Cabeza, 2011). Whilst the neural intricacies of the aging brain are beyond the scope of this thesis, they highlight that 1) the older brain is not identical to that of younger adults and 2) that whilst there is dysfunction, there is also compensation. These two points are imperative to remember in consideration of the hearing-cognitive link, and in the management of hearing dysfunction in older individuals.

2.2.3 The Aging Auditory System

As with cognitive function, there is a known decline in auditory structures and auditory function with age. Davis and colleagues (2016) coined the term “hearing health trajectory”, which begins at conception and develops throughout life. The hearing health trajectory is a good example of intrinsic and extrinsic time-related degeneration and age-related susceptibility to disease as described by The Working Group on Speech Understanding and Aging (1988). Environmental and other age-related health factors may speed up the progression of age-related audiological decline. Age-related hearing loss, also known as presbycusis, is the most common form of hearing loss, with increased age generally increasing the severity of sensorineural hearing loss experienced (Dubno, Eckert, Lee, Matthews, & Schmiedt, 2013; Gates, 2012). The World Health Organization classifies the severity of sensorineural hearing loss on a scale from normal to profound, with significant differences in functional communication found between each step (Humes, 2019). Dubno and colleagues (2013) also described different audiometric profiles that highlight the different mechanisms underlying age-related hearing loss. For many years, pathological differences were used to categorize presbycusis into four groups: sensory, neural, metabolic and mechanical. These four categories reflected the different areas within the auditory system in which age-related damage/atrophy was thought to occur (i.e. sensory hair/support cells, spiral ganglion neurons, lateral wall of the cochlea and the conductive characteristics of the inner ear) (Dubno et al., 2013; Schuknecht, 1974). Using these categories and animal model research, in addition to pure-tone audiometric data collected from 1,728 audiograms of individuals aged 50.4- to 97.5 years, Dubno et al. (2013) labelled five audiometric phenotypes: older-normal, pre-metabolic, metabolic, sensory, and mixed metabolic plus sensory. These phenotypes negatively impact on the severity of sensorineural hearing loss experienced by the individual, mostly in the higher frequencies. This worsening is attributed to pathological age-related change combined with environmental factors (such as noise exposure) and other health-factors (such as ototoxic drugs), highlighting a perfect example of the three defined processes that contribute to age-related change in structure and function (Working Group on Speech Understanding and Aging, 1988).

The audiometric phenotypes are derived from PTA measurements of sensorineural hearing loss, and consequently (like the four categories of presbycusis), pertain primarily to peripheral auditory structures (e.g. the cochlea) (Dubno et al., 2013; Schuknecht, 1974). However, auditory difficulties experienced by older adults extend beyond damaged peripheral auditory structures and the pure-tone audiogram. A common age-related hearing difficulty is the inability to listen to speech in complex listening environments (Besser et al., 2015). Older adults with only a mild sensorineural hearing loss may have impaired listening skills beyond what may in indicated from an audiogram alone (Middlebrooks, Simon, Popper, & Fay, 2017). Another component to the hearing difficulties experienced by older adults may be their cognition and other pathological auditory mechanisms that are not included in the description of the audiometric phenotypes. Comprehending speech in challenging situations (i.e. a cocktail party), requires a combination of sensory (peripheral auditory), CAP and cognitive abilities (Pichora-Fuller et al., 2017). In fact, in one study an individual's PTA threshold explained less than 5% of the variance in speech recognition in complex, fluctuating listening conditions whilst cognitive ability explained approximately 40% of the variance (Lunner & Sundewall-Thorén, 2007). In another study assessing differences in speech understanding in older adults, 60% of the variance in speech understanding was explained by: one global cognitive-processing factor, degree of hearing loss, and four measures of CAP performance (Humes, Kidd, & Lentz, 2013a).

Older listeners often have poorer word recognition scores in both quiet and background noise than younger adults, needing approximately a 2-4 dB better signal to noise ratio on average to perform equal to younger counterparts (Pichora-Fuller et al., 2017). Cochlear pathologies are not the only factor influencing speech recognition performance in older adults (Humes et al., 2013a; Lunner & Sundewall-Thorén, 2007).Thus far, age-related changes in cognitive and peripheral auditory systems have been discussed. Just as there are age-related changes in the peripheral auditory system, there are also age-related changes in central auditory structures such as the auditory nerve, auditory brainstem and auditory cortex. These structures contribute to different components of central auditory function (described in further detail in the narrative review later in this chapter). As summarized by Pichora-Fuller et al. (2017) neural changes within the central auditory system (that are not evident in a pure-tone audiogram) may provide a physiological explanation for the decreased ability to hear in complex speech environments experienced by older adults. Behavioral evidence suggests that central auditory function declines significantly faster than peripheral auditory function with age (Gates et al., 2008b). This evidence suggests that older adults have poorer gap and duration coding, poorer use of envelope cues, reduction in synchrony or periodicity coding, as well as decreased auditory temporal processing, dichotic listening skills and spatial processing ability (Eddins & Hall, 2010; Fitzgibbons & Gordon-Salant, 2010; Glyde et al., 2013; Pichora-Fuller et al., 2017; Walton, 2010). Of importance for this dissertation is spatial processing ability. Spatial processing (SP) will be discussed in further detail in subsequent chapters throughout the thesis. A brief overview of SP and the primary outcome measure used to measure SP in this study (the LiSN-S test) will now be given.

Spatial release from masking refers to a phenomenon where speech understanding improves when target speakers are spatially separated from each other compared to when speakers are collocated (Litovsky, 2012). SP ability refers to an individual’s ability to use spatial separation of target and distractors to increase the SNR of a desired speaker. Consequently, SP dysfunction (SPD) refers to when one does not achieve a greater SNR from spatial separation. In general, older adults have poorer SP ability than younger listeners, which can be further exacerbated by decreased pure-tone hearing acuity (Besser et al., 2015; Glyde et al., 2011; Murphy, Daneman, & Schneider, 2006). The LiSN-S test (Cameron & Dillon, 2007) can provide a measure of SP.

The LiSN-s test presents a target sentence in background noise with two competing speakers. It has four test conditions (high cue/DV90, DV0, SV90, low cue/SV0) which provide four outcome Speech Reception Threshold (SRT)’s. These conditions vary depending on whether there are spatial or voice differences between target and distractor speakers. In the *high cue* (DV90: different voice 90º) condition, the target speaker is presented in front, with distractor speakers spatially separated by 90º with tonal differences. In the DV (difference voice 0º) condition, the speaker and distractors are tonally different, but collocated at 0º azimuth to the front of the listener. In the SV90 (same voice 90º) condition, the speaker and distractors are again spatially separated, but unlike the high cue condition, share the same voice (i.e. are tonally identical). Lastly, in the low cue condition (SV0: same voice 0º) the target and distractor speakers are collocated and share the same voice. By comparing SRT scores across the conditions, *spatial advantage* and *tonal advantage* scores can be derived, indicative to how much performance improved when spatial cues or tonal cues are present (respectively). A total advantage score can also be calculated from how much benefit is gained when both cues are present. Overall, LiSN-S SRT scores are reportedly poorer in older adults over the age of 65, even in those with good pure-tone audiometry thresholds (Besser et al., 2015; Cameron, Glyde, & Dillon, 2011; Glyde et al., 2013). It is also worth noting that each test condition can be presented with an amplified signal to an individual based on their audiometric thresholds with a prescribed National Acoustics Laboratory Revised Profound (NAL-RP) amplifier. The NAL-RP is a common prescription in hearing aid fittings used to provide amplification for sensorineural hearing losses. A key goal of this dissertation was to assess how LiSN-S performance in older adults related to pure-tone audiometry results and cognitive function.

As discussed, there are anatomical and functional changes in both the peripheral and central auditory systems with age. Across different texts, the term ‘hearing impairment’ may refer to either peripheral or central hearing impairment. For this thesis, the term hearing *loss* will refer to sensorineural hearing loss measured via PTA, unless otherwise stated. The term hearing *impairment* will incorporate a broader definition, referring to more complex listening difficulties that may be attributed to central auditory dysfunction and/or cognition (or a combination of both), potentially in addition to (but not dependent on) sensorineural hearing loss.

2.2.4. The Hearing Brain

A pertinent point made in the opening chapter of *The Auditory System at the Cocktail Party* is that humans “hear with their brains, not just their ears” (Middlebrooks et al., 2017, p. 5). Thus far, the aging brain and aging auditory system have been discussed as two discrete systems. However, listening requires both auditory and cognitive systems. In fact, how audiological decline and cognitive decline are related is a research question explored in a large body of literature (including this dissertation).

Information from a single cochlea will not allow listeners to process all complex sounds (Middlebrooks et al., 2017). An intricate process that occurs across an incredibly small time frame (hundreds of milliseconds only), known as stream segregation, allows a listener to best attend to a target speaker amongst background noise. A binaural auditory input is required at a peripheral auditory level, which travels in a bottom-up progression to central auditory structures such as the binaural nuclei in the auditory brainstem. Once in the auditory cortex, linguistic and other cognitive functions work to contribute to the analysis of the signal, to provide meaning and context (Middlebrooks et al., 2017). Age-related differences in word recognition may be due to bottom-up effects of auditory decline. In cognitively-healthy older adults, these declines may be offset by compensatory cognitive gains such as greater contextual cues and knowledge (Pichora-Fuller et al., 2017). This top-down use of context and knowledge is an example of how older adults can employ compensatory mechanisms. However, if there is cognitive dysfunction in the areas of memory and attention, this compensatory mechanism may be impaired, creating greater listening difficulties. The proposed framework for understanding effortful listening (FUEL) (Pichora-Fuller et al., 2016) reinforces that ‘ears’ and ‘hearing’ are not the only contributors to listening, particularly in challenging situations. Listening effort is defined as “the deliberate allocation of mental resources to overcome obstacles … when carrying out … tasks [that] involve listening” (Pichora-Fuller et al., 2016, p.55). It is obvious that cognitive resources are required for listening. Pichora-Fuller and colleagues (2016) highlight that listening is influenced by the demands of the situation, the motivation of the listener, and the effort that can be applied. When auditory quality is reduced (either by the acoustical environment or impaired audition), listeners can expend more mental effort to direct attention to sounds of importance. Consequently, cognition is a topic of high importance to audiologists, evident in the inclusion of cognitive theory in audiology textbooks and practice guidelines (Pichora-Fuller et al., 2016). Models such as the FUEL recognize the hearing-cognition link and its application to hearing/hearing difficulties. This link is particularly important in an older listener, who may require a top-down compensatory approach to hearing when auditory systems decline (Pichora-Fuller et al., 2017).

Just as hearing and cognitive functions were previously described as independent, so too were the pathological declines in the auditory system and the brain. However, pathological age-related changes in auditory and cognitive systems may not be discrete processes. The theories and evidence for the relation between hearing and cognitive function are discussed in detail throughout this thesis, particularly in the forthcoming narrative review. This subsection will continue to focus on pathological age-related changes in these systems, particularly the changes that affect both hearing and cognitive decline. Neurological changes are commonly seen in those with hearing loss which share similarities to the brain pathology of dementia patients (Kral, 2013; Kral & Sharma, 2012; Peelle, Troiani, Grossman, & Wingfield, 2011; Wong et al., 2009). There are also physical changes within the peripheral auditory system that are more common in Alzheimers dementia patients compared to age matched controls, specifically in the basal turn of the cochlea (Sinha, Saadat, Linthicum, Hollen, & Miller, 1996). A greater degree of high frequency SNHL has been significantly associated with a reduction in gray matter brain volume and enlarged lateral ventricle volume (Eckert, Vaden Jr, & Dubno, 2019). Other pathological changes noted in dementia patients include atrophy in central auditory structures. Early studies suggested that deterioration in the medial temporal lobe could define a diagnosis of dementia (Erkinjuntti et al., 1993; Scheltens et al., 1992). Additionally, neurological degeneration of central auditory nuceli is more common in dementia patients than aged-match controls (Sinha, Hollen, Rodriguez, & Miller, 1993). Behaviorally, a poorer SRT has been found to be significantly associated with a reduction in whole-brain matter volume (primarily in the temporal and frontal cortexes and in the lower hippocampus) (Rudner, Seeto, Keidser, Johnson, & Rönnberg, 2019).

It is evident that there are many age-related changes to auditory and cognitive functions and structures, and that these changes may be co-dependent. As highlighted in chapter one, this dissertation is focused on further understanding how auditory and cognitive functions are related, using a behavioural test battery. The subesequent sections of the literature review will examine current behavioural evidence for a relation between hearing loss and cognitive function.

2.3 NARRATIVE REVIEW: Peripheral and Central Hearing Impairment and their Relationship with Cognition: A Review.

The following peer-reviewed publication is incorporated in its entirety in this chapter:

Published paper

- Nixon, G. K., Sarant, J. Z., & Tomlin, D. (2019). Peripheral and central hearing impairment and their relationship with cognition: a review. International Journal of Audiology, 1-12. doi:10.1080/14992027.2019.1591644

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REVIEW ARTICLE

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Peripheral and central hearing impairment and their relationship with cognition: a review

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ABSTRACT
Objective: To consider the relationships between both peripheral and central hearing impairment and cognition.
Design: Narrative review.
Study sample: Numerous studies exploring the relationship between hearing impairment and cognitive function, particularly in an older population.
Results: In addition to the well-documented relationship between peripheral hearing loss and cognition highlighted in previous comprehensive reviews, there is also some evidence to suggest that there is a relationship between central hearing impairment and cognition. Further research is required to better understand this relationship and its effects on hearing aid benefit in people with both peripheral hearing loss and central hearing impairment.
Conclusions: To fully understand the relationship between hearing impairment and cognitive impairment, not only peripheral but central hearing needs to be considered. Such knowledge could be of benefit in the clinical management of people with both peripheral hearing loss and central hearing impairment.

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1. Introduction

The number of older adults, particularly those over the age of 85, is expected to grow markedly within the next few decades as a result of increases in both population and life expectancy (United Nations 1999; Wilson 2012; Census Bureau 2016). The financial burden of public healthcare for the growing population is considered to be unsustainable (Zweifel et al. 1999; Bongaarts 2004). This review will focus on two highly prevalent health conditions in the aging population: cognitive impairment and hearing impairment (HI) (Hofman et al. 1991; Cruickshanks et al. 1998; Gurgel et al. 2014). In this review, the term "hearing loss" will refer to peripherally measured hearing difficulties, whereas "hearing impairment" will encompass central hearing and/or overall hearing difficulties (that are not specifically defined). The relationship between cognition and both peripheral hearing loss and central HI will be examined using current evidence.

1.1. Cognitive impairment

Cognitive impairment is one of the most prevalent and expensive health conditions affecting older adults (Access Economics 2006; Gurgel et al. 2014). It encompasses a spectrum of disorders that can affect psychomotor function, memory, executive function, attention and learning, and ranges from mild cognitive impairment (MCI) through to dementia (Gurgel et al. 2014). In this review, the term cognitive impairment includes both MCI and varying forms of dementia. This includes having poorer performance on cognitive tests that does not interfere with daily life (MCI), as well as a clinical diagnosis of dementia. The World Health Organisation (2017) classifies dementia as a chronic health condition which leads to a deterioration in thinking, behaviour, ability to perform everyday tasks, and memory and is clinically diagnosed under the guidelines presented in the Diagnostic and Statistical Manual V (Dementia Australia 2012; Gauthier, Reisberg et al. 2006). Depending on dementia subtype, the morphology of an individual's brain may differ, but commonly cerebral atrophy (particularly of the hippocampus) is one of the first notable physiological symptoms (Wurthmann et al. 1995; Alzheimer's Society 2017). Early research has also demonstrated significant relationships between Alzheimer's Dementia (AD) and increased atrophy of the temporal lobe (Scheltens et al. 1992; Erkinjuntti et al., 1993).

1.2. Hearing impairment

Age-related hearing loss (ARHL), otherwise known as presbycusis, is the most common form of hearing loss (Gates 2012). Ascending pathways in the auditory system carry sound signals from the cochlea to the auditory cortex (Lesicko and Llano 2017). Presbycusis involves the degeneration of peripheral auditory structures such as outer hair cells in the cochlea, resulting in a loss of hearing sensitivity, particularly in the high frequencies (Stach et al. 1990; Kortlang et al. 2016). ARHL, commonly leads to problems with speech clarity and understanding, particularly in background noise (Glyde et al. 2013; Besser et al. 2015; Kortlang, Mauermann et al. 2016; Lesicko and Llano 2017). ARHL not only disrupts the ability to interpret the acoustic signal, but can also disrupt neurons in the central auditory nervous system pathway, particularly in the area of the inferior colliculus (Musiek and Chermak 2013). Results from early studies have

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demonstrated the complexity of age-related hearing degeneration with morphological changes found throughout the auditory system. This includes peripheral structures such as the cochlea, and central structures such as the eighth nerve, the auditory brainstem and the auditory cortex (Jorgensen 1961; Kirikae et al. 1964; Schuknecht 1964; Krmpotic-Nemanic 1971; Stach, Spretnjak et al. 1990). Thus, like dementia, HI can result in age-related morphological changes to neural structures.

Currently, the assessments and intervention for hearing and cognitive impairment are performed independently. However, it has been suggested that there may be significant value in addressing the dual impact of both conditions concurrently (Lin et al. 2011; Lind et al. 2016). This is particularly appropriate for older populations (Lind et al. 2016). For example, the use of neurocognitive tests that identify and help to explain difficulties with speech recognition may yield advantages in rehabilitation for audiology appointments by tailoring management to an individual's needs (Vaughan et al. 2008). Cognition is typically measured through auditory means (i.e. verbal questions/instructions that rely on hearing ability to be correctly interpreted). If hearing ability is not considered at the time of neurocognitive assessments, cognitive abilities may be underestimated because of limitations to perform on the test due to sensory rather than cognitive deficits (Dupuis et al. 2015; Iliadou et al. 2018a, 2018b). Thus, there may be great benefit from gaining an increased understanding of the relationship between HI and cognitive decline in older adults, particularly to help guide the future practice of clinicians working with these populations.

2. The relationship between peripheral hearing impairment and cognitive impairment

HI and cognitive decline are both positively associated with age, and several studies have investigated whether the two are independently associated with each other. A recent meta-analysis of 33 journal articles published between 1991 and 2014 investigating the association between hearing loss and cognitive ability concluded that hearing loss is significantly associated with cognitive problems, with treatment of hearing loss decreasing cognitive deficit (Taljaard et al. 2016). The meta-analysis focussed on both the presence and treatment of HI in adults (from a mean age of 25 years and above) as the main outcome measure. The majority of the 33 studies reviewed measured hearing via pure tone audiometry (PTA) (where reported) and reported quantified performance on different cognitive domains (i.e. attention, memory, executive function, etc.) rather than scores on cognitive screening tests or the presence/absence of diagnosed dementia. It was concluded that while hearing loss appeared to negatively impact cognitive function, assuming a causal relationship between the two is premature due to differences in methodology between the studies conducted to date (i.e. sample size, measurement of hearing and cognition).

When considering further evidence on the relationship between hearing and cognition, it is important to note that cognitive impairment is defined as below average scores on cognitive assessments in some studies and in others by a diagnosis of dementia. Furthermore, HI is also reported in different ways (e.g. self-report or PTA). Sample sizes between studies varied, and other factors predictive of hearing loss were not always controlled for statistically or consistent between studies. Collectively over time, however, epidemiological evidence has demonstrated that peripheral hearing loss was more prevalent in populations suffering from dementia, was negatively associated with cognitive function (Lindenberger and Baltes 1994; Gussekloo et al. 2005; Lin 2011) and was positively associated with an increased risk of dementia (Lin et al. 2011, 2013; Gurgel et al. 2014). Furthermore, self-reported hearing disability has been shown to be significantly associated with accelerated cognitive decline, potentially mediated by depressive symptoms and social isolation (Amieva et al. 2015).

Some of the studies which were representative of the breadth of research in this area were not considered in Taljaard et al.'s (2016) meta-analysis due to restrictive search criteria (i.e. cognitive screening tools, comparison between dementia sufferers and controls); these are shown in Table 1. Of the 12 studies included in Table 1, 10 support a relationship between hearing and cognition. Gates et al. (1995) found no significant relationship between hearing loss and probable AD (pAD). However, the sample size of those presenting with pAD in this study was relatively small, making the generalisability of the results to those for other populations questionable. More recently, longitudinal population-based research by Hong et al. (2016), which included a large sample size of 3654 individuals, also did not find a relationship between cognitive decline and sensory impairment, once external factors (such as age) were accounted for. Limitations of this research however, include the use of the Mini Mental State Examination (MMSE) screening test as a measure of cognition, which has been demonstrated to lack sensitivity, in addition to being auditorily presented (Folstein et al. 1975).

3. Hearing aids and cognition

Although there is no known treatment for cognitive decline, audiological rehabilitative practices focus on the alleviation of HI using hearing aid (HA) technology (Mulrow et al. 1990; Kochkin and Rogin 2000; Meister et al. 2015; Desjardins 2016). Given the reported association between hearing loss and cognition, it seems reasonable that the alleviation of hearing loss may aid in the improvement of cognition, as proposed by the "resource allocation hypothesis" (Sekuler and Blake 1987; Lindenberger and Baltes 1994; Pichora-Fuller 2003; Valentijn et al. 2005; Desjardins 2016). Yet, the way in which HAs interact with cognition remains unclear.

Limited research has examined the impacts of HA use on cognition, with conflicting results. One study of 115 HA users over the age of 60 explored self-reported hearing handicap after six weeks of HA use (Chmiel and Jerger 1996). While self-reported hearing handicap improved after HA use, there was no influence of HA use on memory and attention (Chmiel and Jerger 1996). However, the study considered cognitive changes over a six-week period of HA use only, which may not have allowed sufficient time for changes to occur in cognitive functioning. Additionally, in a cross-sectional analysis examining the relationship between cognition and hearing loss, no association between self-reported HA use and scores on a cognitive test battery was found (Lin et al. 2011). However, only 46 of the 347 participants (with an average age of 71 years) in the study self-reported HA use over a four-year period.

In contrast, several studies have shown an association between the use of HAs and improvement in cognitive function (Lin 2011; Kalluri and Humes 2012; Amieva et al. 2015; Dawes et al. 2015; Doherty and Desjardins 2015; Desjardins 2016). A review of the short- and long-term outcomes of HA use on cognitive function acknowledged the accumulating evidence for short-term changes in cognitive function with the use of HAs, such as greater performance on cognitive tasks in hearing-impaired

Table 1. Summary of the research investigating the relationship between peripheral hearing loss and cognitive decline.

Author	Population	Hearing measures	Cognitive measures	Conclusion
Amieva et al. (2015)	3670 participants 65 and over ($m = 76.5$, SD = 6.2).	Questionnaire assessing self-perceived hearing loss.	MMSE	Hearing loss was associated with accelerated cognitive decline.
Gurgel et al. (2014)	4463 participants over the age of 65, 836 with hearing loss at baseline ($m = 79.45$, SD = 7.5) and 3 627 with no hearing loss at baseline ($m = 74.53$, SD = 6.3).	Observation of hearing difficulties during testing or interview.	Modified MMSE.	Hearing loss was associated with an increased rate of developing dementia, and more rapid decline on cognitive test scores.
Hong, Mitchell, Burlutsky, Liew and Wang (2016)	1883 participants over the age of 49. 1 308 with no impairment ($m = 66.9$, SD = 7.4), 152 with a visual impairment ($m = 74.3$, SD = 8.4), 330 with a hearing loss ($m = 73.4$, SD = 7.8) and 93 with a dual impairment (both hearing loss and visual impairment) ($m = 80.4$, SD = 7.0).	PTA. Measured at 4 frequencies: 500Hz, 1000 Hz, 2000Hz and 4000Hz.	MMSE	No significant association between sensory impairment and cognitive decline after age/other external factors were accounted for.
Lin et al. (2013)	1984 participants aged 70–79. 882 with normal hearing ($m = 76.8$, SD = 2.7), and 1162 with a hearing loss ($m = 77.9$, SD = 2.8).	PTA. Measured between 250Hz to 8000Hz, and average pure-tone thresholds calculated from 500Hz, 1000Hz, 2000Hz and 4000Hz thresholds.	Modified MMSE. Digit Symbol Substitution test (DSST) (psychomotor speed and executive function).	Hearing loss was independently associated with accelerated cognitive decline and incident cognitive impairment.
Lin (2011)	605 participants aged 60–69 ($m = 64.1$, SD = 2.9).	PTA. Measured at 4 frequencies: 500Hz, 1000 Hz, 2000Hz and 4000Hz.	The DSST (component of the Wechsler Adult Intelligence Test).	Hearing loss was negatively associated with cognitive test scores. 25dBHL of hearing loss was equivalent to 7 years of cognitive decline.
Lin et al. (2011)	347 participants over age 55 ($m = 71.0$, SD = 7.2).	PTA. Measured at 4 frequencies: 500Hz, 1000 Hz, 2000Hz and 4000Hz.	FCSRT (memory). AMNART (verbal IQ). Letter Fluency Task. Trail Making Test. Stroop Test.	Hearing loss was independently associated with lower scores on tests of memory and executive function.
Gussekloo et al. (2005)	459 participants aged 85.	PTA. Measured at 3 frequencies: 1000Hz, 2000Hz and 4000Hz.	MMSE Further testing for those who scored above 18 points on MMSE: 12-Word learning test (long-term memory), Letter Digit Coding Test (processing speed) and the Stroop test (attention).	Hearing loss was associated with lower scores on the MMSE, but not on other cognitive tasks.
Valentijn et al. (2005)	418 participants over age 55 ($m = 65.1$, SD = 6.6).	PTA. Measured at 3 frequencies: 1000Hz, 2000Hz and 4000Hz.	The Verbal Fluency Test. The Letter-Digit Substitution Test. The Concept Shifting Task. The Stroop Colour Word Test. The Visual Verbal Learning Test.	Poorer visual acuity was associated with a decrease in performance on most cognitive measures.
Gates et al. (1995)	82 participants over age 65 ($m = 76.5$, SD = 7.5) (42 with probable Alzheimer's Dementia and 40 without cognitive impairment).	PTA. Measured between 250Hz–8000Hz, and average pure-tone thresholds calculated from 500Hz, 1000Hz, 2000Hz and 4000Hz thresholds.	The Clinical Dementia Rating scale (for those with dementia status). Non-verbal test battery: Boston Naming Test, Trail-making A test, the Wechsler Adult Intelligence Scale Digit Symbol Subtest, the Benton Visual Retention Test and the Aphasia Battery. Verbal test battery: Logical Memory, the Associate Learning subtest and Information subtest from Wechsler scales, the Pfeiffer Short Portable Mental Status Questionnaire and the Short Blessed Test.	Hearing loss was not significantly related to probable Alzheimer Dementia diagnosis.

(*continued*)

Table 1. Continued.

Author	Population	Hearing measures	Cognitive measures	Conclusion
Lindenberger and Baltes (1994)	156 participants aged 70–103 years ($m = 77.3$, SD = 4.6).	PTA. Measured 8 frequencies: 250Hz, 500Hz, 1000Hz, 2000Hz, 3000Hz, 4000Hz, 6000Hz and 8000Hz.	Independent tests of cognitive function measuring: Processing speed, Reasoning, Knowledge, Memory and Fluency.	Poorer auditory acuity explained 34.6% of the reliable total variance in poorer intellectual functioning.
Uhlmann, Larson, Rees, Koepsell and Duckert (1989)	200 participants, 100 with dementia ($m = 77.1$, SD = 6.3) and 100 age-, sex- and education-matched controls ($m = 77.0$, SD = 6.3).	PTA. Measured 4 frequencies: 500Hz, 1000Hz, 2000Hz, and 3000Hz.	MMSE (for controls without a prior dementia diagnosis)..	Hearing loss was more prevalent in those with dementia than those without. Cognitive dysfunction in both AD and control groups was greater when HL was present.
Granick, Kleban and Weiss (1976)	47 males ($m = 71.5$, SD = 4.8) with "excellent health status" and 38 females ($m = 75.9$, SD = 5.3) with a "significant physical pathology".	PTA Measured 10 frequencies: 250Hz, 500Hz, 1000Hz, 1500Hz, 2000Hz, 3000Hz, 4000Hz, 6000Hz and 8000Hz.	Wechsler Adult Intelligence Scale (excluding Comprehension, Picture Arrangement, and Object Assembly). The Raven Coloured Progressive Matrices. Ammons Full Range Picture Vocabulary Test (Form B).	Both samples of participants demonstrated an association between hearing loss and cognitive scores.

listeners with HAs than without, arguably because of reduced cognitive load (Kalluri and Humes 2012).

Although there is now mounting evidence of short-term cognitive benefits with HA use, there is a dearth of research on long-term changes in cognitive function due to HA use, with few longitudinal studies available. For example, HAs were found to provide an immediate increase in performance on tests of working memory improvement for 24 participants after six weeks of use (Doherty and Desjardins 2015). However, this improvement was not sustained when the same participants performed the test of working memory without wearing their HAs. A further study of six HA users over an 18-month period also demonstrated that HA use improved short-term cognitive skills of memory, attention and processing speed (Desjardins 2016); however, once HA use was discontinued, these skills returned to baseline levels. In contrast, one recent longitudinal study by Amieva et al. (2015) produced promising results for the longitudinal benefit of HA use on cognition. Over a 25-year period, a significant difference in the rate of cognitive decline was found between groups of older adults with and without hearing loss, but not between the group with normal hearing and that which used HAs. This epidemiological study is the first to note a significant slowing in the rate of cognitive decline due to HA use. Further research on long term cognitive change due to HA use is needed.

4. Current theories

The association between cognition and sensory impairments, including exploring whether a decline in cognition is due to hearing loss, whether cognitive decline causes HI, or whether the two are related via a common cause has been examined for decades (Lindenberger and Baltes 1994; Baltes and Lindenberger 1997). A brief overview of these theories is presented in Figure 1.

4.1. The sensory deprivation hypothesis

The "sensory deprivation" hypothesis suggests that there may be cognitive deterioration at a neuronal level because of reduced adequate sensory input over a prolonged period (Desjardins 2016; Lindenberger and Baltes 1994; Valentijn et al. 2005). This hypothesis suggests that any cognitive deterioration is permanent, because over time, reallocation of cognitive resources can produce permanent neural changes impacting an individual's cognitive performance (Lindenberger and Baltes 1994; Wayne and Johnsrude 2015). Atrophy in areas of the auditory system has been suggested as a potential mechanism for the sensory-deprivation hypothesis, as compensation for such atrophy may induce neurophysiological changes in the brain, similar to those found in dementia (Wong et al. 2009; Peelle et al. 2011; Kral 2013; Wayne and Johnsrude 2015). As explained in a review by Wayne and Johnsrude (2015), there is some morphological evidence of cortical reorganisation with sensory deprivation, and evidence of subsequent increased activation of networks for working memory and attention (see Peelle et al. 2011 and Wong et al. 2009). However, if the sensory deprivation hypothesis were to fully explain the relationship between cognition and HI, hearing loss should precede cognitive decline given the hypothesis implies that the physiological changes that result from hearing loss may lead to cognitive deficits. The evidence in the literature does not support the theory that hearing loss always comes before cognitive deficits, with cognitive impairment reported in people with normal hearing also.

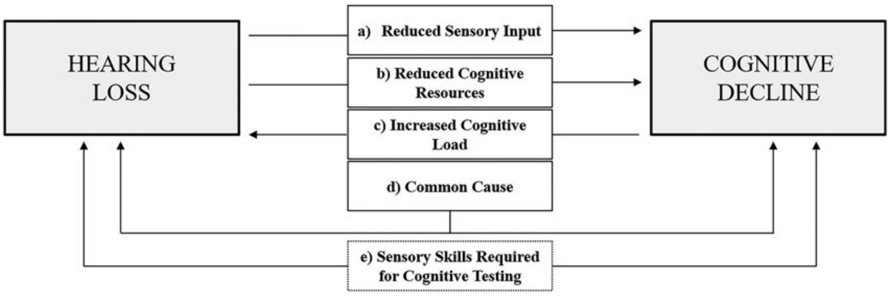

Figure 1. Proposed hypotheses on the causal direction of the relationship between hearing loss and cognitive decline.

4.2. The resource allocation hypothesis

Similar to the sensory deprivation hypothesis, a second hypothesis, the "resource allocation" hypothesis, or "information degradation" hypothesis, argues that because of increased sensory impairments, cognitive processes are restricted. That is, individuals may attempt to compensate for sensory deficits by relying on cognitive resources such as working memory and attention. As a consequence, more cognitive resources are used to perceive speech, which results in fewer resources available for higher order cognitive processes (Lindenberger and Baltes 1994; Pichora-Fuller 2003; Valentijn et al. 2005; Desjardins 2016). Previous research has demonstrated that both IQ test scores and degree of hearing loss interact to determine performance in making correct inferences about an auditory signal (Rabbitt 1991). The "resource allocation" hypothesis advocates that any change in cognition is only temporary and is a direct result of additional energy and resources being used to compensate for hearing difficulties (Wayne and Johnsrude 2015). If this hypothesis is true, cognitive decline related to hearing loss should be reversible and temporary. Although one study has reported that long-term self-reported HA use (measured over 25 years) attenuates cognitive decline, this research was restricted by the use of self-report for both HI and HA use (Amieva et al. 2015). This is a relatively new area of research, with hearing loss first recognised by the Lancet Commission as a modifiable risk factor for cognitive decline only in 2017 (Livingston et al. 2017). There is currently no high-quality evidence regarding the effect of treatment of hearing loss on cognitive decline long term.

4.3. Cognitive load on perception hypothesis

Unlike the two previous hypotheses, which suggest that cognitive decline may result from reduced sensory function, the "cognitive load on perception" hypothesis suggests that cognitive decline leads to sensory decline (Lindenberger and Baltes 1994; Wayne and Johnsrude 2015). This hypothesis is based on a similar principle to the "resource allocation" hypothesis, although in the opposite direction. Unlike the first two hypotheses, the "cognitive load on perception" theory lacks support, as no morphological or behavioural studies have demonstrated evidence of cognitive decline preceding hearing loss. One study demonstrated that the rate of decline in hearing thresholds was predicted by cognitive impairment, however this study relied on only a screening tool to measure cognition (Kiely et al. 2012).

4.4. Common cause hypothesis

A fourth theory, known as the "common cause" hypothesis, suggests that a third, common factor "confounds the association between sensory functioning and cognition" (Valentijn et al. 2005, p. 374). That is, decline in cognition and sensory function may be the result of a common causal mechanism such as age-related degeneration of the central nervous system (Lindenberger and Baltes 1994; Baltes & Lindenberger, 1997; Valentijn et al. 2005). Both cognitive and HI are highly correlated with age. Age-related neural degeneration, characterised by widespread reductions in cortical volume and dendrite length, particularly in the pre-frontal cortex, is a common characteristic of cognitive impairment. ARHL may also result in neurodegeneration, and changes across multiple domains such as cognition and sensory perception may suggest a central nervous system pathology with common neurodegenerative aetiology (Wayne and Johnsrude 2015, p.160). While morphological evidence exists relating to age-related degneration in sensory and cognitive domains, a theory which broadly considers age as a factor must recognise other age-related comorbidities that may also affect these two domains.

4.5. Alternative hypotheses

Another theory alternatively suggests that on tests of cognition, performance may be disadvantaged as a direct result of sensory impairment (i.e. visual- and/or hearing-impairment) (Gussekloo et al. 2005; Valentijn et al. 2005). This hypothesis was supported somewhat by the results of the Leiden 85+ study, in which both hearing and visual impairment were associated with lower scores on a screening questionnaire for cognitive dysfunction (Gussekloo et al. 2005). However, only increasing visual impairment was associated with poorer scores on memory and cognitive speed. Because both memory and cognitive speed were visually presented tests, and HI did not correlate with either factor, the authors advocated that their results were at least partially due to the use of the impaired visual sensory function in evaluating cognitive function.

A recent review concluded that causal inferences about the nature of the relationship between these two disabilities are difficult to make due to inconsistencies in how cognition and hearing have been assessed, as well as the "correlational nature of much of the research" (Wayne and Johnsrude 2015, p. 162). A key point of the critical analysis was that the nature of the link between HI and cognitive decline is obscured by limitations in measurement; none of the reported studies used the same test battery for measurements of cognition. The reviewers proposed their own "alternative framework" which took into consideration the complimentary and interdependent processes that connect hearing and cognition. One of these interdependent processes includes negative psychosocial outcomes. Wayne and Johnsrude (2015) suggested that perceptual difficulty may affect communication and increase social withdrawal, which also may occur when cognitive deficits are present. Moreover, the lack of social interaction and/or presence of depression may precipitate or exacerbate cognitive decline (Wayne and Johnsrude 2015). Evidence in the literature provides some support for this theory. Both hearing loss and cognition are associated with depression and social isolation (Fratiglioni et al. 2000; Bennett et al. 2006; Kiely et al. 2013; Li et al. 2014; Frampton 2016) and these factors may mediate the relationship between hearing loss and cognition. For example, one recent epidemiolocal study described the potential mediation of depressive symptoms and social isolation in individuals aged over 65 years (Amieva et al. 2015). As previously highlighted, limitations of this study included self-reported hearing loss and cognition measured using an insensitive screening tool. Nevertheless, this 25-year study provided new information on the association between hearing loss and cognitive decline.

In their review, Wayne and Johnsrude (2015) also highlighted the fact that most research to date has focussed on hearing sensitivity measured only on a peripheral level (i.e. audiometric thresholds only). It was contended that using tests of higher order listening function and collecting detailed information about the nature of the hearing loss may result in a greater understanding of whether there is a causal relationship between hearing and cognition.

5. The relationship between central hearing impairment/central auditory processing and cognition

Thus far this review has considered the research addressing a possible relationship between peripheral hearing and cognition. As suggested by Wayne and Johnsrude (2015), it is also important to examine the evidence regarding higher order listening, often referred to in the literature as "central hearing" or "Central Auditory Processing" (CAP) as both peripheral and central auditory systems need to function correctly for the recognition and interpretation of a sound signal. Central auditory systems share neurophysiological connections with systems associated with cognition and dementia (e.g. atrophy of the temporal lobe) (Scheltens et al. 1992; Erkinjuntti et al. 1993). As such, considering hearing on a peripheral level only may not be sufficient to understand the relationship between hearing and cognition.

5.1. Central hearing and central auditory processing

CAP is the ability of the central nervous system to perceive and interpret auditory information (American Academy of Audiology 2010). Successful CAP relies on a working central auditory system and includes listening skills such as temporal and frequency discrimination, as well as binaural processing (Nelson and Soli 2000; Picard and Bradley 2001). Functional imaging studies have demonstrated activation of temporal, parietal and frontal lobes in response to an auditory signal, highlighting a hierarchy of neural networks required to not only perceive, but to interpret speech (see Hackett, 2009). CAP skills develop with age, reaching peak performance in young adulthood, and subsequently decrease in older adults (Ponton et al. 2000; Gates et al. 2008; Glyde et al. 2011). Animal studies of these networks have identified a physiological change in neural function with age (see Willott et al. 1988). One geriatric population study concluded that along with decreases in cognitive ability, both the peripheral and central auditory systems decline with age (Parham et al. 2013). Given CAP deficits are often present along with peripheral hearing loss and may contribute to cognitive issues, more research is needed to explore the relationship between HI and cognition with CAP as a focus.

Generally, people with ARHL report an inability to understand speech in complex listening situations (Glyde, Cameron et al. 2013; Besser, Festen et al. 2015; Kortlang, Mauermann et al. 2016; Lesicko and Llano 2017). As summarised by Musiek and Chermak (2013), there are three primary hypotheses that attempt to explain the decreased ability of older listeners to understand speech in challenging listening situations. Firstly, the "peripheral hypothesis" suggests that there is age-related dysfunction in the cochlea and eighth nerve which creates difficulty with processing speech. A second "central hypothesis" theory contends that age-related structural changes in the central auditory nervous system explain the difficulty experienced by older adults, regardless of peripheral auditory function. Lastly, "the cognitive hypothesis" suggests that general age-related cognitive deterioration leads to poorer processing in other modalities such as listening and speech processing (Musiek and Chermak 2013). Multiple researchers have concluded that all three systems (peripheral, central and cognitive) contribute in a complex, multiplicative manner and that to successfully communicate, a combination of both peripheral and central auditory pathways as well as cognitive systems need to function effectively (Musiek and Chermak 2013; Parham, Lin et al., 2013; Schneider, Pichora-Fuller and Danemen 2010). Binaural integration and binaural interaction are the CAP skills heavily relied on for interpreting speech in complex listening situations, and are thus most commonly investigated when considering the relationship between cognition and CAP. More recently, temporal resolution has also been a focus of cognitive research (Iliadou et al. 2017). These CAP skills are therefore subsequently defined before reviewing current evidence.

CAP is suspected when there is difficulty understanding speech in the presence of background noise, particularly if peripheral hearing (the ability to hear in quiet) remains relatively normal (Gates et al., 2011). Age-related dysfunction of the central auditory system, otherwise known as central presbycusis, is common, yet poorly understood (Stach et al. 1990; Gates 2012; Kortlang et al. 2016; Lesicko and Llano 2017). Early research showed that like peripheral presbycusis, the prevalence of central presbycusis increases with age (Stach et al. 1990), with 95% of people over the age of 80 years demonstrating signs of central presbycusis (Stach et al. 1990).

5.2. Binaural integration

Binaural integration is an integral aspect of auditory processing which allows a listener to extract meaning from a complex auditory signal by processing competing signals arriving at the two ears (Musiek and Schochat 1998). Listening with both ears is referred to as "dichotic listening", and is a particularly important skill for listening in background noise when conflicting auditory signals are heard and require attention (Musiek and Pinheiro 1985; Asbjørnsen et al. 2000). Commonly, binaural integration ability is assessed by presenting two separate signals to each ear simultaneously. It is expected that with good binaural integration skills that both ears should have similar performance (Kimura, 1967). Tests commonly used for the assessment of binaural integration include the Dichotic Sentence Identification (DSI) and Dichotic Digits Test (DDT) (Gates et al. 2008; Gates, Anderson et al. 2011). These tests differ in complexity (i.e. listening for a whole sentence or two numbers) and time taken to administer. However, both the DSI and DDT have similar degrees of sensitivity (DSI: 83.8%, DDT: 84.0%) and specificity (DSI: 58.6%, DDT: 54.1%), with performance on both showing a significant relationship with cognitive performance (Gates, Anderson et al. 2008; Gates et al. 2010; Gates, Anderson et al. 2011).

5.3. Temporal resolution

Temporal resolution refers to the ability to perceive time-related changes in a continuous auditory stream of information (Iliadou, Bamiou et al. 2017). Timing processes are important for understanding language, as they help to provide pitch and rhythm perception, as well as phoneme discrimination (Phillips 2002; Chermak and Lee 2005; Elangovan and Stuart 2008). Typically, temporal resolution is measured by gap detection tests, where an individual is required to detect the smallest possible gap that occurs in an otherwise constant stimulus (Iliadou, Bamiou et al. 2017). A common test chosen on the basis of clinical guidelines is the Gaps in Noise (GiN) test (American Academy of Audiology 2010). This test is reportedly less cognitively demanding as a motor rather than verbal response is required, providing a more specific measure of temporal processing (Iliadou, Bamiou et al. 2017).

5.4. Binaural interaction

Binaural interaction broadly refers to using two ears and their neural connections to help locate the source of a sound by comparing both arrival time and intensity differences (Cameron et al. 2006). This process contributes to the "cocktail party effect" – the ablity to understand what one person is saying when others are speaking at the same time in the background (Cherry 1953). It has been demonstrated that when a signal is spatially separated from noise, there is a significant improvement in understanding equivalent to 12 dB of amplification (Brown et al. 2010). When people are unable to gain benefit from binaural interaction cues when a signal and distractor are spatially different, a spatial processing disorder may be suspected (Glyde, Hickson et al. 2011; Cameron et al. 2014). Tests of binaural interaction commonly include the Synthetic Sentence Identification with Ipsilateral Competing Message (SSI-ICM) and the Listening in Spatialised Noise-Sentences (LiSN-S) test. SSI-ICM has presented with a reasonable sensitivity and specificity (78.5% and 60.8% respectively) and is commonly used in past research (Gates, Anderson et al. 2008; Gates, Gibbons et al. 2010; Gates, Anderson et al. 2011). More recently, studies have also begun to consider how LiSN-S may relate to cognition (Glyde, Cameron et al. 2013; Besser, Festen et al. 2015). LiSN-S has been shown to have no significant practice effects or gender effects, with limited inter- and intra-participant variation in those over the age of six (Cameron et al. 2006; Cameron and Dillon 2007).

5.5. Summary of the literature

A systematic review of the literature concluded that CAP disorders may exist several years before a diagnosis of AD (Iliadou and Kaprinis, 2003). The review also suggested that CAP dysfunction may precede AD by a minimum of five years and a maximum of ten years. CAP assessments include tests of sound localisation, phoneme discrimination, tonal memory and perception of tones. Of note were clinical psychoacoustic results that involved binaural integration for AD patients. These tests in particular revealed significantly lower scores in the AD group in comparison to normal-hearing controls (Iliadou and Kaprinis, 2003).

Table 2 presents eight studies that have considered the relationship between CAP and cognitive function as measured by either tests of binaural integration, temporal resolution or binaural interaction. One of these studies, which used a cognitive screening tool, found that the ability to listen in background noise was significantly correlated with cognitive performance, but only before age and peripheral hearing was accounted for (Glyde, Cameron et al. 2013). This study demonstrated that central and peripheral hearing, age and cognition share some associations, however it did not provide specific evidence for a direct connection between CAP and cognition. However, as previously highlighted, it is important to note that only a screening tool was used to measure cognition in this study. More recently, a study using tests of temporal resolution investigated the link between CAP and cognitive dysfunction (Iliadou, Bamiou et al. 2017). In this study, the GiN test provided a measurement of left temporal cortical thinning associated with the transition between MCI to AD (Iliadou, Bamiou et al. 2017). This study thus links the relationship between CAP and cognition on a structural rather than purely behavioural level, providing further information on not only *whether* CAP and cognition are related but also *how*.

As mentioned earlier, ARHL can lead to morphological changes in the central auditory system in the eighth nerve, brainstem and auditory cortex (Jorgensen 1961; Kirikae Sato et al. 1964; Schuknecht 1964; Krmpotic-Nemanic 1971; Stach, Spretnjak et al. 1990). As dementia is associated with morphological changes in the affected person's brain, when investigating the link between cognition and CAP, considering the results of objective electrophysiological studies may assist with further understanding how cognition and CAP are related. Many behavioural tests of CAP rely on the use of cognitive resources such as memory and attention, which may make interpretation of results difficult. There is some evidence to suggest that the results of central Auditory Evoked Potentials (AEPs) are different in children diagnosed with CAP disorder, who have poorer morphology, to those without (Tomlin and Rance 2016). Furthermore, in adults, AEPs are impacted by cognitive ability (semantic memory) in auditorily presented tasks (Bentin et al. 1993; Kutas and Federmeier 2000). There is therefore some evidence that electrophysiological function may be poorer when CAP is present, and also when there is poorer cognitive ability. Electrophysiological research in populations with CAP difficulties and cognitive ability in older adults is limited. As discussed previously, a recent study has shown that cortical thinning of the temporal lobe, associated with poor behavioural performance on a CAP test, was associated with the transition between no cognitive impairment to MCI. This study thus has begun to highlight the value of combining morphological and behavioural measures in assessing the relationship between CAP and cognition (Iliadou, Bamiou et al. 2017). Given the current evidence of abnormal AEPs in children with CAP disorder and of the impact of cognitive processes on AEPs, further behavioural and electrophysiological research is required to increase our understanding of the relationship between CAP ability and cognition.

Table 2. Summary of research investigating the relationship between central hearing loss and cognitive decline.

Author	Population	Auditory processing measures	Auditory domain	Cognitive measures	Conclusion
Iliadou et al. (2017)	29 participants; a group diagnosed with mild cognitive impairment ($N = 18$) aged 51–82 years and a group with no cognitive impairment ($N = 11$) aged 50–73 years.	GiN test.	Temporal resolution.	Those with MCI were examined with: • Clinical Dementia rating. • MMSE. • Montreal Cognitive Assessment.	Scores on the Gaps in Noise test were significantly poorer in the MCI group than in the group with no cognitive impairment.
Besser et al. (2015)	52 participants; a younger group ($N = 26$) aged 18–27 (m=21.7, SD = 2.6) and an older group ($N = 26$) aged 66–82 ($m = 72$, $SD = 4.3$).	LiSN-S: high cue, low cue, spatial advantage, talker advantage and total advantage measure.	Binaural interaction and spatial processing.	Montreal Cognitive Assessment.	Poorer Listening in Spatialised Noise-Sentences test speech reception thresholds were predicted by poorer MoCA scores in the older group but none of the advantage measure scores.
Glyde et al. (2013)	80 participants; 7–89 years ($m = 50.17$, $SD = 26.33$).	LiSN-S: high cue, low cue, spatial advantage, talker advantage and total advantage measure.	Binaural interaction and spatial processing.	COGNISTAT screening tool.	All Listening in Spatialised Noise-Sentences test measures apart from the talker advantage measure were significantly correlated with COGNISTAT scores, but only before age and hearing thresholds were accounted for.
Gates et al. (2011)	274 participants ($m = 79.6$, SD=5.2); 21 were diagnosed with dementia.	SSI-ICM DSI DDT	Binaural interaction and binaural integration.	Cognitive Ability Screening Instrument. Diagnosis of dementia based on Diagnostic and Statistics Manual (IV).	Mean scores on each central auditory processing test were significantly poorer in the dementia group.
Gates et al. (2010)	313 participants; 232 cognitively normal, 60 memory- impaired, and 21 with dementia.	SSI-ICM DSI DDT	Binaural interaction and binaural integration.	Cognitive Ability Screening Instrument. Mental concentration and category fluency subtests.	All three measures of central auditory processing were significantly associated with executive function.
Gates et al. (2008)	313 participants; 232 control participants without dementia (m=78.8, $SD = 4.7$), 64 memory- impaired without AD (m=82.3, $SD = 6.1$) and 17 memory-impaired with AD (m=84.0, $SD = 5.1$).	SSI-ICM. DSI DDT	Binaural interaction and binaural integration.	Cognitive Ability Screening Instrument.	The mean score on each central auditory test significantly different across the three cognitive groups, with the control group performing the best and the memory impaired with AD performing the worst.
Gates et al. (1996)	1 662 aged 63–95 (m=72).	SSI-ICM Staggered Spondaic Words (SSW) Phonetically Balanced Words.	Binaural interaction.	MMSE	Central auditory dysfunction preceded senile dementia in a significant number of cases. Higher chance of being diagnosed with dementia if synthetic sentence identification scores were poor in one ear, which doubled if scores were poor in both ears.
Gates et al. (1995)	82 aged 65 to 74 participants, either non-demented ($N = 40$) or with probable Alzheimer's Dementia ($N = 42$).	SSI-ICM or Contralateral Competing Message.	Binaural interaction.	Clinical criteria and the Clinical Dementia Rating Scale, which was used to distinguish between participants who were either cognitively normal or had dementia.	Central auditory function (as measured by competing noise tests) was significantly reduced for those with dementia.

6. Summary and conclusion

Consideration of the wider literature examining the relationship between HI and cognition highlights the need to consider a range of auditory abilities. Results of decades of research have consistently demonstrated a connection between HI and cognition. Early research on the relationship between hearing loss and cognition considered hearing loss only on a peripheral level as measured by PTA, or via self-reported hearing loss, with a significant relationship between peripheral hearing and cognition/cognitive impairment found (Granick et al. 1976; Uhlmann, Larson et al. 1989; Lindenberger and Baltes 1994; Gates 2012; Gurgel, Ward et al., 2014; Amieva et al. 2015). The ability to interpret a sound signal however, does not rely on peripheral auditory structures alone. Central auditory structures (such as the auditory nerve and auditory cortex) are also required for the successful transmission of a sound signal. As with peripheral hearing loss, a relationship between cognition/cognitive impairment and CAP has become evident. For example, CAP disorders have been found to exist several years before the diagnosis of AD, with poorer scores on CAP tests increasing the relative risk of dementia (Gates, Cobb et al. 1996). Correlations between CAP function and performance on cognitive tests have also been demonstrated (Gates, Anderson et al. 2008; Gates, Gibbons et al. 2010).

Although there is evidence of a relationship between peripheral and central auditory function and cognition, methodology has not been consistent across studies. For example, when measuring cognition, the most commonly used test has been the MMSE, a screening tool which lacks sensitivity when the degree of dementia is not severe (the MMSE has an 18% sensitivity for MCI) (Uhlmann, Larson et al. 1989; Munshi et al. 2006; Gurgel, Ward et al. 2014; Amieva et al. 2015; Hong et al. 2016). Other studies have examined individual domains of cognition (e.g. memory, executive function etc.) (Valentijn et al. 2005; Lin et al. 2011) and some have compared groups of people diagnosed with dementia and those with no dementia diagnosis (Uhlmann, Larson et al. 1989; Gates, Karzon et al. 1995). In terms of classification of hearing loss, many studies have used audiometric data to calculate a PTA. However, the frequencies tested and used in these analyses differed across studies. Even though high frequency hearing is more impaired in older people, many studies still used mid-range frequency averages, which may have underestimated the overall degree of HI. Similarly, in terms of CAP tests used, many studies have focussed on the singular CAP domains (e.g. temporal resolution and binaural integration) and not on the direct testing of performance in background noise, which is a major difficulty in ARHL (Gates, Anderson et al. 2008; Iliadou, Bamiou et al. 2017). Further research relied on subjective perceptions of hearing loss, which in addition to being inaccurate (Lin et al. 2011) does not enable a determination of whether the impairment is peripheral and/or central to be made. Additionally, in much of the research conducted to date, peripheral and central hearing have been treated as two separate entities. Early research by Gates et al. (1995) examining both peripheral hearing (as measured by PTA) and binaural interaction skills and found that it was only the latter that were significantly poorer in a population of older adults with probable dementia. However, it is unclear if all or only some of the participants in this study had both a peripheral and CAP deficit. Given the above methodological limitations, there is therefore no definitive understanding of how HI and cognition are related, but rather multiple and differing causal theories (Wayne and Johnsrude 2015). What does appear clear however, is that assessing hearing not only peripherally but also on a central level may help to define this relationship, especially when considering any underlying neurophysiological connections that may exist, such as dementia-related atrophy of the temporal lobe.

This narrative review has assessed a broader range of studies compared to previous reviews in the area such as Taljaard et al. (2016), who were limited to stricter search criteria. This includes research investigating the relationship between CAP and cognition, an idea postulated but not explored within the literature in detail by Wayne and Johnsrude (2015). Research on both peripheral and central HI collectively supports a relationship between these variables and cognition. However, the exact nature of this relationship is yet to be defined. Future research should address some of the methodological limitations of previous work to further explore this. The use of more comprehensive cognitive assessment tools that consider different domains of cognition may help to identify whether only certain cognitive domains are driving this relationship. Furthermore, the use of a wider and more appropriate assessment of peripheral hearing loss (e.g. low and high frequencies, poorer or better ear etc.) would yield important information. When testing CAP, the use of tests which replicate real-life listening situations (such as the LiSN-S test) (Cameron and Dillon, 2009) would help to assess the primary complaint of CAP disorder, along with tasks specifically measuring domains of processing. Additionally, comparing cognitive performance between individuals with peripheral and/or central HI would help to further define the relationship between HI and cognition. Lastly, in terms of support for hearing and/or cognitively-impaired patients, this knowledge could be useful in the prescription and management of rehabilitation devices such as HAs. Additionally, if older patients with ARHL are identified as being at higher risk of cognitive impairment, appropriate referrals and management may be generated with reduced cost and time (Gates, Anderson et al. 2011). Thus, considering the *how* of the relationship between HI and cognition and the *so what* in terms of patient outcomes should be the main goals of future research.

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2.4 ADDITIONAL LITERATURE

In the time since the submission of the narrative review, a substantial number of papers evaluating the hearing-cognition link have been published. Of significant interest was a finding only briefly touched on in the narrative review - the Lancet Commission’s recognition of hearing loss as a modifiable risk factor for cognitive decline (Livingston et al., 2017). Peripheral age-related hearing loss was identified as a significant risk factor for incident dementia with a pooled risk ratio of 1.94. Moreover, it was estimated that approximately 9% of dementia globally may be reduced if hearing loss was minimised (Livingston et al., 2017). This approximation was based on a meta-analysis of the results of three large studies which presented evidence for an association between hearing loss and cognitive function, as detailed in the published literature review.

Since Livingston et al.’s (2017) publication, further evidence on the existence of a relationship between hearing and cognition has become available, albeit with mixed findings. A systematic review and meta-analysis presented by Loughrey and colleagues in 2018 found a small but statistically significant association between peripherally measured age-related hearing loss and cognition. They reported a significant negative association between increased hearing loss and cognitive function across multiple cognitive domains including memory (episodic and semantic), processing speed, visuospatial ability, executive function and overall cognitive performance; the presence of increased cognitive impairment in both cross-sectional and cohort study designs that included those with age-related hearing impairment; and associations between the presence of age-related hearing loss and dementia (Loughrey et al., 2018). In another study published in 2018, poorer hearing impairment measured at baseline (defined by 4FA in the better hearing ear) was associated with cognitive decline across a two-year period in older adults (Armstrong et al., 2018). In this instance however, associations were found only with tests of auditory attention and verbal memory, and not with any visually presented task. As detailed in the narrative review, administering cognitive assessments using audition may have potentially confounded the results of this study. Additionally, the changes in cognitive performance were not correlated with the degree of deterioration in hearing, with the authors suggesting that decreased peripheral auditory function may have affected verbal cognitive abilities in a short time-frame. Although this research was arguably limited by the method of presentation of cognitive assessments, the findings were later supported by those of further longitudinal studies. In a large longitudinal study over eight years among over 10 000 males, self-reported hearing loss was significantly associated with higher subjective reports of cognitive decline (Curhan, Willett, Grodstein, & Curhan, 2019). In comparison to normal-hearing participants, the risk of subjective cognitive decline was 30% higher in men with a reported mild hearing loss, increasing to up to 54% in those with a moderate or worse hearing loss (Curhan et al., 2019). The methodology of this study was again limited, in this instance by its reliance on self-report which has been shown to provide unreliable information. However, the large number of participants, in addition to the longitudinal nature, provides promising results in support of the conclusion presented by the Lancet Commission that hearing loss is a modifiable risk factor for dementia. Further evidence that increased hearing loss is significantly associated with incident dementia was provided by an even larger retrospective propensity-matched cohort study in the United States (Deal et al., 2019). Over five- (*n* =44 852) and ten- (*n* =4 728) year periods, peripherally-measured hearing loss at baseline was significantly associated with an approximate relative risk increase of 1.5 in incident dementia at five years. The ten-year relative risk that was attributed to hearing loss was 3.2 per 100 persons for dementia (Deal et al., 2019). Another interesting finding of this research was that hearing loss measured at baseline significantly increased the risk of depression at five- and ten-year time points.

These recent findings continue to support the existence of a significant association between hearing and cognition. However, if the claim by Livingston and colleagues (2017) that hearing loss is a modifiable risk factor for dementia is to be verified, more research is required to identify whether there is a causal relationship between hearing and cognitive impairment, and if so, what can be done to help prevent dementia through targeting the remediation of hearing loss.

Research in mice also provides support for the theory that the relationship between hearing and cognitive impairment is causal in nature (Park et al., 2016). At six months after noise exposure , a group of mice with noise-induced hearing loss demonstrated significantly poorer performance on memory tasks than did a control group (Park et al., 2016). This result may not be applicable to those with age-related hearing loss (in comparison to noise induced) however, as age appears to be a significant factor mediating the relationship between hearing and cognition (Wu & Chiu, 2016).

Since the submission of the literature review, two additional papers have been made available detailing the impact of hearing aids on cognition for older adults with hearing loss. Both studies, published in 2019 found no significant improvement in cognition through hearing aid use (Curhan et al., 2019; Nkyekyer, Meyer, Pipingas, & Reed, 2019). The large, longitudinal study presented by Curhan et al. (2019) found only a small positive impact of self-reported hearing aid use on subjective cognitive decline, however this difference was not statistically significant. As mentioned previously, similar to earlier studies assessing the impact of hearing aid use on cognition, this study was limited by reliance on categorical and self-reported measures (“yes” or “no”) of hearing use. Another shorter study presented by Nkyekyer et al. (2019) similarly found no improvement in cognition with full-time hearing aid use (as tracked with objective internet-based data logging) and auditory training. However, the data-collection period was only six-months after hearing aid fitting in this instance, which may not have allowed sufficient time for a cognitive effect (if there was one) to be seen. An additional factor that may have impeded the ability of these studies to find an effect of hearing aid use, was the lack of a significant association between cognitive function across multiple domains and peripheral hearing thresholds at baseline. In this study, it was the participant’s speech perception ability and not pure-tone thresholds that were significantly correlated with the multiple domains of cognition measured (i.e. the eight cognitive domains measured by the SUCCAB cognitive assessment tool) (Nkyekyer et al., 2019).

A common theme of recent research, consistent with much of the previous research, is the focus on peripheral hearing loss and not on measurements of central auditory processing such as speech perception ability in background noise. Aside from the findings of Nkyekyer et al. (2019), which recognised that speech perception ability and not peripheral hearing thresholds, was primarily related to multiple cognitive domains of cognitive performance, little research has explored central auditory processing specifically in the years since the submission of the narrative review. This is despite the fact that researchers continually highlight the importance of considering central auditory processing in the relationship between hearing and cognition particularly in understanding any potential causal mechanisms (Panza, Solfrizzi, & Logroscino, 2015; Wayne & Johnsrude, 2015). In some cases, it has even been suggested that tests of central auditory processing may have "greater predictive value for incident AD or dementia than do other commonly used cognitive tests" (Panza et al., 2015, p. 7). With this in mind, it is clear that more research on the hearing-cognition link is necessary, particularly in the area of central auditory processing. Additionally, there continue to be significant methodological limitations in the current literature which need to be addressed. Overall however, more and more evidence is highlighting the important role hearing impairment seems to play in cognitive decline. With a growing aging population, it is imperative to understand the burdens facing older adults and to better understand the complex relationship between age-related health conditions. This is particularly true if the treatment of hearing impairment may reduce the impacts of cognitive decline. Moreover, audiologists currently focus on peripheral audiometric data for assessing and managing patients, but there may be hearing (and cognitive) difficulties beyond what is recognised in the audiogram contributing to patient disability. Furthermore, extensive research is necessary to see how hearing rehabilitation impacts, and is impacted by, cognitive function.

2.5 RESEARCH QUESTIONS, AIMS AND HYPOTHESES

2.5.1 Study 1: The Relationship between Peripheral Hearing Loss and Higher Order Listening Function and Cognition in Older Adults.

Research question: Are there relationships between level of hearing impairment, auditory processing ability, and cognitive function as measured by scores on the Cogstate cognitive test battery?

Hypothesis: There will be a positive relationship between poorer scores on the Cogstate cognitive test battery and: 1) increased level of peripheral hearing impairment, and 2) decreased binaural integration and interaction performance.

2.5.2 Study 2: Spatial Processing Ability and Executive Function in Older Australians.

Research question: Is there a difference in cognitive function between those presenting with hearing loss alone and those with both hearing loss and impaired higher order listening function as measured by scores on cognitive tests and psychoacoustic speech perception measures respectively?

Hypothesis: Those presenting with both hearing loss and impaired higher order listening ability will perform more poorly on tests of cognition than those presenting with hearing loss alone.

2.5.3 Study 3: Hearing Aid Uptake, Benefit and Use: The Impact of Hearing, Cognition and Personal Factors.

Research question: Are there factors (e.g. hearing thresholds, cognitive function, auditory processing or personal) that influence the uptake, use and/or perceived benefit of hearing aids?

Aims and Hypotheses: The first aim of the study was to assess whether degree of hearing loss and cognition had an impact on whether individuals chose to uptake HAs, and it was hypothesised that the uptake of hearing aids would be positively influenced by poorer hearing measured peripherally and/or through tests of CAP. The second aim of the study was to assess whether degree of hearing loss and/or cognition influenced self-reported HA benefit and use in the HA-user group. It was hypothesised that poorer hearing would have a positive influence on HA uptake and use. Additionally, health and pscyhosocial factors (as measured through self-reported measures) were also hypothesised to positively influence HA uptake, perceived benefit and use.

It was also hypothesised that cognitive performance would influence hearing aid uptake (aim 1), perceived benefit and use (aim 2).

CHAPTER 3 METHODS

The following chapter summarises the participants, procedures and tests presented in the following chapters.

3.1 ETHICS

This study was approved by the School of Health Sciences Human Ethics Advisory Group of the University of Melbourne (Ethics ID: 1748836). Written informed consent was obtained from all participants.

3.2 PARTICIPANTS

85 adults who attended the University of Melbourne Audiology clinic and who met the below inclusion criteria were enrolled into this study. There were 40 males, 44 females and one non-binary individual, between the ages of 60.33 and 80.08 (*m =70.23, SD = 5.17*). Group demographics are provided in chapter 4.

All participants met the following inclusion criteria:

1. Aged 60 years or above.
2. No previous diagnosis of dementia.
3. Had not been previously fitted with (or used) a hearing aid in the last year.

4. Deemed unlikely by clinicians or family to have dementia at initial screening assessment.
5. Did not present with a visual or English impairment that precluded the ability to complete the assessment tasks.

3.3 SOCIOECONOMIC STATUS

Based on residential postcode information for each of the participants, an Index of Relative Socio-economic Advantage and Disadvantage (IRSAD) was recorded. The ISRAD, calculated from the Australian-Bureau-of-Statistics (2018), provides information about the social and economic conditions within an area, with a higher score indicative of greater advantage in general. All provided scores are standardised to a distribution with an average of 1000 and a standard deviation of 100. All areas were also ordered from lowest to highest index score, with the lowest 10% of areas given a decile number of 1 and the highest 10% of areas given a decile number of 10, dividing indexes into 10 equal-sized groups.

3.4 TEST BATTERY

3.4.1 Audiological assessment

All participants were assessed by an audiologist as part of the University of Melbourne Audiology Clinic standard diagnostic test battery. Audiometric assessment included: bilateral air conduction thresholds at octave frequencies between and including 250 Hz and 8000 Hz, 3000 Hz and 6000 Hz, bilateral bone conduction thresholds at octave frequencies between and including 500 Hz and 4000 Hz, and tympanometry (with tympanograms defined as outlined by Jerger (1970)). PTA was assessed using the Interacoustics Affinity 2.0 Audiometer in a sound proof room. Degree of hearing impairment was classified as either normal (<20 dB HL), mild (20 to 40 dB HL), moderate (45-65 dB HL), severe (70-90 dB HL) or profound (>90 dB HL) (Clark, 1981; Davis & Silverman, 1970). It is worth noting that the World Health Organization have revised the grading system of hearing impairment (see Humes (2019)) and as such, this research used PTA values as a continuous variable rather than categorical in analysis to allow for various definitions of hearing impairment. A low frequency (250 Hz, 500 Hz and 1000 Hz) and high frequency average (>1000 Hz) was calculated for both ears. As a reflection of past literature, a four frequency average of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz was used to summarise overall hearing (Besser et al., 2015).

3.4.2 Auditory Processing Assessments

The Auditory Processing (AP) test battery was chosen to assess the domains of binaural integration and the ability to use spatial and talker advantage cues in complex listening environments. The tests included in the battery were a reflection of past literature in the area (Gates et al., 2008a; Gates et al., 2011). Additionally, the tests were readily accessible and quick to administer. The two tests selected were the Dichotic Digits Test (DDT) and the Listening in Spatialized Noise-Sentences (LiSN-S) test. Both of these tests have demonstrated moderate to strong test-retest reliability (Cameron et al., 2009; Moore, Cowan, Riley, Edmondson-Jones, & Ferguson, 2011; Musiek, Gollegly, Kibbe, & Verkest-Lenz, 1991; Sharma, Purdy, & Kelly, 2012).

3.4.2.1 The Dichotic Digits Test

The DDT (Musiek, 1983) assesses binaural integration and requires the participant to repeat four numbers (two presented simultaneously to each ear) out of a total of 20 trials, with an additional three initial practice trials. The test was performed under headphones at a volume reported as both clear and comfortable for the participant. If a hearing asymmetry was present, volume levels were balanced until the participant reported the volume to be subjectively equal in both ears. Percentage scores were calculated for each ear, and these were converted into Z scores based on an equivalent-age normative score of 12 years, where full maturity of auditory processing skills are expected to be developed, with a standard deviation score below -2.0 being considered a deficit in function (Tomlin, Dillon, & Kelly, 2014). A difference in performance between the left and right ear was also calculated, and a significant asymmetry was defined as a difference between ears of 20% or greater (Moncrieff, Keith, Abramson, & Swann, 2017).

3.4.2.2 The Listening in Spatialised Noise-Sentences test

The LiSN-S test (Cameron & Dillon, 2007) assesses how an individual performs in background noise when there is an advantage of spatial separation or voice cues. A three-dimensional auditory environment in which there is one target speaker and multiple distractors is created under headphones. Four conditions are created from differing combinations of spatial separation (either 0º or ±90º) of the target speaker and distractors, and with voice cues (distractors either have the same or different voices to the target speaker). Two speech reception thresholds are calculated from a high cue condition (target and distractors are spatially separated by 90° with speaker differences) and a low cue condition (target and distractors are from the same direction with the same voice). Also reported is the spatial and tonal advantage score which is the dB improvement that results from spatial and tonal cues. A deficit in spatial processing was identified if there was a pattern of depressed scores on the spatially separated conditions of the LiSN-S in comparison to conditions where the signal and distractor were co-located. That is, a spatial processing deficit pattern was recognised when standard deviations of high-cue SRT and spatial advantage scores (i.e. conditions where target and distractor were separated by 90°) were poorer than the standard deviations of low cue and talker advantage scores (i.e. conditions where target and distractor were not spatially separated) (Cameron, Dillon, Glyde, Kanthan, & Kania, 2014).

The LiSN-S was administered using a personal computer, Sennheiser HD215 circumaural headphones and a Buddy 6G USB soundcard. Initial presentation level for the speaker was 62dBSPL and for the distractor 55 dB SPL. The participant was required to repeat the target sentence heard for up to a total of 30 sentences in each condition (fewer sentences were completed if a minimum of 17 sentences were scored and their standard error was calculated at less than 1dB). The Signal to Noise Ratio (SNR) was adjusted adaptively in response to a participant's scores (i.e. if a participant scored more or less than 50% of the number of words in a sentence correct, the SNR decreased or increased by 2dB respectively – a score of exactly 50% resulted in the SNR remaining the same) (Cameron et al., 2014).

All participants were assessed in LiSN-S prescribed gain amplifier mode, in which a participant's bilateral hearing thresholds (for both bone- and air-conduction) were entered. This mode amplifies and shapes the target and distracting stimuli according to the National Acoustic Laboratories – Revised Profound (NAL-RP) prescription (Cameron et al., 2014; Glyde et al., 2013). This amplified signal is designed to negate the effect of peripheral hearing impairment on the performance on the LiSN-S test. At the time of testing, age-related norms for the results of the LiSN-S were only available for those between the ages of six and 60 years. As such, when calculating standard deviations scores, all participants were compared to age-related norms of a 60 year old (Cameron et al., 2009; Cameron & Dillon, 2007).

3.4.3 Cognitive Testing

3.4.3.1 Cognitive Screening – The Mini Mental State Examination

Cognitive screening was conducted for all participants before any testing commenced. The Mini Mental State Examination (MMSE) (Folstein, Folstein, McHugh, & Fanjiang, 2000) was used. The MMSE is a brief assessment (approximately 5-10 minutes) that tests cognitive function in older adults (Folstein, Folstein, & McHugh, 1975; Godin, Keefe, & Andrew, 2017). It was chosen as it was clinically convenient (fast and non-invasive) and one of most commonly used screening instruments for the detection of AD (De Roeck, De Deyn, Dierckx, & Engelborghs, 2019; Folstein et al., 1975). The MMSE has a reported high specificity (96%) and a lower sensitivity (64%) (Munshi et al., 2006). The MMSE is scored out of a total of 30. A score of <24 was considered abnormal and patients were required to achieve a score within the normal range in order to continue with the test battery (Folstein et al., 1975).

3.4.3.2 Cogstate

The Cogstate Brief Battery (CSBB) was used as the primary outcome measure in this study, consisting of four tasks with an additional fifth task (the Groton Maze Learning Test) which is commonly used in the Cogstate Alzheimer's Battery (Collie et al., 2003; Falleti, Maruff, Collie, & Darby, 2006; Maruff et al., 2009; Westerman, Darby, Maruff, & Collie, 2001). The tests are subsequently described. The test battery was presented on a Windows laptop with an additional wired mouse. Two conditions were run, with at least a 30-minute break between conditions. The first condition was a practice condition in which the assessor remained in the room with the participant. The instructions were presented on a screen for the participant to read and were also read out loud by the assessor to minimise any effect of vision or hearing difficulties. A smaller version of each of the tasks was then given in an interactive demonstration. Once participants demonstrated an understanding and ability to perform the task, the full task began. The four tasks from the CSBB were in the form of card games in which the participant was required to respond "yes" and/or "no" to a stimulus via the right and left mouse click or the "k" and "d" keys on the keyboard (this was the participant's choice). The second condition consisted of exactly the same test battery and was the condition for which the results were recorded. This was performed independently, with the assessor outside of the room. Two conditions only were performed, as it has been demonstrated that after the second assessment, performance remains relatively stable, with test-retest reliability for each measure estimated to range between .84 and .94 (Collie et al., 2003; Falleti et al., 2006; Maruff et al., 2009). Each recorded result was calculated for both the speed and accuracy of response (reported as a percentage correct/incorrect) and raw scores were then transformed to produce normalised data distributions (Falleti et al., 2006; Maruff et al., 2009).

The Groton Maze Learning Test assessed *executive function* and typically takes seven minutes to administer. Using a maze learning paradigm, it measures the total number of errors made when attempting to learn the same hidden pathway across five trials presented immediately after one another. A 10 x 10 grid of tiles is presented on the computer screen and the participant is required to find a ‘hidden’ 28-step pathway from the top left corner of the grid (start titles indicated by a blue square) to the bottom right corner (finish tile indicated by red circles) of the grid. The participant is required to move one tile at a time in either a horizontal or vertical direction, one space from the previous correct tile. A green tick indicates a correct move and a red cross indicates an incorrect move (Cogstate, 2017).

The Detection Test assessed *psychomotor function* and typically takes three minutes to administer. The participant must respond “yes” when a card in the centre of the screen turns over. The task continues until 25 correct responses are obtained, or the maximum time limit (two minutes) has been reached (whichever occurs first). Speed of performance (in milliseconds) to complete the task (mean of the log10 transformed reaction times for *correct* responses) is recorded (Cogstate, 2017; Maruff et al., 2009).

The Identification Task assessed *attention* and typically takes three minutes to administer. It measures attention using a choice reaction paradigm in which the participant must answer “Is the card red?” when a playing card in the centre of the screen turns over. Using the “yes” or “no” responses, the participant is instructed to respond as quickly and accurately as possible. Speed of performance (in milliseconds) to complete the task (mean of the log10 transformed reaction times for *correct* responses) is recorded (Cogstate, 2017; Maruff et al., 2009).

The One Card Learning Test assessed *visual learning* and typically takes six minutes to administer. It measures visual learning using a pattern separation paradigm in which the participant must answer “Have you seen this card before in this test?” when a playing card in the centre of the screen turns over. The participant must respond “yes” if they believe they have seen the card before in the task, and “no” if not. Accuracy of performance (arcsine transformation of the square root of the proportion of correct responses) is recorded (Cogstate, 2017; Maruff et al., 2009).

The One Back Test assessed *working memory* and typically takes four minutes to administer. It measures working memory using an n-back paradigm in which the participant must answer “Is the previous card the same?” when a playing card in the centre of the screen turns over. The participant must respond “yes” if they believe the card was the same as the previous card that was presented, and “no” if not. Both the speed and accuracy of performance are measured (using mean of the log10 transformed reaction times for *correct* responses and arcsine transformation of the square root of the proportion of correct responses respectively).

3.5 QUESTIONNAIRES

3.5.1 Take Home Questionnaires

On the day of assessment, participants were given six self-administrated questionnaires (see appendices) with a return envelope, with instructions to complete the questions any time prior to their hearing aid fitting. In total, the questionnaires were estimated to take no more than one hour to fill in. The questionnaires chosen assessed a variety of potential cofounding variables, and had moderate to high test-retest correlations (Boston College, 2017; Cox & Alexander, 1995; Crook, Feher, & Larrabee, 1992; De Jong-Gierveld & Kamphuls, 1985; Furlong, Feeny, & Torrance, 2000; Zigmond & Snaith, 1983). The questionnaires are subsequently described.

3.5.1.1 Case/Educational History

The Case History Questionnaire contained four sections which collectively provided a detailed health history including: family medical history (including family history of psychological and neurological illnesses), personal health history (including previous/current: medical conditions, medications, smoking and alcohol use), hearing history (including any noted changes to hearing, diagnosis of loss, degree of loss etc.) and a history of the etiology of the hearing loss (including known causes, family history, and tinnitus).

The Educational History Questionnaire contained four questions which identified the participant’s highest completed level of education.

3.5.1.2 Lubben Social Network Scale

The Lubben Social Network Scale (LSNS-18) is an extended version of the original LSNS questionnaire (Lubben, 1988) designed to assess social isolation in older adults through questions pertaining to perceived social support received by family, friends and neighbours. Participants answered 18 questions (e.g. “How many relatives do you see or hear from at least once a month?”) on a five-point scale ranging from 0 to 5 (e.g. “0=none” to “5=nine or more”). The numbers are added to provide a total score with a higher score indicative of less social isolation (Boston College, 2017; Lubben et al., 2006; Lubben, 1988).

3.5.1.3 Loneliness Scale

The Loneliness Scale (De Jong-Gierveld & Kamphuls, 1985) is a scale consisting of 11 items, six of which are negatively formulated. Participants are required to circle the appropriate answer to questions pertaining to social and emotional loneliness (e.g. “There is always someone I can talk to about my day to day problems”) on a five-point scale (“Yes!”, “Yes”, “More or less”, “No” and “No!”). From this, social, emotional and total loneliness scores are calculated, with a higher score indicative of a greater degree of loneliness (De Jong-Gierveld, 1999; De Jong-Gierveld & Kamphuls, 1985).

3.5.1.4 Memory Complaint Questionnaire

The Memory Complaint Questionnaire (MCQ) (Crook et al., 1992) is a six-item scale measuring age-related memory decline. Participants were asked to compare how they remember now to how they remembered when they were in their “late teen years or early 20s” (e.g. Remember the name of a person just introduced) on a five-point scale from “Much better now” to “Much poorer now”. A higher score was indicative of greater memory complaints (Crook et al., 1992).

3.5.1.5 Hospital Anxiety and Depression Scale

The Hospital Anxiety and Depression Scale (HADS) (Zigmond & Snaith, 1983) is a 14-item questionnaire used to assess generalised levels of anxiety (e.g. “I feel tense or ‘wound up’”) and depression (e.g. “I still enjoy the things that I used to enjoy” (seven-items each). A score of 0 to 3 can be obtained on each question and overall scores range from 0-21 for each category with a higher score indicative of greater levels of generalised anxiety and/or depression (Snaith, 2003; Zigmond & Snaith, 1983).

3.5.1.6 Health Utilities Index Mark 2 and 3

The Health Utilities Index Mark 2 and 3 (HUI2/HUI3) (Furlong et al., 2000) is a 17-item questionnaire used to assess an individual’s overall self-perceived health over the domains of vision, mobility, hearing, cognition, emotion and pain. Scores were calculated according to the Mark 2 and Mark 3 procedures manual (Furlong et al., 2000). A higher number indicated better perceived overall health.

3.5.1.7 Abbreviated Profile of Hearing Aid Benefit

The Abbreviated Profile of Hearing Aid Benefit (APHAB) (Cox & Alexander, 1995) is a 24-item questionnaire that asks a variety of questions about how an individual hears either without and/or with their hearing aid, on a six point scale ranging from “Always” to “Never”. Unaided, aided and benefit scores for the following four subscales were calculated: Ease of Communication (EC), Reverberation (RV), Background Noise (BN) and Aversiveness (AV).

3.5.2 Follow-Up Questionnaires

Participants who selected to use hearing aids in the months following the in-house assessment were sent the following two questionnaires at three and six months post their hearing aid fitting: APHAB (Cox & Alexander, 1995) and a hearing aid case history.

Participants were required to fill in the right-hand column of the APHAB “with my hearing aid” to produce an APHAB aided score. These responses were then compared to the baseline “without my hearing aid” score to produce benefit scores for before their hearing aid(s) and after three months of use, and before their hearing aid(s) and after six months of use.

In the follow-up hearing aid case history, participants were asked a series of questions about how often they used their hearing aid(s), how they used their aids (i.e. left/right/bilateral) and in which situations. This information was used as a subjective report of hearing aid use.

3.5.3 Missing Questionnaires

Any participants that failed to return questionnaires (baseline, three- and/or six-month post HA fitting) were contacted via email, phone and/or letter requesting follow up information.

CHAPTER 4

STUDY SAMPLE DEMOGRAPHICS & INITIAL RESULTS

4.1 OUTLINE

The following chapter presents the demographic characteristics of the study sample and preliminary results that are not included in the later experimental chapters.

4.2 DEMOGRAPHICS

All participants completed tests of peripheral hearing (PTA) and cognition (MMSE and CSBB). Two participants were unable to complete the LiSN-S test due to a profound unilateral hearing loss. Seventy-eight (91.76%) participants returned initial questionnaires. Of the 62 participants who chose to be fitted with hearing aids, 52 (83.87%) returned at least one follow-up HA questionnaire at three-months post HA fitting and 47 (75.81%) returned at least one follow up HA questionnaire at six-months post HA fitting.

There were 40 males, 44 females and one non-binary individual, between the ages of 60.33 and 80.08 (*m =70.23*, *SD = 5.17*). Table 1 presents the demographics of this group.

Table 1. Demographics (*N=85 unless otherwise stated**)

	Mean (SD)[a]/Count (%)[b]	Range
Age[a]	70.7 (5.2)	60.33 to 83.08
MMSE Score[a]	28.9 (1.3)	24 to 30
Pure tone four frequency average[a]		
Better ear	28.9 (8.8)	11.25 to 56.25
Worse ear	36.2 (12.5)	13.75 to 93.75
Socio-Economic Score	1052.2 (49.1)	911.0 to 1130.0
Education level [b] (N=77)		
≤High school	16 (20.78)	-
University degree	47 (61.04)	-
PhD	14 (18.18)	-
Retired [b] (N=75)		
Yes	58 (77.33)	-
No	17 (22.67)	-
Marital status [b] (N=78)		
Single	16 (20.51)	-
Partnered	53 (67.95)	-
Widowed	9 (11.51)	-
LSNS-18[a] (N=78)		
Friends	15.6 (5.57)	0 to 25
Family	18.5 (5.97)	0 to 29
Neighbours	10.3 (5.89)	0 to 22
Loneliness Scale [a] (N=78)		
Emotional	1.3 (1.75)	0 to 6
Social	1.7 (1.77)	0 to 5
MCQ [a] (N=78)	24.6 (3.81)	14 to 34
HADS[a] (N=78)		
Anxiety	4.5 (2.95)	0 to 15
Depression	2.7 (2.42)	0 to 11
HUI[a] (N=78)		
HUI2	0.83 (0.13)	0.28 to 1.0
HUI3	0.76 (0.20)	0.24 to 1.0

[a] Mean (SD), **[b]** Count (%)

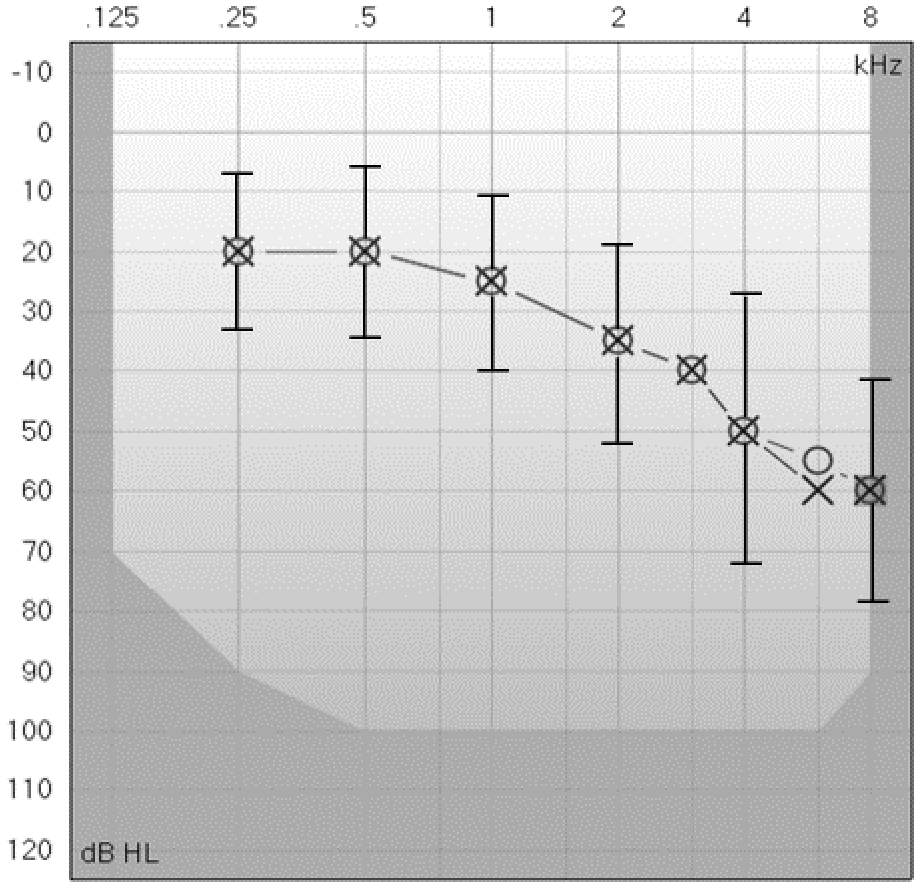
*Reduced N as a result of missing questionnaires

The socio-economic status (SES) of this cohort as defined by the IRSAD score (Australian-Bureau-of-Statistics, 2018) did not follow a normal distribution and was significantly negatively skewed, as displayed by an Anderson-Darling test of normality (AD=5.3, $p<0.005$). Approximately 62% of the participants came from the highest-ranked (top 20%) areas of Australia. No significant relationship was found between participants' SES score and any of the objective test measures (i.e. PTA, DDT, LiSN-S or CSBB primary outcome score), however this result is not surprising given the lack of variation in SES in this cohort.

4.3 HEARING

Figure 1 details the average audiogram across the participants (as averaged by participants audiometric thresholds at each frequency), reflective of a bilateral mild sloping to moderate sensorineural hearing loss that was worse in the high frequencies, consistent with what would be expected in this age group (Helzner et al., 2005). Table 2 provides further detailed information on participants hearing loss.

Figure 1. Average audiogram with standard deviation bars (averaged between left and right ear at intermediate frequencies).



4.4 AUDITORY PROCESSING AND COGNITION

Group descriptive statistics of performance on AP and cognitive tasks, along with the relationship with 4FA and age, are displayed in table 2. As demonstrated, 4FA is significantly correlated with all four LiSN-S conditions and some performance on the DDT. Age was significantly correlated with LiSN-S low cue and spatial advantage performance, some performance on the DDT, and the primary outcome score for executive function. In this cohort, there was no significant correlation found between age and 4FA, (r = 0.134, n = 85, p = 0.221).

4.4.1 The Dichotic Digits Test

The majority of participants obtained a score of greater than 80% on both the left and right ear of the DDT (within normal limits) (Tomlin et al., 2014). The Anderson-Darling test for normality was used to assess whether results were normally distributed and the results were negatively skewed (AD=2.187, $p<0.005$; AD=6.171, $p<0.005$), highlighting a plateau in performance. Nevertheless, 32 participants presented with a left-ear deficit (38.55%) and 9 participants (10.84%) presented with a right-ear deficit. On average, performance was greater in the right ear on the DDT, consistent with Kimura's theory of dichotic listening (Kimura, 1967). This theory suggests that because there are dominant contralateral pathways in the brain and because all speech signals must arrive to the auditory cortex (present on the left side of the brain in more than 95% of the population), that when sound is presented to the left ear, it requires interhemispheric transfer, creating greater neural load. Performance in the left ear was significantly correlated with participants' age (see table 2). This result, in addition to the lack of a significant relationship found between DDT and cognitive tests, further supports previous research presented by Westerhausen, Bless and Kompus (2015). In their research, increased age, without a significant influence of cognitive function, significantly impacted the symmetrical performance of the brain ("laterality"). Left ear performance on dichotic listening tasks was significantly impacted by aging whilst the right ear remained stable with age (Westerhausen et al., 2015).

Table 2

Descriptive statistics and correlations with 4FA and age on performance on auditory processing and cognitive test battery (N=85 unless otherwise stated)

Test	Descriptive Statistics					Pearson Correlation	
	Mean	SD	Median	Minimum	Maximum	**4FA**	**Age**
LiSN-S (SRT) (N=83)[1]							
High cue[a]	-8.743	5.352	-9.6	13.8	-19.8	0.599**	0.149
Low cue[a]	-0.054	1.125	-0.1	2.7	-2.6	0.400**	0.395**
Spatial advantage	8.561	2.565	8.5	2.0	14.0	-0.608**	-0.276*
Tonal advantage	3.518	1.433	3.5	0.4	8.5	-0.230*	-0.054
DDT (% Correct)							
Left ear	82.29	15.59	85	22.5	100	-0.189	-0.239*
Right Ear	90.32	13.42	95	15	100	-0.255*	-0.150
Absolute Difference between ears	12.88	14.28	7.5	0	70	0.237*	0.233*
CSBB (Primary outcome score)							
Attention[a]	2.78	0.06	2.77	2.74	2.94	0.05	0.138
Psychomotor function[a]	2.59	0.09	2.58	2.43	2.85	0.008	0.197
Executive function[a]	53.86	16.08	44.0	25.	116	0.170	0.253*
Visual learning	0.98	0.11	1.01	0.55	1.23	0.050	-0.015
Working memory[a]	2.95	0.09	2.71	2.95	3.15	0.076	0.147

[1] Two participants were unable to complete LiSN-S

[a] Results are reversed score with a lower score indicating better performance

*P<0.05, **P<0.001.

4.4.2 Listening in Spatialised Noise sentences tests

Unlike the DDT, excluding the high cue LiSN-S condition, results from all other conditions on the LiSN-S test were significantly correlated with at least one cognitive measure. These findings are subsequently described in the results chapters (chapter 5 and 6).

In this cohort, most participants (74.12%) performed outside of normal limits (as compared to a 60-year-old normal-hearing performer) in the high cue LiSN-S condition with PGA. This is consistent with previous reports that understanding speech in background noise (with or without amplification) is a common issue for hearing- impaired adults, despite amplification (Glyde et al., 2011), particularly given the moderate correlation found between poorer high cue performance and poorer hearing thresholds (see table 2). In contrast with previous research, in this cohort of 85 individuals, age was not related to high-cue LiSN-S performance, however in comparison to other studies such as Cameron, Glyde and Dillon (2011) with 132 participants aged 12 years to 60.6 years, and Glyde et al. (2013) with 80 participants aged 7 to 89 years, this sample size and age range was smaller.

As previously mentioned, the LiSN-S test aims to identify spatial processing disorder in individuals. In this cohort, 49 (59.04%) of participants presented with a spatial processing disorder. This result is not surprising given that all participants had some degree of hearing loss, and that spatial processing as measured by the spatial advantage measure has previously been shown to be negatively affected by hearing impairment (Glyde et al., 2013). This finding was further supported in this study with spatial advantage measure performance negatively correlated with 4FA (see table 2).

4.6 GENDER EFFECTS

To explore the effects of gender, an independent-samples t-test was conducted for each objective test measure. Previous literature has reported a greater prevalence of hearing loss in males than females (Helzner et al., 2005). A significant difference in the HFA was found between males (M=51.1, 13.9) and females (M=44.2, SD=12.4); t(78)=-2.40, p=0.019), suggesting that on average, males had significantly poorer hearing in the high frequencies than females.

A significant difference in performance on the DDT left ear was found between males (M=78.8, SD=17.9) and females (M=86.0, SD=17.9); *t*(67)=2.14, *p* = 0.036). These results suggest that females performed better on the DDT in the left ear than did males. In further analysis, a Pearson-correlation coefficient showed a significant weak, negative correlation between HFA and DDT performance in the left ear (r=-0.214, n=84, p=0.05). A multiple linear regression was then calculated to predict DDT left performance based on both gender and HFA. In combination, HFA and gender accounted for a significant 8% of the variability in DDT left ear performance. A second multiple linear regression model was used to predict DDT left ear performance based on HFA and gender in addition to the interaction between HFA and gender. After accounting for the interaction effect, HFA remained a significant predictor of DDT left ear performance. That is, although being male increased the chance of an individual having a high frequency hearing loss, HFA alone was related to DDT performance while gender was not.

Overall, these results are consistent with previous reports that males are more likely to experience a greater severity of hearing impairment than females, and that peripheral hearing significantly impacts performance on auditory processing tasks (Helzner et al., 2005).

4.7 INTER-TASK CORRELATIONS

Correlational analysis of pure-tone audiometry results (as separated by frequency ranges and ear performance) and the raw score performance on tests of central auditory processing (LiSN-S and DDT) are presented in table 3. The correlational analysis of the two test measures of central auditory processing are shown in table 4. Given the many correlations present between all three measures (i.e. PTA, DDT and LiSN-S), multiple regression analyses were conducted to determine if the significant relationships between the intercorrelated three DDT and three LiSN-S measures were still present after controlling for the HFA in the worse ear (correlated with all six measures; see table 3) in each of the nine associations. The relationship between the LiSN-S high cue condition and DDT percentage difference conditions, and the LiSN-S spatial advantage condition and left ear DDT performance remained significant (β = 0.0864 (0.0164-0.1564)**;** p=0.016 and β = 0.0454 (0.0009-0.0898)**;** p=0.045). All other correlations were no longer significant (p>0.05) once HFA was controlled for. That is, LiSN-S performance and HFA could not account for the variance in DDT performance alone. However, after controlling for hearing there was a significant relationship between performance in the LiSN-S high cue condition and the difference in DDT performance between ears. That is, the greater the difference between left and right ear DDT performance, the poorer the performance (on average) in the high cue LiSN-S condition.

Likewise, a significant relationship was found between DDT performance in the left ear and LiSN-S spatial advantage scores after controlling for the effects of hearing. That is, a greater score in left ear DDT performance was significantly related to greater performance in the LiSN-S spatial advantage condition. This result supports a link between different domains of central processing skills in this cohort, that is not determined by peripheral hearing.

Table 3.
Pearson correlation-coefficient between measures of pure tone hearing thresholds and central auditory processing.

PTA		LiSN-S (dB score)				DDT (% correct)		
		High cue	Low cue	Spatial advantage	Tonal advantage	Left ear	Right ear	Difference between ears
4FA[b]		.599***	.400***	-.608***	-.230*	-.189	-.255*	.237*
	Better ear	.582**	.376***	-.532***	-.246*	-.023	-.086	-.092
	Worse ear	.686***	.388***	-.624***	-.196	-.152*	-.316**	.414***
LFA[a]		.379***	.134	-.342**	-.207	-.054	-.073	.172
	Better ear	.183	.099	-.283**	-.194	.081	.067	-.070
	Worse ear	.480***	.154	-.369**	-.204	-.145	-.168	.328**
HFA[c]		.509*	.506**	-.463***	-.157	-.227***	-.299	.220***
	Better ear	.341**	.516**	-.433***	-.186	-.123	-.198	.001
	Worse ear	.576***	.465***	-.464***	-.118	-.281**	-.339**	.372***

*$p<0.05$, **$p<0.01$, ***$p<0.001$.

[a] 250 Hz, 500 Hz & 1000 Hz

[b] 500 Hz, 1000 Hz, 2000 Hz & 4000 Hz

[c] 2000 Hz, 3000 Hz, 4000 Hz, 5000 Hz, 6000 Hz & 8000 Hz

Table 4. Inter-correlations between Auditory Processing Assessments

DDT (% correct)	LiSN-S dB score			
	High Cue	Low Cue	Spatial advantage	Tonal advantage
Left ear	-.298**	-.281*	.339**	.141
Right ear	-.312**	-.219*	.251**	.215
Difference between ears	.413***	.190	-.239*	-057

*p<0.05, **p<0.01, ***p<0.001

4.8 DEMOGRAPHIC CONCLUSION

These results highlight an average mild to moderate hearing loss for this group of participants, with few participants having a severe or greater degree of hearing impairment. Additionally, on average, males had a significantly greater degree of hearing loss than females. There was a significant negative skew in the SES status of this cohort in comparison to the general Australian population.

The degree of hearing impairment appeared to share a significant relationship with performance on all LiSN-S measures, despite the use of the PGA. The left ear DDT condition and the percentage difference in DDT performance between the two ears was significantly related to age. The results highlight that there are many inter-task correlations. After controlling for hearing, DDT percentage difference performance remained an independent predictor of LiSN-S high cue performance, however all other present correlations were no longer significant. Therefore, it is important to control for known variables in further analysis such as allowing for the effect of pure-tone hearing sensitivity. Beyond this, future research will benefit from controlling for the influence of these demographic factors and inter-task correlations, particularly given the complexity of the relationship between age, peripheral hearing, central hearing and cognitive processes.

CHAPTER 5 EXPERIMENT 1

The following peer-reviewed publication is incorporated in its entirety in this chapter:

Published paper

- Nixon, G, Sarant, J. Z., & Tomlin, D., & Dowell, R. (2019). The relationship between peripheral hearing loss and higher order listening function on cognition in older Australians. International Journal of Audiology, 1-12. doi: 10.1080/14992027.2019.1641752

This is the authors accepted manuscript of an article published as the version of record in **International Journal of Audiology** © Taylor & Francis Ltd 2019 Informa UK Limited, trading as Taylor & Francis Group, https://www.tandfonline.com/eprint/MNWZK555BGXSVAMPRHFF/full?target=10.1080/14992027.2019.1641752

Aim: to examine the relationship between hearing impairment and cognitive impairment, examining both peripheral hearing impairment and Central Auditory Processing (CAP ability).

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https://doi.org/10.1080/14992027.2019.1641752

ORIGINAL ARTICLE

The relationship between peripheral hearing loss and higher order listening function on cognition in older Australians

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ABSTRACT

Objective: Peripheral hearing, central auditory processing (CAP) and cognition are all important for comprehension of speech and deteriorate with increased age. This study aimed to examine the relation between hearing impairment and cognitive impairment by assessing both peripheral hearing impairment and CAP ability.

Design: Cognition was measured using the CogState Brief Battery (CSBB). Peripheral hearing was measured across eight frequencies (250 Hz–8000 Hz) using pure tone audiometry, and CAP was measured using the Listening in Spatialised Noise-Sentences test (LiSN-S) and the Dichotic Digits Test. Data were analysed using correlation and regression analyses.

Study sample: Around 85 adults aged 60.33–83.08 years who attended the Melbourne Audiology clinic and had no previous diagnosis of dementia were included in the study.

Results: A significant association was found between degree of peripheral hearing impairment and the cognitive skills of attention and executive function as measured by the CSBB. Additionally, CAP abilities as assessed using the LiSN-S test were significantly correlated with at least one cognitive measure.

Conclusions: This study adds to the knowledge that peripheral hearing and CAP ability both share an association with cognition, specifically identifying cognitive skills and measures of "hearing" that mediate this relationship.

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KEYWORDS
Peripheral hearing; central hearing; cognition; auditory processing; dementia; aging

Introduction

Two highly prevalent conditions in older adults are hearing and cognitive impairment, with greater age leading to an increased likelihood of an individual experiencing one or both conditions (Hofman et al. 1991; Cruickshanks et al. 1998; Gurgel et al. 2014). Due to the combined effect of a tripling of the world's population between the years 1946 and 1964, and increased life expectancy, the number of people over the ages of 65- and 85-years-old are expected to increase by a factor of 2.3 and 3.4, respectively, between the years 2003 and 2031 (United Nations 1999; Booth and Tickle 2003; Wilson 2012; United States Census Bureau 2016). With such a large number of people experiencing some degree of one or both of these chronic health conditions, there is likely to be a greater emotional and economic burden on individuals and society. It has been estimated that up to 60% of people over 65 years, and up to 90% of people over 85 years have some degree of hearing impairment (Humes et al. 2012; Amieva et al. 2015). Furthermore, by the year 2040, the number of people affected with Alzheimer's dementia (AD) is predicted to reach 81.1 million worldwide (Ferri et al. 2005). There is therefore an urgent need to gain greater knowledge of the interaction of these two conditions associated with aging, in order to provide appropriate intervention and support for these people.

People who seek help for hearing loss typically do so to gain a clearer understanding of speech (Dillon 2012). However, it is important to recognise that in order to clearly understand speech, peripheral and central auditory systems as well as cognitive systems need to be functioning effectively (Schneider, Pichora-Fuller, and Daneman 2010; Parham et al. 2013). Ascending peripheral and central nervous system pathways in the auditory system carry sounds from the cochlea to the auditory cortex (Lesicko and Llano 2017). Once the sound signal reaches the auditory cortex, cognitive resources are required to provide meaning and assist with interpretation of the sound (Schneider, Pichora-Fuller, and Daneman 2010; Parham et al. 2013).

Cognition includes skills such as the ability to maintain focus and prioritise information of interest (attention; Petersen and Posner 2012), the ability to organise one's thoughts to apply them to a present task (executive function; Petersen and Posner 2012), temporary storage and immediate recall of information (memory; Nittrouer et al. 2017), the speed, coordination and movement of physical skills (psychomotor function; Shukitt-Hale et al. 2017) and the ability to acquire new, or modify current, knowledge and behaviours (learning; Santrock 1988). These skills are commonly screened in a range of clinical indications such as cognitive decline following brain injury, Alzheimer's disease and other forms of dementia (Cogstate 2017). Cognitive impairment is defined as poorer than expected performance for an individual's age, in any of these skill areas. There is a continuum of impairment from mild cognitive impairment (MCI) through to dementia (Gurgel et al. 2014). MCI can manifest as poor performance in any one subset of cognitive skill, although amnestic memory (e.g. the ability to remember appointments or recall recent events) is the most commonly affected ability (Petersen

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et al. 1999; Gauthier et al. 2006). Dementia, however, is a chronic health condition that can severely impact a person's ability to perform everyday tasks and impacts at least two cognitive skills concurrently (e.g. amnestic memory as in MCI in addition to impaired attention) (World Health Organisation 2017).

Hearing loss has been shown to be negatively associated with cognitive performance, and is more prevalent in dementia populations (Granick, Kleban, and Weiss 1976; Uhlmann et al. 1989; Lindenberger and Baltes 1994; Lin 2011; Lin et al. 2011b; Gurgel et al. 2014; Amieva et al. 2015), with more recent longitudinal research showing that hearing loss is associated with accelerated cognitive decline (Lin et al. 2013; Amieva et al. 2015). Examples of this and further research in this area have been described in Table 1. It has been suggested that there is an association between hearing and outcomes of cognitive tests because many tests of cognition are presented auditorily, and therefore those with hearing loss are disadvantaged (Folstein et al. 2000). However, there is some evidence to dispute this claim, with an association between cognition and hearing also found using cognitive tests that do not rely on audition (see Wayne and Johnsrude 2015). Numerous researchers have attempted to examine whether degree of hearing impairment and cognitive impairment, which both show positive associations with aging, are related independently to each other (Hofman et al. 1991; Cruickshanks et al. 1998; Gurgel et al. 2014). A recent meta-analysis which included 33 journal articles examining the association between hearing and cognition concluded that hearing impairment is significantly associated with increased cognitive problems (Taljaard et al. 2016). Furthermore, hearing impairment has been identified as a modifiable risk factor of dementia, particularly in those with hearing loss in mid-life or older, accounting for a 9% increased risk of dementia (Livingston et al. 2017).

It is important to note when considering the available evidence on this topic that cognition/cognitive impairment has been measured and diagnosed differently across different studies. The term "cognition" has been used in many studies, and the broad conclusion that there is a relationship between "cognition" and hearing impairment made. However, it is often unclear what the term "cognition" refers to. For example, the term "cognition" has referred to one domain of cognitive function such as executive function (Lin et al. 2011a), poor performance on a screening test of "cognitive function" (Gurgel et al. 2014; Amieva et al. 2015) and dementia diagnosis (Gates et al. 2011). Therefore, the term "cognition" has been used interchangeably across different studies. Results of a minority of studies have not provided support for an association between hearing loss and cognition (Gussekloo et al. 2005; Hong et al. 2016). However, these studies have used limited screening tools for the measurement of cognition (Folstein, Folstein, and McHugh 1975; Munshi et al. 2006). In the previously mentioned meta-analysis, it was noted that the tools used for assessing cognitive function were not consistent across 33 studies (Taljaard et al. 2016). Taljaard et al. (2016) acknowledged these significant differences, highlighting the importance of selecting sensitive and appropriate cognitive tests. Additionally, calculations and definitions of hearing impairment also varied between studies (including the studies in Taljaard et al.'s (2016) meta-analysis, and the broader literature in the field). In many cases, the measurement of hearing has been focussed on only a few frequencies, commonly in the mid frequency range, providing an incomplete assessment of hearing loss. It is not appropriate to assess only the mid-frequencies, as age-related hearing loss typically begins in higher frequencies, gradually impacting the mid- then low-frequency range (Glyde et al. 2013; Besser et al. 2015; Lesicko and Llano 2017).To adequately explore the relationship between hearing loss and cognition, multiple frequencies should be considered, and a validated cognitive screening tool that assesses multiple domains of cognition should also be used.

As mentioned previously, people with age-related hearing loss typically seek help to gain a clearer understanding of speech, as there is generally a reduced ability to listen in complex listening situations such as background noise (Dillon 2012; Glyde et al. 2013; Besser et al. 2015; Lesicko and Llano 2017). Central auditory processing (CAP) is the ability of the central nervous system to interpret auditory information (Nelson and Soli 2000; Picard and Bradley 2001). CAP is made up of a multitude of functions that are relied on for the interpretation of spectral and temporal properties of speech. Two examples of CAP functions are binaural interaction and integration. Binaural interaction refers to how the brain uses information from two ears to help locate a source of sound, by comparing arrival time and intensity differences between the ears (i.e. the differences generated by the same source signal at different ears) (Cameron, Dillon, and Newall 2006). Spatial processing relies on the successful use of binaural interaction skills and is defined as the ability to segregate streams of auditory information based on their location in space (Cameron and Dillon 2008). Binaural integration (sometimes referred to as dichotic listening) allows a listener to intepret a complex auditory signal by processing and comparing competing signals arriving at two ears (Kimura 1967; Musiek and Pinheiro 1985; Musiek and Schochat 1998; Asbjørnsen et al. 2000). These are two of many CAP skills important for the successful interpretation of speech, and are processes that are typically assessed using tasks requiring a listener to interpret a speech signal amongst background noise. Subsequently, they have been most commonly investigated when assessing the relationship between cognition and CAP. For example, as early as 1995 Gates and colleagues recognised that CAP ability was significantly reduced in those with dementia by measuring binaural interaction performance (Gates et al. 1995). Continued research by Gates et al. in this area used a similar test battery, additionally including tests of binaural integration (see Table 1). Recently, however, another area of CAP known as temporal resolution (the ability to perceive time-related changes in a continuous auditory stream of information) has also been a focus of cognitive research (Iliadou et al. 2017). The results of this research presented evidence that performance on CAP tasks assessing temporal resolution ability (the gaps in noise test) was significantly poorer in a group with MCI than in people without cognitive impairment. CAP skills develop with age, reaching peak performance in young adulthood, and then decrease with increasing age (Ponton et al. 2000; Gates, Feeney, and Mills 2008). Research on age-related central hearing dysfunction has shown that central hearing declines at a significantly faster rate than does peripheral hearing function, and is estimated to be present in 95% of people over the age of 80 years (Stach, Spretnjak, and Jerger 1990; Gates, Feeney, and Mills 2008). Given this, research considering the relation between age-related hearing impairment and cognitive skills in older people should consider central hearing ability in addition to peripheral hearing ability. Examples of past studies in this area and the domains of central auditory function tested are presented in Table 1. As seen in research with peripheral hearing, a limitation of many studies includes the use of cognitive screening tools as the means of cognitive assessment. Nonetheless, the results of many studies have

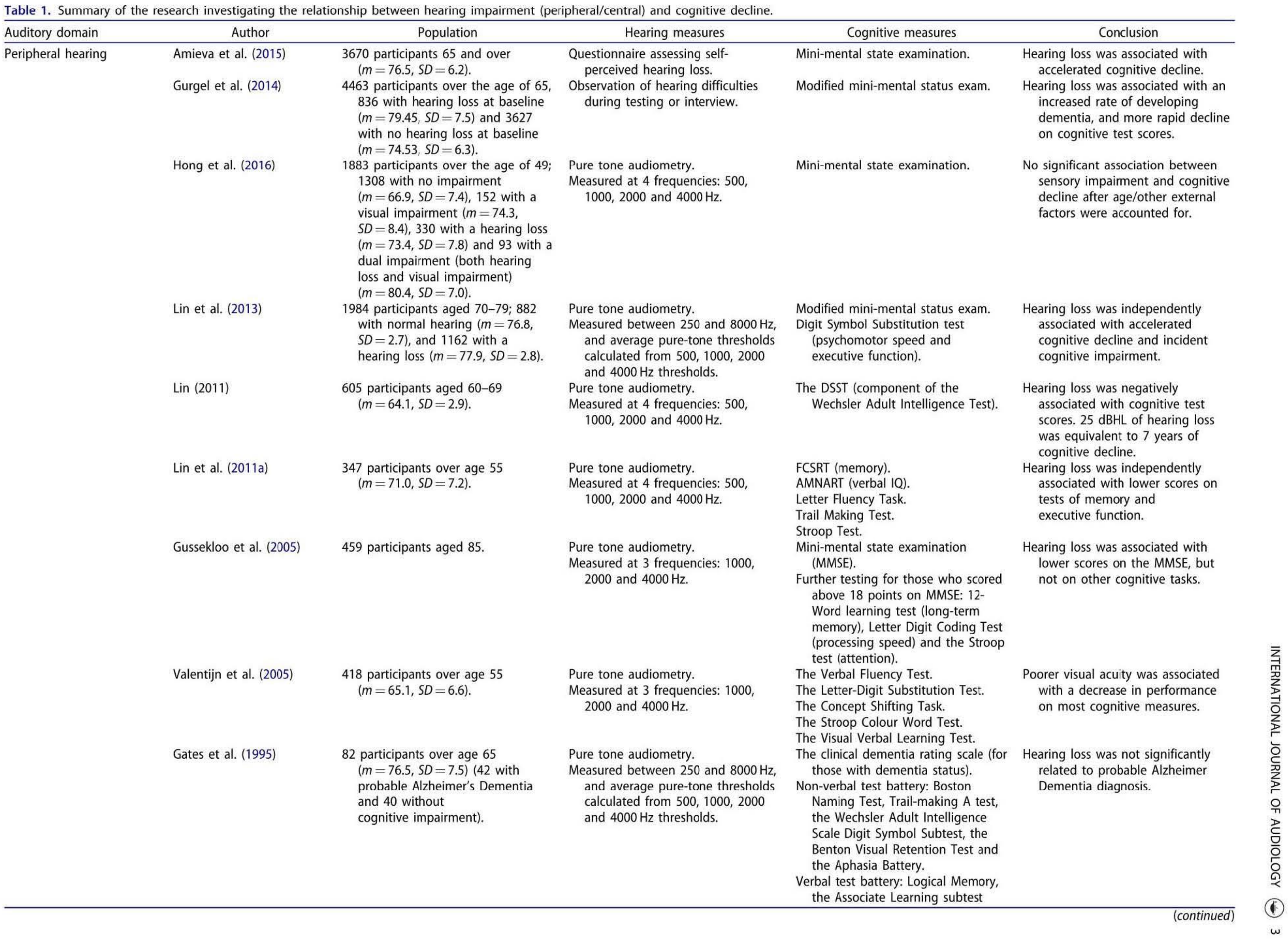

Table 1. Summary of the research investigating the relationship between hearing impairment (peripheral/central) and cognitive decline.

Auditory domain	Author	Population	Hearing measures	Cognitive measures	Conclusion
Peripheral hearing	Amieva et al. (2015)	3670 participants 65 and over ($m = 76.5$, $SD = 6.2$).	Questionnaire assessing self-perceived hearing loss.	Mini-mental state examination.	Hearing loss was associated with accelerated cognitive decline.
	Gurgel et al. (2014)	4463 participants over the age of 65, 836 with hearing loss at baseline ($m = 79.45$, $SD = 7.5$) and 3627 with no hearing loss at baseline ($m = 74.53$, $SD = 6.3$).	Observation of hearing difficulties during testing or interview.	Modified mini-mental status exam.	Hearing loss was associated with an increased rate of developing dementia, and more rapid decline on cognitive test scores.
	Hong et al. (2016)	1883 participants over the age of 49; 1308 with no impairment ($m = 66.9$, $SD = 7.4$), 152 with a visual impairment ($m = 74.3$, $SD = 8.4$), 330 with a hearing loss ($m = 73.4$, $SD = 7.8$) and 93 with a dual impairment (both hearing loss and visual impairment) ($m = 80.4$, $SD = 7.0$).	Pure tone audiometry. Measured at 4 frequencies: 500, 1000, 2000 and 4000 Hz.	Mini-mental state examination.	No significant association between sensory impairment and cognitive decline after age/other external factors were accounted for.
	Lin et al. (2013)	1984 participants aged 70–79; 882 with normal hearing ($m = 76.8$, $SD = 2.7$), and 1162 with a hearing loss ($m = 77.9$, $SD = 2.8$).	Pure tone audiometry. Measured between 250 and 8000 Hz, and average pure-tone thresholds calculated from 500, 1000, 2000 and 4000 Hz thresholds.	Modified mini-mental status exam. Digit Symbol Substitution test (psychomotor speed and executive function).	Hearing loss was independently associated with accelerated cognitive decline and incident cognitive impairment.
	Lin (2011)	605 participants aged 60–69 ($m = 64.1$, $SD = 2.9$).	Pure tone audiometry. Measured at 4 frequencies: 500, 1000, 2000 and 4000 Hz.	The DSST (component of the Wechsler Adult Intelligence Test).	Hearing loss was negatively associated with cognitive test scores. 25 dBHL of hearing loss was equivalent to 7 years of cognitive decline.
	Lin et al. (2011a)	347 participants over age 55 ($m = 71.0$, $SD = 7.2$).	Pure tone audiometry. Measured at 4 frequencies: 500, 1000, 2000 and 4000 Hz.	FCSRT (memory). AMNART (verbal IQ). Letter Fluency Task. Trail Making Test. Stroop Test.	Hearing loss was independently associated with lower scores on tests of memory and executive function.
	Gussekloo et al. (2005)	459 participants aged 85.	Pure tone audiometry. Measured at 3 frequencies: 1000, 2000 and 4000 Hz.	Mini-mental state examination (MMSE). Further testing for those who scored above 18 points on MMSE: 12-Word learning test (long-term memory), Letter Digit Coding Test (processing speed) and the Stroop test (attention).	Hearing loss was associated with lower scores on the MMSE, but not on other cognitive tasks.
	Valentijn et al. (2005)	418 participants over age 55 ($m = 65.1$, $SD = 6.6$).	Pure tone audiometry. Measured at 3 frequencies: 1000, 2000 and 4000 Hz.	The Verbal Fluency Test. The Letter-Digit Substitution Test. The Concept Shifting Task. The Stroop Colour Word Test. The Visual Verbal Learning Test.	Poorer visual acuity was associated with a decrease in performance on most cognitive measures.
	Gates et al. (1995)	82 participants over age 65 ($m = 76.5$, $SD = 7.5$) (42 with probable Alzheimer's Dementia and 40 without cognitive impairment).	Pure tone audiometry. Measured between 250 and 8000 Hz, and average pure-tone thresholds calculated from 500, 1000, 2000 and 4000 Hz thresholds.	The clinical dementia rating scale (for those with dementia status). Non-verbal test battery: Boston Naming Test, Trail-making A test, the Wechsler Adult Intelligence Scale Digit Symbol Subtest, the Benton Visual Retention Test and the Aphasia Battery. Verbal test battery: Logical Memory, the Associate Learning subtest	Hearing loss was not significantly related to probable Alzheimer Dementia diagnosis.

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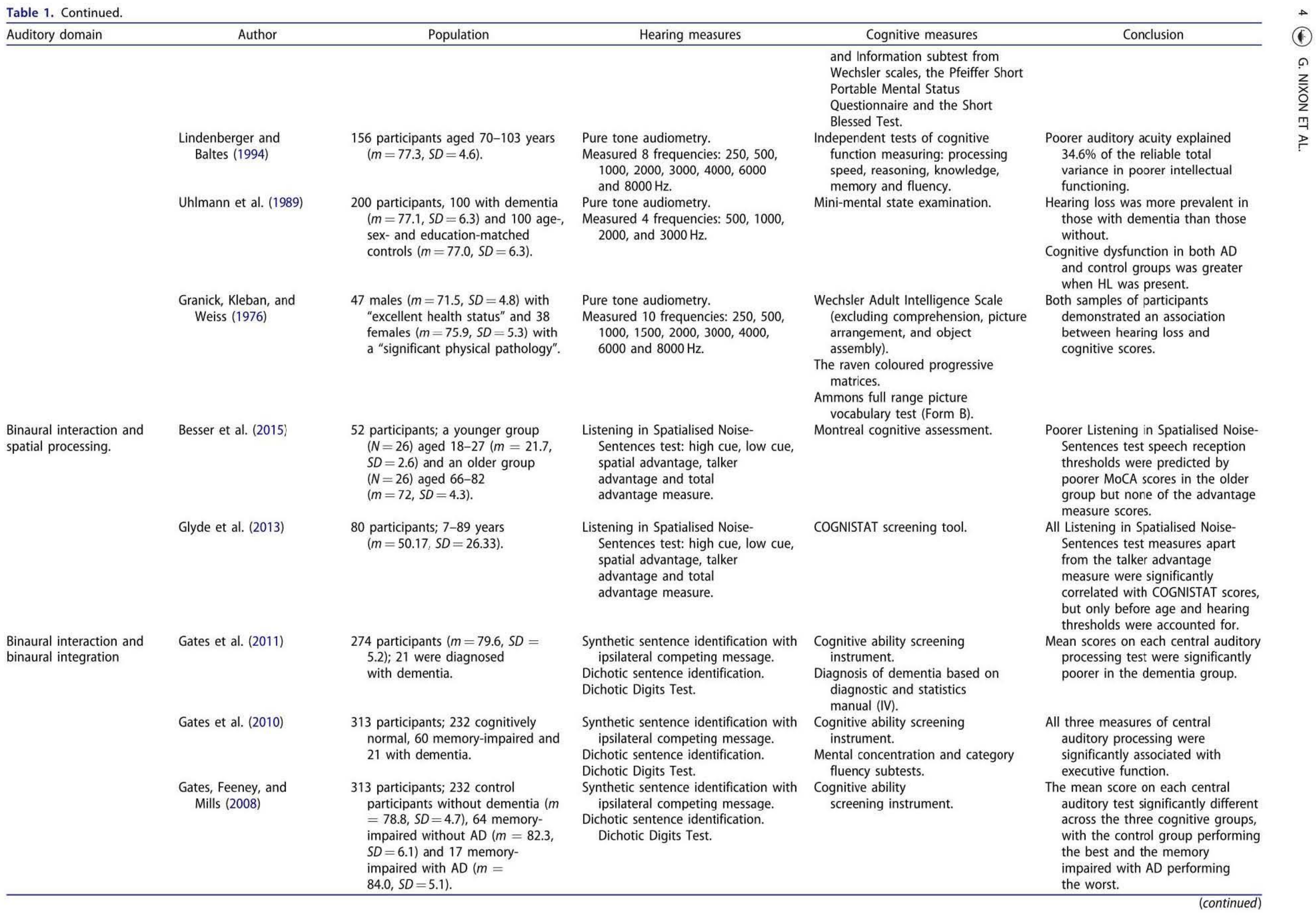

Table 1. Continued.

Auditory domain	Author	Population	Hearing measures	Cognitive measures	Conclusion
				and Information subtest from Wechsler scales, the Pfeiffer Short Portable Mental Status Questionnaire and the Short Blessed Test.	
	Lindenberger and Baltes (1994)	156 participants aged 70–103 years ($m = 77.3$, $SD = 4.6$).	Pure tone audiometry. Measured 8 frequencies: 250, 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz.	Independent tests of cognitive function measuring: processing speed, reasoning, knowledge, memory and fluency.	Poorer auditory acuity explained 34.6% of the reliable total variance in poorer intellectual functioning.
	Uhlmann et al. (1989)	200 participants, 100 with dementia ($m = 77.1$, $SD = 6.3$) and 100 age-, sex- and education-matched controls ($m = 77.0$, $SD = 6.3$).	Pure tone audiometry. Measured 4 frequencies: 500, 1000, 2000, and 3000 Hz.	Mini-mental state examination.	Hearing loss was more prevalent in those with dementia than those without. Cognitive dysfunction in both AD and control groups was greater when HL was present.
	Granick, Kleban, and Weiss (1976)	47 males ($m = 71.5$, $SD = 4.8$) with "excellent health status" and 38 females ($m = 75.9$, $SD = 5.3$) with a "significant physical pathology".	Pure tone audiometry. Measured 10 frequencies: 250, 500, 1000, 1500, 2000, 3000, 4000, 6000 and 8000 Hz.	Wechsler Adult Intelligence Scale (excluding comprehension, picture arrangement, and object assembly). The raven coloured progressive matrices. Ammons full range picture vocabulary test (Form B).	Both samples of participants demonstrated an association between hearing loss and cognitive scores.
Binaural interaction and spatial processing.	Besser et al. (2015)	52 participants; a younger group ($N = 26$) aged 18–27 ($m = 21.7$, $SD = 2.6$) and an older group ($N = 26$) aged 66–82 ($m = 72$, $SD = 4.3$).	Listening in Spatialised Noise-Sentences test: high cue, low cue, spatial advantage, talker advantage and total advantage measure.	Montreal cognitive assessment.	Poorer Listening in Spatialised Noise-Sentences test speech reception thresholds were predicted by poorer MoCA scores in the older group but none of the advantage measure scores.
	Glyde et al. (2013)	80 participants; 7–89 years ($m = 50.17$, $SD = 26.33$).	Listening in Spatialised Noise-Sentences test: high cue, low cue, spatial advantage, talker advantage and total advantage measure.	COGNISTAT screening tool.	All Listening in Spatialised Noise-Sentences test measures apart from the talker advantage measure were significantly correlated with COGNISTAT scores, but only before age and hearing thresholds were accounted for.
Binaural interaction and binaural integration	Gates et al. (2011)	274 participants ($m = 79.6$, $SD = 5.2$); 21 were diagnosed with dementia.	Synthetic sentence identification with ipsilateral competing message. Dichotic sentence identification. Dichotic Digits Test.	Cognitive ability screening instrument. Diagnosis of dementia based on diagnostic and statistics manual (IV).	Mean scores on each central auditory processing test were significantly poorer in the dementia group.
	Gates et al. (2010)	313 participants; 232 cognitively normal, 60 memory-impaired and 21 with dementia.	Synthetic sentence identification with ipsilateral competing message. Dichotic sentence identification. Dichotic Digits Test.	Cognitive ability screening instrument. Mental concentration and category fluency subtests.	All three measures of central auditory processing were significantly associated with executive function.
	Gates, Feeney, and Mills (2008)	313 participants; 232 control participants without dementia ($m = 78.8$, $SD = 4.7$), 64 memory-impaired without AD ($m = 82.3$, $SD = 6.1$) and 17 memory-impaired with AD ($m = 84.0$, $SD = 5.1$).	Synthetic sentence identification with ipsilateral competing message. Dichotic sentence identification. Dichotic Digits Test.	Cognitive ability screening instrument.	The mean score on each central auditory test significantly different across the three cognitive groups, with the control group performing the best and the memory impaired with AD performing the worst.

(continued)

Table 1. Continued.

Auditory domain	Author	Population	Hearing measures	Cognitive measures	Conclusion
Binaural interaction	Gates et al. (1996)	1662 aged 63–95 (m = 72).	Synthetic sentence identification with ipsilateral competing message. Staggered spondaic words (SSW) Phonetically balanced words.	Mini mental state examination.	Central auditory dysfunction preceded senile dementia in a significant number of cases. Higher chance of being diagnosed with dementia if synthetic sentence identification scores were poor in one ear, which doubled if scores were poor in both ears.
	Gates et al. (1995)	82 aged 65–74 participants, either non-demented ($N = 40$) or with probable Alzheimer's Dementia ($N = 42$).	Synthetic sentence identification with ipsilateral competing message or contralateral competing message.	Clinical criteria and the clinical dementia rating scale, which was used to distinguish between participants who were either cognitively normal or had dementia.	Central auditory function (as measured by competing noise tests) was significantly reduced for those with dementia.

indicated that deficits in CAP skills are associated with impaired cognition and/or the likelihood of developing dementia.

The current study explores the relationship between degree of peripheral hearing loss, CAP skills and cognitive function as measured by scores on the CogState cognitive test battery (CogState Brief Battery: CSBB). The primary focus of the CAP skills examined will be binaural integration and interaction. This will include tests used in past literature such as the Dichotic Digits Test (DDT) (which is relatively robust to the influence of mild-to-moderate peripheral hearing loss; Fifer et al. 1983), but will also consider a relatively new area of CAP specifically in a population of older adults, in relation to cognition through use of the Listening in Spatialised Noise-Sentences (LiSN-S) test. The aim of this research is to gain a greater understanding of how hearing (measured both peripherally and centrally) is related to cognition in older people. Furthermore, this research aims to address the limited knowledge on the association between different CAP skills. It is hypothesised that there will be a negative relationship between scores on the CogState cognitive test battery and:

1. Increased level of peripheral hearing impairment,
2. Decreased binaural integration and interaction performance.

Methods

This study was approved by the School of Health Sciences Human Ethics Advisory Group of the University of Melbourne (Ethics ID: 1748836). Written consent to participate was obtained from all participants.

Procedures

Participants were recruited from the University of Melbourne Audiology Clinic, at which time an audiological assessment was conducted. Following this, participants attended one 2-h appointment in which cognitive and auditory processing (AP) assessments were administered. Written questionnaires were used to obtain information about participants' socio-economic status (SES) and education level.

Participants

Eighty-five adults who attended the University of Melbourne Audiology clinic and who met the following inclusion criteria were enrolled into this study:

1. Aged 60 years or older.
2. No previous diagnosis of dementia.
3. No previous hearing aid use.
4. No visual or language impairment that precluded the ability to complete the assessment tasks.

Forty males, 44 females and one non-binary individual, between the ages of 60.33 and 83.08 years ($m = 70.23$, SD = 5.17) participated in the study.

Socioeconomic status

Based on residential postcode information for each of the participants, an index of relative socio-economic advantage and disadvantage (IRSAD) was recorded. The ISRAD, calculated by the Australian-Bureau-of-Statistics (2018), provides information about the social and economic conditions within a geographic area, with a higher score indicative of greater advantage in general. All scores are standardised to a distribution with an average of 1000 and a standard deviation of 100. All areas are also ordered from lowest to highest index score, with the lowest 10% of areas given a decile number of 1 and the highest 10% of areas given a decile number of 10, dividing the indices into 10 equal-sized groups. The SES of this cohort as defined by the IRSAD score (Australian-Bureau-of-Statistics 2018) did not follow a normal distribution and was significantly negatively skewed (Anderson-Darling test of normality; AD = 5.3, $p < 0.005$). Approximately 62% of the participants in this study came from the highest ranked (top 20%) areas of Australia.

Education level

An Educational History Questionnaire containing four questions identified the participants' highest completed level of education. Participants were then categorised into whether they had completed high school education or below, a university degree or a PhD degree. As the majority of participants (78%) had completed some form of tertiary degree, to provide a better representation of this sample's demographics, tertiary degrees were stratified into PhD and non-PhD. Additionally, participants were asked "How many years of education did you complete?" and were then categorised into five discrete categories: "0–6 years", "7–8 years", "9–12 years", "13–15 years" and "15+ years". Most participants (76%) reported completing 15 years or more of education. As few participants reported belonging to the other four educational categories, the educational categories were collapsed into two groups for analysis: <15 years of education and ≥15 years education.

Test battery

Audiological assessment

All participants were assessed by an audiologist as part of the University of Melbourne School of Audiology standard workup. Audiometric assessment included: bilateral air conduction thresholds using modified Hughson Westlake technique at octave frequencies between 250 Hz and 8000 Hz, 3000 Hz and 6000 Hz, bilateral bone conduction thresholds at octave frequencies between 500 Hz and 4000 Hz, bilateral speech discrimination using AB words, and tympanometry. Pure tone audiometry was assessed using an Interacoustics Affinity 2.0 Audiometer in a sound-proofed room. Degree of hearing impairment was classified as either normal (<20 dbHL), mild (20–40 dBHL), moderate (45–65 dBHL), severe (70–90 dBHL) or profound (>90 dBHL) (Davis and Silverman 1970; Clark 1981). A low frequency (250, 500 and 1000 Hz) and high frequency average (>1000 Hz) was calculated for both ears. In accordance with current practice, a four-frequency average of 500, 1000, 2000 and 4000 Hz was used to summarise overall hearing (Besser et al. 2015). Hearing was also categorised by "better-hearing" and "worse-hearing" ear. This is because, like as in previous research (see Lin 2011 for example), the better-hearing ear was logically presumed to be the best reflection of everyday listening ability. Figure 1 and Table 3 present information regarding hearing impairment across the frequency categories used.

Auditory processing assessments

An AP test battery was administered to assess binaural integration and interaction. As described in the "Introduction", binaural integration and interaction are commonly assessed when investigating associations between CAP and cognition and were therefore chosen as target CAP areas in the present study. These tests were chosen as a reflection of tests currently used in the field (Gates, Feeney, and Mills 2008; Gates et al. 2011). The two tests selected were the DDT (Musiek 1983) and the LiSN-S test (Cameron and Dillon 2007) which assesses the ability to use spatial and talker advantage cues in complex listening environments. These tests were selected specifically because both tests have demonstrated moderate to strong test–retest reliability. Moreover, as demonstrated in Table 1, the DDT and LiSN-S are frequently used in this area of research and are commonly assessed as part of a CAP test battery (Musiek et al. 1991; Cameron et al. 2009; Moore et al. 2011; Sharma, Purdy, and Kelly 2012).

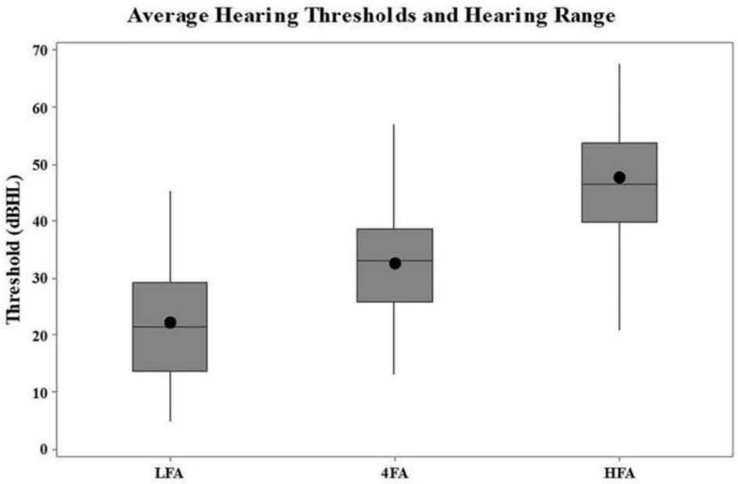

Figure 1. LFA: low frequency average (250, 500 and 1000 Hz); 4FA: four frequency average (500, 1000, 2000 and 4000 Hz); HFA: high frequency average (2000, 3000, 4000, 5000, 6000 and 8000 Hz).

Table 2. Descriptive statistics on the primary test measures ($N = 85$ unless otherwise stated).

	Descriptive statistics				
Test	Mean	*SD*	Median	Minimum	Maximum
Pure tone audiometry					
Better ear					
LFA[a]	18.96	8.95	16.67	1.17	43.33
4FA[b]	28.87	8.77	28.75	11.25	56.25
HFA[c]	43.36	13.38	42.00	12.00	96.0
Worse ear					
LFA[a]	25.59	12.32	23.33	6.67	60.00
4FA[b]	36.22	12.54	35.00	13.75	93.75
HFA[c]	51.88	16.00	50.00	17.00	119.00
LiSN-S (SRT) ($N = 83$)[d]					
High cue[a]	−8.743	5.352	−9.6	13.8	−19.8
Low cue[a]	−0.054	1.125	−0.1	2.7	−2.6
Spatial advantage	8.561	2.565	8.5	2.0	14.0
Tonal advantage	3.518	1.433	3.5	0.4	8.5
DDT (% correct)					
Left ear	82.29	15.59	85	22.5	100
Right ear	90.32	13.42	95	15	100
Difference between ears	12.88	14.28	7.5	0	70
CSBB (primary outcome score)					
Attention[e]	2.78	0.06	2.77	2.74	2.94
Psychomotor function[e]	2.59	0.09	2.58	2.43	2.85
Executive function[e]	53.86	16.08	44.0	25.	116
Visual learning	0.98	0.11	1.01	0.55	1.23
Working memory[e]	2.95	0.09	2.71	2.95	3.15

LiSN-S: Listening in Spatialised Noise Sentences test; DDT: Dichotic Digits; CSBB: Cogstate Brief Battery.

[a] 250, 500 and 1000 Hz.

[b] 500, 1000, 2000 and 4000 Hz.

[c] 2000, 3000, 4000, 5000, 6000 and 8000 Hz.

[d] Two participants were unable to complete LiSN-S.

[e] Results are reversed score with a lower score indicating better performance.

The DDT. The DDT (Musiek 1983) assesses binaural integration and requires the participant to repeat four numbers (two presented simultaneously to each ear) in a total of 20 trials, with an additional three initial practice trials. The test was delivered under headphones at a volume reported as both clear and comfortable for each participant. For most participants, this level was approximately 60 dBHL. If a hearing asymmetry was present, volume levels were balanced until the participant reported the volume to be subjectively equal in both ears. The DDT is reported to be not greatly impacted by a mild-to-moderate hearing loss (Fifer et al. 1983). Raw scores (percentage correct) were used in the statistical analysis for this study.

The LiSN-S test. The LiSN-S test (as described by Cameron and Dillon 2007) also evaluates binaural integration as well as assessing how an individual performs in background noise when there are advantages of spatial separation or voice cues. The LiSN-S was administered using a personal computer, *Sennheiser HD215 circumaural* headphones and a *Buddy 6 G USB soundcard*. The initial presentation levels for the speaker and distractor were 62 and 55 dBSPL, respectively. All participants were assessed in LiSN-S prescribed gain amplifier mode in which participants' bilateral hearing thresholds (for both bone- and air-conduction) were entered into the software. This mode amplifies and shapes the target and distracting stimuli according to the National Acoustic Laboratories – Revised Profound prescription (Glyde et al. 2013; Cameron et al. 2014). Four conditions were created from differing combinations of spatial separation (either 0° or ± 90°) of the target speaker and distractors, and with voice cues (distractors either have the same or different voices as the target speaker). Two speech reception thresholds were calculated from a high cue condition (target and distractors were spatially separated by 90° with tonal differences) and a low cue condition (target and distractors came from the same direction with the same voice). Also reported is the spatial and tonal advantage score, which is the dB improvement that results from the spatial and tonal cues when they were present compared to when they were absent. The raw scores of the high cue and low cue conditions as well as the spatial and tonal advantage scores were used in the statistical analysis.

Cognitive screening assessment

Mini mental state examination. Cognitive screening was conducted for all participants before any testing commenced using the mini mental state examination (MMSE) (Folstein et al. 2000). The MMSE is a brief assessment of cognitive function in older adults with a high reported specificity (96%) and a lower sensitivity (64%) (Munshi et al. 2006). The MMSE is scored out of a total of 30, with a score of <24 considered to be abnormal and indicative of cognitive impairment (Folstein et al. 2000). Participants were required to achieve a score within the normal range in order to continue with the test battery.

Cognitive assessment

The CSBB. The CSBB (Cogstate 2017) was the primary outcome measure in this study. It comprises four tasks with an additional fifth task (the Groton Maze Learning Test) which is commonly used in the CogState Alzheimer's Battery (Westerman et al. 2001; Collie et al. 2003; Falleti et al. 2006; Maruff et al. 2009). This tool is ideal for use with people with hearing loss, as it is visually presented. Furthermore, it has a very low practice effect, with test–retest reliability for each measure estimated to range between 0.84 and 0.94 (Collie et al. 2003; Falleti et al. 2006; Maruff et al. 2009), therefore allowing for a practice session to ensure the task was understood prior to commencing data collection. Both the speed and accuracy of the response were recorded and transformed to produce normalised data distributions (Falleti et al. 2006; Maruff et al. 2009).

The Groton Maze Learning Test assessed *executive function* and typically takes 7 min to administer. Using a maze learning paradigm, it measures the total number of errors made when attempting to learn the same hidden pathway across five trials presented immediately after one another. A 10 × 10 grid of tiles is presented on the computer screen and the participant is required to find a "hidden" 28-step pathway from the top left corner of the grid (start titles indicated by a blue square) to the bottom right corner (finish tile indicated by red circles) of the grid. The participant is required to move one tile at a time in either a horizontal or vertical direction, one space from the previous correct tile. A green tick indicates a correct move and a red cross indicates an incorrect move.

The Detection Test assessed *psychomotor function* and typically takes 3 min to administer. The participant must respond "yes" when a card in the centre of the screen turns over. The task continues until 25 correct responses are obtained, or the maximum time limit (2 min) has been reached (whichever occurs first). The test measures the speed of performance (in milliseconds) taken to complete the task.

The Identification Task assessed *attention* and typically takes 3 min to administer. It measures attention using a choice reaction paradigm in which the participant must answer "Is the card red?" when a playing card in the centre of the screen turns over. Using the "yes" or "no" responses, the participant is instructed

Table 3. Demographics ($N = 85$ unless otherwise stated).

	Mean (SD)^{a}/Count (%)^{b}	Range
Age^{a}	70.7 (5.2)	60.33–83.08
MMSE score^{a}	28.9 (1.3)	24–30
Pure tone four frequency average^{a}		
Better ear	28.9 (8.8)	11.25–56.25
Worse ear	36.2 (12.5)	13.75–93.75
Socio-economic score	1052.2 (49.1)	911.0–1130.0
Education level$^{b\ (N\,=\,75)}$		
≤High school	16 (21.3)	
University degree	45 (60)	
PhD	14 (18.7)	

to respond as quickly and accurately as possible. Performance speed (in milliseconds) to complete the task was recorded.

The One Card Learning Test assessed *visual learning* and typically takes 6 min to administer. It measures participants ability to learn through a visual modality using a pattern separation paradigm in which the participant must answer "Have you seen this card before in this test?" when a playing card in the centre of the screen turns over. The test measures performance accuracy.

The One Back Test assessed *working memory* and typically takes 4 min to administer. It measures working memory using an n-back paradigm in which the participant must answer "Is the previous card the same?" when a playing card in the centre of the screen turns over. This test measures both the speed and accuracy of performance

Table 3 presents the demographic information (age, SES and education level) and average results for Pure Tone Audiometry (PTA) and MMSE performance for the participants in this study.

Statistical analysis

Minitab 17 (2010) Statistics package was used for analysis. Initial exploratory correlational analyses were used to examine the associations between predictive and outcome measures. Stepwise regression models (with an alpha value of 0.05 to enter and remove) were then used (where appropriate) to further explore the associations between the outcome variable (cognitive performance) and potential predictive variables (i.e. different measurements of hearing performance). The variance inflation factor (VIF) was used to assess multi-collinearity, with a value of <4.0 indicating low correlation among variables.

Results

Age, education and SES

Descriptive statistics for the four objective measures (PTA, LiSN-S, DDT and CSBB) are presented in Table 2. No significant correlation was found between age and participants' 4FA ($r = 0.134$, $p = 0.221$). Additionally, no significant correlation was found between age and PTA when categorised into different frequency ranges or for the better and worse hearing ears (see Table 2). However, age was negatively correlated with dichotic digits performance in the left ear ($r = -0.239$, $p = 0.027$), and was also positively correlated with the degree of asymmetry in dichotic digit performance between the two ears ($r = 0.233$, $p = 0.032$). Increased age was also correlated with poorer performance on the low cue LiSN-S condition ($r = 0.395$, $p < 0.001$) and with poorer performance on executive function tasks ($r = 0.253$, $p = 0.020$). Thus, age was added as a covariate where appropriate into the multiple regression analyses.

To explore the effects of education when categorised into the two aforementioned groups (coded as 0/1), an independent-samples *t*-test was conducted for each of the objective test measures. As there was a negative skew, a Spearman rank-order correlation coefficient was used when assessing the SES data. No significant association was found between participants' education/SES score and any of the objective test measures (PTA, LiSN-S, DDT and CSBB).

Peripheral hearing and CAP test scores

Combined ear 4FA was negatively correlated with the right ear DDT score ($r = -0.255$, $p = 0.019$) and was positively correlated with the difference between left and right ear DDT score performance ($r = 0.237$, $p = 0.029$), but no significant correlations were found between 4FA and left ear DDT score performance ($r = -0.189$, $p = 0.084$). The high cue, low cue and spatial advantage scores on the LiSN-S test were all significantly correlated with 4FA ($p < 0.001$ in all cases); however, this was not the case for the tonal advantage score.

Peripheral hearing and cognitive test scores

Combined ear 4FA was not significantly associated with scores on any of the five cognitive test measures; however, poorer low frequency average (LFA) in the better hearing ear was correlated with poorer scores on tests of attention ($r = 0.289$, $p = 0.008$), and a poorer four frequency average in the better hearing ear was correlated with poorer scores on tests of executive function ($r = 0.228$, $p = 0.037$).

CAP and cognitive test scores

No significant associations were found between any of the DDT measures and cognitive test measures at the 0.05 level. Three of the four LiSN-S conditions demonstrated a significant correlation with at least one cognitive measure. Poorer low cue LiSN-S performance was correlated with poorer executive function performance ($r = 0.275$, $p = 0.012$). Likewise, poorer spatial advantage scores were correlated with poorer executive function performance ($r = -0.224$, $p = 0.028$). Spatial advantage scores were also correlated with visual learning performance ($r = -0.158$, $p = 0.033$). Tonal advantage scores were correlated with poorer performance on tests of attention ($r = -0.224$, $p = 0.019$), and psychomotor function ($r = -0.242$, $p = 0.009$).

Stepwise regression prediction of executive function

A stepwise regression analysis was conducted to evaluate the predictive value of the four variables that showed significant correlations with executive function (age, 4FA in the better hearing ear, and LiSN-S low cue and spatial advantage scores). At step 1 of the analysis, low cue LiSN-S scores were entered into the regression equation and were significantly related to executive function, $F(1,82) = 6.65$. $p = 0.012$ with a VIF of 1.0, accounting for approximately 7.58% of the variance in executive function scores. The other three variables (Age ($t = 1.47$), 4FA in the better hearing ear ($t = 0.68$) and LiSN-S spatial advantage score ($t = -0.97$)) did not add significant predictive value and were rejected from the model in the following steps of the analysis

($p > 0.05$). Thus, the regression equation for predicting executive function was:

$$\text{Executive function} = 53.96 + 3.94 \text{ Low cue LiSN-S score.}$$

Discussion

This study examined the relation between cognitive skills and peripheral and central hearing impairment in older adults. It was hypothesised that there would be a negative association between performance on the CSBB and a greater degree of peripheral and central hearing impairment. This hypothesis was supported, with peripheral hearing and binaural interaction demonstrating a significant association with some areas of cognitive performance.

Peripheral hearing and cognition

4FA and executive function

No significant association was found between peripheral hearing thresholds as measured by the 4FA average and any of the five cognitive test measures. However, worse hearing as measured by the 4FA in the *better* hearing ear predicted poorer executive function performance. This result supports previous research findings of a relation between 4FA of both ears and a test of executive function and psychomotor processing (Lin 2011), as well as an association between 4FA in the better hearing ear and tests of executive function and memory (Lin et al. 2011a). Other studies have measured cognition either longitudinally or via a diagnosis of dementia (Uhlmann et al. 1989; Lin et al. 2013). The current study adds to these findings with results on single and comprehensive assessments of both cognitive ability (in the area of executive function) and hearing that demonstrate an association between poorer hearing and poorer cognition in older adults without a current dementia diagnosis. These results further support previous findings that greater hearing loss is associated with poorer executive function performance (see Lin 2011).

A shared neuropathological aetiology may exist between peripheral hearing loss and cognitive dysfunction. Executive function is an important function of the frontal lobe (Hauser, Lukomski, and Hillman 2008), with research on the neurological underpinnings of hearing loss demonstrating that age-related neural degeneration can impact the pre-frontal cortex, and functional imaging studies showing that the frontal lobe is activated in response to auditory signals (Hackett 2009; Wayne and Johnsrude 2015). Executive function (responsible for behavioural control, metacognition and attention) has also been reported as being significantly poorer in children with hearing loss (Hauser, Lukomski, and Hillman 2008). It develops as young children grow and is known to deteriorate in older adults (Zekveld et al. 2014). If hearing loss can impact the development of executive functioning in young children, it may also influence the deterioration of executive functioning in older adults. For example, it could be postulated that hearing loss is associated with pre-frontal degeneration in older adults (or development in young children), and as a result leads to cognitive deficits in skills primarily reliant on the pre-frontal lobe such as executive function.

LFA and attention

Previous studies examining the cognitive domain of attention did not report a significant relation between scores on tests of attention and PTA as measured by the mid three frequencies (500, 1000 and 2000 Hz) (Gussekloo et al. 2005). In this study, PTA, as measured by a four-point mid-frequency average (4FA), was also not related to attention. Poorer low frequency hearing however, as measured by the LFA of the better hearing ear, was significantly related to poorer performance on tasks of attention. Age-related hearing loss typically impacts the higher frequencies more than the low frequencies; however, in many cases with increased severity of loss in the high frequencies, can gradually begin to impact the mid- and low-frequency ranges as well. Accordingly, the participants in this study presented with a mild or worse high frequency hearing loss, however not all presented with a low frequency hearing loss. Participants with low frequency hearing impairment had a greater hearing impairment overall than those with hearing impairment only in the mid and/or high frequencies. As proposed by the “fuel cognitive model” (Pichora-Fuller et al. 2016), tasks requiring more focus and motivation increase the cognitive load. Attention is the ability to maintain focus, which requires cognitive effort. Decreased redundancy in the auditory signal may have occurred as a result of having hearing loss across a wider frequency range, which may have increased the cognitive load for this task.

DDT and cognition

Scores on the DDT were not correlated with any of the cognitive test scores. In previous studies, tests of binaural integration have yielded promising results in terms of flagging cognitive deficits (Gates, Feeney, and Mills 2008; Gates et al. 2010, 2011). However, these studies used other tests of binaural integration in addition to the DDT, all of which demonstrated greater sensitivity than the DDT (see Gates, Feeney, and Mills (2008) for further information on the sensitivity and specificity of tests of binaural integration). Additionally, it has also been found that on tests of binaural integration, people with a higher level of education performed better overall (Gates et al. 2011). This is particularly relevant to the current study given most of the current participants were tertiary educated. The combination of the lower sensitivity of the DDT in comparison to other tests of binaural integration, and a highly educated sample may have made it more difficult to detect an association between binaural integration and cognitive performance, if one existed, in comparison to other studies.

LiSN-S and cognition

No study to date has demonstrated a significant independent relation between LiSN-S scores and performance on specific cognitive domains in older adults. In past research, LiSN-S scores in one study were only related to cognitive scores before age and peripheral hearing were controlled for (Glyde et al. 2013), and in another study with 26 older adults using a cognitive screening tool, overall cognitive performance was significantly related to both age and LiSN-S (particularly the low cue condition) performance (Besser et al. 2015). In the present study, poorer low cue LiSN-S performance was significantly correlated with poorer executive function. Additionally, spatial advantage performance was also related to executive function. After accounting for age, 4FA in the better ear, and spatial advantage performance, low cue LiSN-S performance remained the most significant predictor of executive function, accounting for over half of the explained variance in executive function given by the four variables combined. That is, executive function performance was best predicted by low cue LiSN-S performance. As the low cue LiSN-S test condition contained few acoustic cues such as voice or spatial differences between the target and distractor signals, it was more difficult for individuals to recognise the target speech. Executive function performance relies on the ability to organise thoughts and apply oneself to completing tasks. Similarly, the low cue LiSN-S condition requires the ability to be able to differentiate the target speech signal and distractors without other cues such as tonal or spatial differences between speakers and distractors.

A novel finding of the present study was that people who gained greater benefit from using tonal differences between target and distractor speakers also performed better on tests of attention and psychomotor function. Zekveld et al. (2014) compared the cognitive processing load of individuals in background noise whilst attempting to listen to a target speaker with either spatial separation or tonal separation from distractor speakers. It was found that people with better ability to make use of the tonal cues in speech were better at reducing their cognitive load (Zekveld et al. 2014). Participants in the current study who had better tonal advantage scores performed significantly better on attention and psychomotor tests, also presumably because of reduced cognitive load.

Another novel finding of this study was the relation found between spatial advantage performance on the LiSN-S test and the cognitive domain of visual learning. As mentioned previously, research by Glyde et al. (2013) also found an association between spatial advantage scores and performance on a cognitive screening tool, but not after age and peripheral hearing ability was controlled for. Besser et al. (2015) found a significant association between some LiSN-S Speech Reception Threshold (SRT) scores and cognitive performance on the Montreal cognitive assessment (MoCA) task; however, the MoCA was not domain-specific, and no relation was found with spatial advantage scores. What Besser et al. (2015) did find, however, was that age-group differences were greatest for the use of spatial separation cues, which the authors contributed to potential age-related cortical changes and changes in temporal nuclei (Gallun et al. 2013; Besser et al. 2015). Further research into if any underlying neurophysiological changes that impact spatial processing may also impact cognitive skills such as learning may help to explain the result found in the current research.

Limitations of this study

Unlike the participants of previous studies, participants of the current study tended to be high SES and were primarily tertiary educated. Sampling from other socioeconomic areas may have yielded different results. Furthermore, the relatively small sample size of 85 people may have limited the study's statistical power to identify a relation between executive function and LFA in the better hearing ear if this existed. The range of degree of hearing impairment was also limited in this study population, with most participants having a mild hearing loss in the better ear, and the maximum degree of hearing loss being moderate. Lastly, the current cohort study assessed both cognition and hearing loss at one time point only. A repeated measures study design may be beneficial in identifying cognitive/hearing changes over time and in monitoring any long-term cognitive impact of hearing loss.

Conclusions

The results of this study demonstrated that both peripheral and central hearing impairment are significantly correlated with cognitive test scores. People with poorer peripheral hearing and/or central hearing ability (as measured by the LiSN-S test) were more likely to have poorer cognitive performance in the areas of attention, executive function and/or psychomotor function. These findings suggest that people with hearing deficits are more likely to experience cognitive impairment than those without hearing deficits. This study provides new and specific information on how different areas of cognition are impacted by severity of hearing loss at different frequencies. In the better hearing ear, poorer peripherally measured hearing was found to be related to poorer executive function and poorer attention. Additionally, it was found that poorer central hearing performance (specifically binaural interaction skills as measured by the LiSN-S test), was associated with poorer cognitive function in the areas of executive function, attention and visual learning.

Audiologists are well-positioned to be sources of early referral for cognitive impairment and decline in older adults, as they work in close proximity with this population and may therefore be more likely to be working with an individual at risk of cognitive dysfunction (Gates et al. 2011). As a result, those at greater risk of cognitive dysfunction may be sooner identified, with appropriate referrals being generated. If an individual were to perform poorer than expected on the LiSN-S test (in the low cue or tonal advantage condition) this may be a helpful trigger for cognitive testing. If future research can identify whether long-term cognitive consequences (e.g. dementia or cognitive decline etc.) are related to LiSN-S test performance, it may be worthwhile to monitor cognitive function/decline in people presenting with central hearing impairment. Furthermore, given the growing evidence of a relation between hearing and cognition, it would seem beneficial to investigate the mechanism of this association, potentially through neurophysiological underpinnings as highlighted by Iliadou et al. (2017). Additionally, if the remediation of hearing loss (i.e. with hearing aids) can mitigate this association, this could potentially further our understanding of the pathophysiological mechanisms relating hearing and cognition.

Overall, this study provides further evidence of an association between hearing impairment and cognitive function in older adults. It is suggested that central hearing impairment should also be explored in addition to peripheral hearing impairment when investigating cognition in this age group. It may also be beneficial to include CAP tests in audiological test batteries in order to gain not only an understanding of an individual's hearing impairment and communication difficulties but also to identify any early cognitive deficits that may otherwise go unnoticed.

Declaration of interest

No potential conflict of interest was reported by the authors.

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CHAPTER 6

EXPERIMENT 2

6.1 OUTLINE

This chapter begins with a submitted experimental paper entitled 'Spatial Processing Ability and Executive Function in Older Australians'. This paper aimed to contribute to the research question: "Is there a difference in cognitive function between those presenting with hearing loss alone and those with both hearing loss and impaired higher order listening function as measured by scores on cognitive tests and psychoacoustic speech perception measures respectively?". Included in the paper is the significant finding that those with a greater degree of hearing loss were more likely to present with a spatial processing deficit (SPD), and subsequently, poorer performance on executive function tasks. Those with an identified SPD had significantly poorer executive function performance than those without. However, given the significant intercorrelations between peripheral hearing, spatial processing and executive function, it was unable to be concluded that those with higher order listening dysfunction were more likely to present with poorer cognitive ability, independent of peripheral hearing function. Rather, what is clear is that there may be a complex interaction between the three processes.

This paper is followed (section 6.3) by the comparisons in cognitive performance between those with identified binaural integration deficits (as identified with the DDT) and those without.

6.2 PERIPHERAL HEARING, SPATIAL PROCESSING ABILITY AND EXECUTIVE FUNCTION IN OLDER AUSTRALIANS

The following paper is incorporated in its entirety in this chapter:

Manuscript under review

- Nixon, G, Sarant, J. Z., & Tomlin, D., & Dowell, R. Peripheral hearing, spatial processing ability and executive function in older Australians. Submitted manuscript January 2020 to American Journal of Audiology (constitutes Chapter 6.2).

Aim: to examine group differences in cognitive performance between those with both a centrally and peripherally measured hearing impairment in comparison to those with a peripherally measured hearing loss alone.

Abstract

Objectives: To examine whether there were group differences in cognitive performance between those with both a centrally and peripherally measured hearing impairment in comparison to those with a peripherally measured hearing loss alone, and to understand better the hearing and cognitive presentation of audiology patients.

Design: Peripheral hearing was assessed with Pure Tone Audiometry. The Listening in Spatialised Noise-Sentences (LiSN-S) test provided a measure of spatial processing ability, as a component of central auditory processing ability. Cognition was assessed with the Cogstate: Brief Battery and Groton Maze Learning task, which measured five cognitive domains: executive function, attention, visual learning, working memory and psychomotor function. 83 participants (38 males) between the ages of 60.33 and 83.08 (m=70.23, SD=5.14) completed the study.

Results: Fifty-nine percent of the participants presented with a Spatial Processing Deficit (SPD). Those with a SPD had a four-frequency average of 35.05dBHL (SD=8.79), and those without a SPD had a four-frequency average of 27.78 (SD=7.01). Participants presenting with a SPD showed significantly poorer performance on tests of executive function than those without, although only before controlling for the effect of peripheral hearing loss.

Conclusions: Overall, the results of this study suggest that the presence of peripherally measured hearing loss in addition to a SPD (as an identifier of impaired higher order listening ability) is significantly related to poorer executive function performance. Given the significant relationship between spatial processing and

peripheral hearing measures, these results highlight the complexity of the relationship between hearing and cognition.

INTRODUCTION

Age-related hearing impairment (ARHI) is labelled as the most common sensory loss overall, and is the third most prevalent chronic medical condition in the older population (Albers et al., 2015; Schiller, Lucas, & Peregoy, 2012). Commonly, ARHI is categorised as peripheral HI or central HI, often with a mixed clinical manifestation (Panza et al., 2015; Yuan, Sun, Sang, Pham, & Kong, 2018). A common complaint in ARHI is the inability to listen to speech in complex listening environments (Besser et al., 2015). The inability to hear in complex listening environments is commonly an indication of central rather than (or at least in part in conjunction with) peripheral HI, yet peripheral HI is the primary focus of current audiological assessment (Gates et al., 2008b; Panza et al., 2019). An individual's ability to communicate relies on a combination of peripheral hearing, central hearing (sometimes referred to as Central Auditory Processing; CAP) and cognitive abilities, and consequently, communication difficulties may result from a combination of dysfunction in any of these areas (Humes, 2007; Panza et al., 2019; Panza, Quaranta, & Logroscino, 2018; Yuan et al., 2018). However, how these abilities interact and influence dysfunction in speech communication in older adults is currently unclear (Humes et al., 2012; Panza et al., 2015).

ARHI can have adverse effects on general health and quality of life, and is a major cause of other chronic health conditions in older age (Panza et al., 2015). Of particular interest in emerging literature is how ARHI (peripheral and/or central) relates to late-life cognitive dysfunction (Humes, Busey, Craig, & Kewley-Port, 2013b; Livingston et al., 2017; Yuan et al., 2018). Like ARHI, cognitive decline is a major issue impacting older populations, and with the aging of the world's population, the effects and incidence of ARHI and cognitive decline are expected to substantially increase within the next two decades (Census Bureau, 2016). An association between HI and cognitive decline has been established in previous literature [see the reviews of Loughrey et al. (2018) and Taljaard et al. (2016)], showing that peripheral hearing loss is negatively associated with a decline in cognitive function (with a dose effect observed) (Gussekloo et al., 2005; Lin, 2011b; Lindenberger & Baltes, 1994b; Rönnberg et al., 2011), and is associated with an increased risk of dementia (Gurgel et al., 2014b; Lin et al., 2011b; Lin et al., 2013). Self-reported hearing disability is also reported to be significantly associated with accelerated cognitive decline, potentially mediated by depression and social isolation (Amieva et al., 2015).

As with peripheral hearing thresholds and cognition, there is a significant relationship between CAP function and age, with one study demonstrating that CAP function declines at a faster rate than does peripheral auditory function (Gates et al., 2008b). Numerous research studies have also demonstrated that a reduction in CAP ability is significantly associated with poorer cognitive function, is more pronounced in those with probable dementia, and may even precede the onset of clinical symptoms of dementia [see Nixon et al. (2019) for a review of this area]. Pooled results from multiple studies found that people with peripheral and central ARHI have a higher risk of cognitive impairment than those with normal hearing (Panza et al., 2018).

Some morphological evidence suggests that there may be neurological underpinnings that contribute to the relationship between cognitive function and peripheral and central auditory function. One recent longitudinal study found that a greater degree of high frequency hearing loss was significantly associated with reduced gray matter brain volume, and larger increases in lateral ventricle volume (Eckert et al., 2019). Another recent study found that poorer central processing performance (as measured by Speech Reception Threshold in Noise [SRTn]) was associated with a reduction in whole-brain matter volume, and specifically in auditory processing regions (temporal cortex) and cognitive processing regions (frontal cortex and lower hippocampus) (Rudner, Seeto, Keidser, Johnson, & Rönnberg, 2019). The neurological changes seen in those with hearing loss share similarities with the brain morphology of dementia patients (Kral, 2013; Kral & Sharma, 2012; Peelle, Troiani, Grossman, & Wingfield, 2011; Wong et al., 2009). Typically, central, rather than peripheral auditory structures, exhibit morphological damage similar to changes seen in dementia patients (Albers et al., 2015). For example, in numerous early research studies, medial temporal lobe atrophy defined a diagnosis of dementia (Erkinjuntti et al., 1993; Scheltens et al., 1992). However, when considering dementia-related morphological changes in peripheral auditory structures, although there were some changes in the basal turn of the cochlea, overall no significant differences were found between the cochlea's of Alzheimer's dementia (AD) patients and age-matched controls (Sinha, Saadat, Linthicum, Hollen, & Miller, 1996). The same authors also reported AD-specific neurodegeneration of central auditory nuceli (Sinha et al., 1993).

As discussed, although behavioural and morphological evidence links cognitive function to ARHI, the distinction between peripheral and central ARHI is not well defined. In fact, it may be that the two are not independent processes. There are two hypotheses that attempt to explain central ARHI in relation to peripheral hearing ability. The ‘direct hypothesis’ suggests that central ARHI occurs via changes independent to a peripheral hearing loss, while the ‘indirect hypothesis’ suggests that central ARHI may be induced from the presence of a peripheral hearing loss as a result of sensory deprivation (Humes et al., 2012; Panza et al., 2019). It is thought that peripheral ARHI may be the primary contributor to early ARHI and central HI becomes increasingly significant in advanced ARHI (Gates & Mills, 2005; Panza et al., 2015). This stepwise progression of HI symptoms may support the indirect hypothesis. Furthermore, peripheral HI may significantly influence CAP performance. Spatial Processing (SP) ability (the ability to suppress sounds from one direction whilst at the same time attending to a target signal from another (Glyde, Hickson, Cameron & Dillon, 2011) is a significant contributor to how individuals listen to speech in background noise (i.e. a measure of CAP). SP ability has been reported to be negatively correlated with degree of peripheral HI (Glyde et al., 2013). However, in other studies such as the Adult Changes in Thought (ACT) study, performance on measures of CAP deteriorated significantly in parallel with memory impairment independent of peripheral hearing, and was significantly related to measures of executive function (Gates et al., 2008a; Gates et al., 2010b). It may be postulated that these findings by the ACT study may support the ‘direct hypothesis’, or perhaps that central ARHI is a greater predictor of cognitive performance and/or decline than is peripheral ARHI. As CAP and cognitive processes both rely on central nervous system function, they may be interacting on a central level, such that central rather than peripheral hearing performance could be more closely related to cognitive performance (Yuan et al., 2018). As highlighted earlier, degraded speech perception may be the result of impaired central auditory networks and/or cognitive networks. For example, the ACT study highlighted that executive function may be a key contributor to performance on CAP tasks (Gates et al., 2010a; Panza et al., 2015). Executive function relies on pre-frontal cortex activation (Dennis & Cabeza, 2011), and as discussed, there is known deterioration of the frontal cortex in those presenting with signs of central HI (Rudner et al., 2019).

In summary, the literature to date suggests that peripheral hearing, CAP and cognitive function may all be contributing to speech perception ability, and that age-related changes in any of these areas may contribute to degraded speech-processing. However, the ways in which these three functions interact in order to influence speech perception ability is currently poorly understood. Audiology assessments currently focus on peripheral hearing evaluations only, despite a large number of patients reporting difficulty processing speech in complex situations rather than in quiet (an ability reliant on central hearing and cognitive processes also). To better understand the difficulties audiology patients may be presentating with at audiology appointments, and to understand the relationship between hearing and cognition, further investigation of central and peripheral hearing dysfunction and if/how these conditions relate to cognition (i.e. independently of each other or not) should be conducted.

A clinically useful tool that measures speech perception in background noise is the Listening in Spatialised Noise-Sentences test (LiSN-S). The LiSN-S is an assessment of SP ability, and measures the Speech Reception Threshold (SRT) of an individual after manipulating the direction of a target speaker (Cameron & Dillon, 2007). A spatial processing deficit (SPD) is suspected when there is "reduced ability to selectively attend to sounds arriving from one direction whilst simultaneously suppressing sounds arriving from another" (Glyde et al., 2011, p. 117). Additionally, the LiSN-S can provide amplification during testing using similar prescriptive measures as those used when fitting hearing aids. This can assess the benefit perceived after amplifying appropriately for an indiviudal's peripheral hearing loss. Whilst some studies have found a relation between LiSN-S SRT scores and cognition (see Besser et al., 2015; Glyde et al., 2013), little research has assessed the association between SP ability as measured by the LiSN-S and cognition specifically in older adults and/or beyond the use of a cognitive screening tool.

This study attempted to add to the findings of previous studies by comparing cognitive performance in older adults with peripheral ARHI between those with and without an identifed SPD across a number of cognitive domains. As detailed earlier, information about performance across different cognitive domains may help to further explain the relation between cognition and hearing. In this study, a cognitive tool that assesses varying domains of cognition (e.g. executive function, memory, attention etc.) was used to elicit more specific cognitive infomormation than would a global cognitive screening tool. As highlighted by the 'indirect hypothesis', age-related changes in brain morphology that impact central hearing/cognitive function may be related to peripheral HI. This study also aimed to gain a greater understanding of the realtions between central hearing and cognitive performance of older adults, which has been relatively unexeplored in previous literature. Given evidence provided by morphological research and studies such as the ACT study (Eckert et al., 2019; Gates et al., 2008a; Rudner et al., 2019), it was hypothesized that participants presenting with both peripheral hearing loss and impaired SP ability (as measured through the LiSN-S), would perform more poorly on tests of cognition than those presenting with hearing loss alone. If older adults with a SPD are found to have poorer cognitive function independent of their peripheral hearing, then this may support the theory that central HI is a greater indicator of cognitive function than are peripheral hearing measures.

METHODS

Written consent was obtained from all participants for this study, which was approved by the School of Health Sciences Human Ethics Advisory group of the University of Melbourne (Ethics ID: 1748836).

Participants

Thirty-eight males, forty-four females and one non-binary individual who attended the University of Melbourne Audiology clinic were enrolled into this study. All participants were aged over 60 years, and between the ages of 60.33 and 83.08 (m =70.23, SD = 5.14). In addition to age, exclusion criteria included a previous diagnosis of dementia, a history of using hearing aids/cochlear implants, or the presence of any visual/English impairment that precluded the ability to complete the assessment tasks as subjectively assessed by clinician at time of recruitment (based on inability to read with glasses/Non-English speaker). The socio-economic status (SES) of this cohort as defined by the IRSAD score (Australian-Bureau-of-Statistics, 2018) did not follow a normal distribution and was significantly negative skewed (Anderson-Darling test of normality; AD=5.3, p<0.005). Approximately 62% of the participants came from the highest ranked (top 20%) areas of Australia. No significant relationship was found between participants' SES score and any of the behavioural test measures (i.e. Pure Tone Audiometry (PTA), LiSN-S or the cognitive scores; see methods for a description of the cognitive tools used).

Test Battery

Pure Tone Audiometry

Participants underwent audiometric assessment including bilateral air conduction thresholds at octave frequencies between 250Hz and 8000Hz, 3000Hz and 6000Hz, bilateral bone conduction thresholds where indicated at octave frequencies between 500Hz and 4000Hz, bilateral speech discrimination using AB monosyllabic words, and tympanometry. Pure tone audiometry was assessed using an Interacoustics Affinity 2.0 Audiometer in a sound attenuating room. A low frequency (250Hz, 500Hz and 1000Hz) and high frequency average (>1000Hz) was calculated for both ears. Four frequency averages for 500Hz, 1000Hz, 2000Hz and 4000Hz were used to summarise overall hearing, as a reflection of past literature (Besser et al., 2015). Degree of HI was classified as either normal (<20dBHL), mild (20 to 40dBHL), moderate (45-65dBHL), severe (70-90dBHL) or profound (>90dBHL) (Clark, 1981; Davis & Silverman, 1970).

The LiSN-S Test

The LiSN-S test (Cameron & Dillon, 2007) has strong test-retest reliability (Cameron et al., 2009; Sharma et al., 2012). It evaluates SP and assesses performance in background noise when there are advantages of spatial separation and/or voice cues (i.e. when a target speaker is 90° azimuth to background speakers and/or has a tone of voice that is distinct from background speakers). The LiSN-S was administered using a personal computer, Sennheiser HD215 circumaural headphones and a Buddy 6G USB soundcard. The initial presentation levels for the speaker and distractor were 62dBSPL and 55dBSPL respectively. All participants were assessed in LiSN-S prescribed gain amplifier (PGA) mode in which participants' bilateral hearing thresholds (for both bone- and air-conduction) are used to amplify the stimuli according to the National Acoustic Laboratories – Revised Profound (NAL-RP) prescription (Cameron et al., 2014; Glyde et al., 2013). A deficit in SP was identified if there was a pattern of depressed scores on the spatially separated conditions of the LiSN-S in comparison to conditions where the signal and distractor were co-located. That is, a SPD pattern was recognised when standard deviations of high-cue SRT and spatial advantage scores (i.e. conditions where target and distractor were separated by 90°) were poorer than those obtained for the low cue and talker advantage scores (i.e. conditions where target and distractor were not spatially separated) (Cameron et al., 2014). Age-related norms for the results of the LiSN-S are only available for people up to age 60 years. Therefore, when calculating standard scores, results for all participants in this study were compared to age-related norms for a 60-year old adult (Cameron et al., 2009; Cameron & Dillon, 2007).

Cognitive assessments

Cognitive screening was conducted for all participants before any testing commenced. The Mini Mental State Examination (MMSE) was used. The MMSE is a brief assessment (approximately 5-10 minutes) that tests cognitive function in adults (Folstein et al., 1975; Godin et al., 2017). The MMSE reportedly has a high specificity (96%) and a lower sensitivity (64%) to identifying significant cognitive impairment (Munshi et al., 2006). The MMSE is scored out of a total of 30. A score of <24 is considered abnormal, and participants were required to achieve a score within the normal range in order to participate in the study (Folstein et al., 1975).

The Cogstate Brief Battery (CSBB) (Cogstate, 2017), consisting of four tasks, was used as the primary outcome measure in this study. An additional fifth task (the Groton Maze Learning Test), which is commonly used in the Cogstate Alzheimer’s Battery (Collie et al., 2003; Falleti et al., 2006; Maruff et al., 2009; Westerman et al., 2001) was also used. The tasks are subsequently described. The test battery was presented on a Windows laptop with an additional wired mouse. Two sessions were run, with at least a 30-minute break between conditions, the first of which was a practice session in which the assessor remained in the room with the participant. The instructions were presented on screen for the participant to read and were also read out loud by the assessor to minimise any effect of vision or hearing difficulties. A smaller version of each of the tasks was then given in an interactive demonstration. Once participants demonstrated an understanding of and ability to perform the task, the full task began. The four tasks from the CSBB were in the form of card games in which the participant was required to respond “yes” and/or “no” to a stimulus via the right and left mouse click or the “k” and “d” keys on the keyboard (this was the participant’s choice). In the second session the same test battery was used, the results were recorded, and the assessor was outside the room. It has been reported that after the second session, performance remains relatively stable, with test-retest reliability for each measure estimated to range between 0.84 and 0.94 (Collie et al., 2003; Falleti et al., 2006; Maruff et al., 2009). Both speed and accuracy of response (reported as a percentage correct/incorrect) were calculated for each task, and the scores were then transformed to produce normalised data distributions (Falleti et al., 2006; Maruff et al., 2009). Table 1 describes the tasks of the Cogstate Battery.

TABLE 1. Description of Cogstate battery

	Test	Domain	Task	Definition of Normal Limits
Cogstate Brief Battery + Groton Learning Test	Detection test	Psychomotor function (processing speed)	Participant must respond yes when a card is turned over.	Compared to age-related norms. Standardised with a mean of 100 and a standard deviation of 10.
	One card learning test	Visual learning	Participant must respond yes or no to whether they had seen a card previously during that task.	
	One back test	Working memory	Participant must respond yes or no to whether the card they are viewing is the same as the card viewed immediately prior.	
	Identification test	Attention	Participant must respond yes or no to whether the card they are viewing is red.	
	Groton Maze learning test	Executive function	Participant must move one step at a time from the start toward the end of a maze to find a hidden pathway, by touching a tile next to their current location.	

Statistical analysis

Parametric correlational analyses were initially performed to examine any associations between continuous variables of interest in this study using the Minitab 17 (2010) Statistics Package. Further analyses included partial correlations, multiple and stepwise regression analyses, and independent sample t-tests (where appropriate). The Variance Inflation Factor (VIF) was used to assess multi-collinearity, with a value of <4.0 indicating low correlation among variables (Hair, Black, Babin, & Anderson, 2010).

RESULTS:

Participant Demographics

Participant demographics and descriptive statistics for the four behavioural measures (PTA, LiSN-S, and CSBB) are presented in table 2, along with results from two sample t-test results for sex (with 38 males and 44 females). All participants had at least a mild hearing loss in at least one of the defined frequency ranges. Twenty-two percent of participants had a high school education or lower, whilst of the remaining 59% of participants with University degrees, 19% had a PhD level degree. This high proportion of University-educated individuals may be the result of recruiting through a University-based Audiology Clinic.

TABLE 2. Descriptive statistics on participant demographics and the primary test measures (N=83):

Demographic/Test	Descriptive Statistics					Two-sampled t-test for male v. female (N=82)
	Mean	SD	Median	Minimum	Maximum	
Age	70.68	5.14	69.58	60.33	83.08	t=-1.05 (-3.48, 1.07) p=0.297
MMSE Score	28.75	1.99	29.00	24.00	30.00	t=-0.47 (-0.65, 1.05) p=0.640
Socioeconomic Score	1052.4	49.3	1068.00	911.00	1130.00	t=-0.68 (-28.90, 14.20) p=0.499
Pure tone audiometry						
LFA[a]	21.91	9.79	21.67	5.00	45.00	t=0.88 (-2.38, 6.16) p=0.381
4FA[b]	32.07	8.83	32.50	13.13	56.88	t=--0.74 (-5.42, 2.48) p=0.461
HFA[c]	47.07	13.14	46.50	15.00	97.00	**t=--2.07 (-11.65, -0.221) p=0.042**
LiSN-S (SRT)						
Spatial advantage score	8.39	3.10	8.50	-7.30	14.00	t=-0.33 (-1.573, 1.124) p=0.741
CSBB (Primary outcome score)						
Attention^	2.78	0.06	2.78	2.61	2.94	t=1.12 (-0.012, 0.043) p 0.269
Psychomotor function^	2.59	0.09	2.59	2.43	2.85	t=-0.60 (-0.485, 0.259) p=0.547
Executive function^	54.17	16.10	54.00	25.00	116.00	t=1.70 (-1.03, 12.88) p=0.094
Visual learning	0.98	.11	1.00	0.55	1.23	t=-1.60 (-0.085, 0.009) p=0.113
Working memory^	2.95	0.09	2.95	2.71	3.15	t=0.10 (-0.037, 0.040) p=0.922

^Results are reverse scored, with a lower score indicating better performance

[a] 250Hz, 500Hz & 1000Hz

[b] 500Hz, 1000Hz, 2000Hz & 4000Hz

[c] 2000Hz, 3000Hz, 4000Hz, 5000Hz, 6000Hz & 8000Hz

LiSN-S, Listening in Spatialised noise sentences-test; DDT, dichotic digits; CSBB, Cogstate Brief Battery

Significant predictor (p<0.05) is shown in bold.

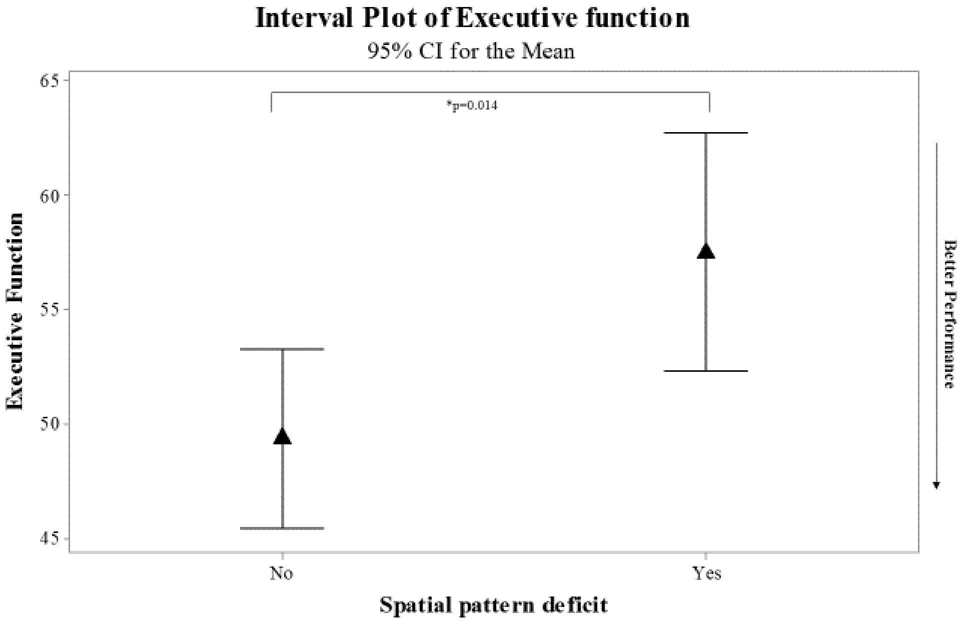
Age effects

There was no significant difference in age between the group of participants with a SPD and those without, t(73)=-1.30, p=.198. However, in one LiSN-S condition (the low cue SRT measure), older people did demonstrate poorer performance (r= .395, *p*<.001). Additionally, increased age was significantly related to poorer performance on executive function tasks (r=.254, *p*=.004). No significant correlation was found between age and participants' hearing loss (4FA) (r=.113, *p*=.310).

LiSN-S and Cognition

Forty-nine participants (59%) presented with a SPD. When comparing those presenting with and without a SPD, an independent t-test showed a significant difference between the two groups in mean executive function performance, t(80)=-2.52, p=0.014 (see Figure 1). Those presenting with a SPD performed more poorly on the test of executive function (results are reversed-scored, with lower scores indicating better function) than did those without. Poorer performance in the LiSN-S spatial advantage condition (as measured by a dB advantage score) was significantly correlated with executive function performance (r=-0.242, p=0.028).

Figure 1. Difference in executive function performance between participants with and without a spatial pattern deficit.



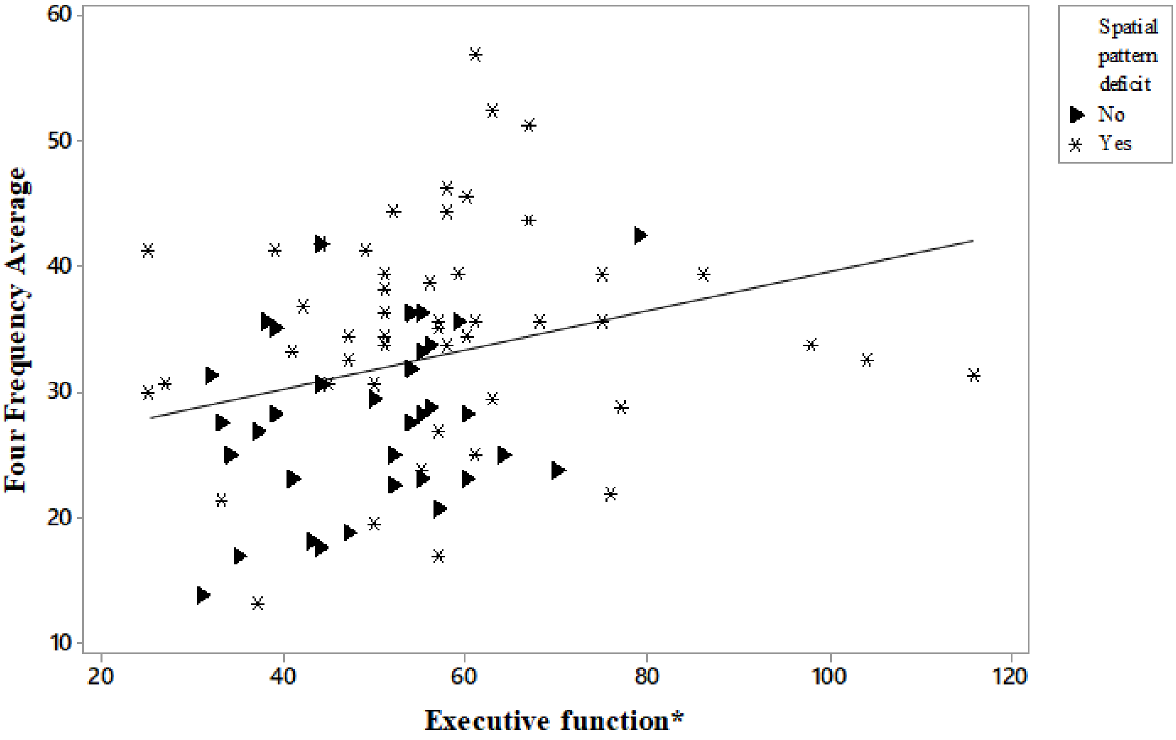
Peripheral Hearing, Cognition and LiSN-S

Participants presenting with a SPD had significantly poorer hearing (as measured by the 4FA) than those without, t(79)=-4.19, p<0.001. Furthermore, examination of the association between spatial advantage score and peripheral hearing (4FA), showed that there was also a strong positive significant relationship (r=-0.608, p<0.001) indicating that the poorer an individual’s peripheral hearing, the poorer their performance on the LiSN-S test with spatial separation cues present, regardless of an identified SPD.

Poorer hearing in the 4FA range was significantly associated with poorer executive function performance (r=0.223, *p*=0.04) (see Figure 2). Additionally, poorer hearing in the low frequencies was significantly correlated with poorer performance on tests of attention (r=0.246, *p*=0.03).

A linear multiple regression analysis was conducted to further explore the associations between 4FA, LiSN-S spatial advantage performance and executive function scores. The combination of these two continuous predictors was not significantly predictive of executive function (F(2,82) = 2.90, p=0.061), with only a small proportion (6.75%) of the variance in executive function scores accounted for by the linear combination of these two predictor variables. Figure 2 presents the association between 4FA and executive function, separated for those with and without an identified SPD.

Figure 2. Scatterplots detailing the correlation between Executive Function scores and Four Frequency Average (4FA) in dBHL, separated by the presence of a spatial pattern deficit (yes/no).
*Results are reverse scored.



A standard multiple regression analysis was conducted to evaluate how 4FA and the presence of a SPD contributed to executive function scores. The combination of these continuous and categorical predictors was significantly related to executive function performance (F(2,82) = 3.49, p=0.035, with a VIF of 1.2). The multiple regression coefficient was 0.214, indicating that 8.02% of the variance in executive function scores could be accounted for by the combination of the presence of a SPD and hearing loss (4FA). Whilst this is a significant finding (F(2,82) = 3.49, p=.035), this relatively low variance score highlights that other factors not accounted for in the model are contributing to the majority of the outcome. A stepwise regression was then conducted to evaluate whether both hearing loss (4FA) and the presence of a SPD were necessary to predict executive function scores. At step 1 of the analysis, the presence of a SPD (yes/no) was entered into the regression equation. This was significantly related to executive function, F(1,82) = 5.43, p=0.022, with 6.28% of the variance of executive function scores accounted for by the presence of a SPD. Hearing loss (4FA) (t = 1.23) was not included in the model (p>0.05), suggesting that the presence of a SPD was a significant predictor of executive function scores whereas peripheral hearing loss (4FA) was not.

DISCUSSION

This research examined the relations between hearing and cognition and aimed to determine whether individuals with a SPD as measured by the LiSN-S test had poorer cognition than those without an identified SPD. The hypothesis of this study was that participants presenting with both peripheral hearing loss and impaired higher order listening ability (measured through the LiSN-S spatial advantage score, or the presence of an identified SPD), would perform more poorly on tests of cognition than those presenting with peripheral hearing loss alone. The hypothesis was supported by the results, with group results for those with an identified SPD showing significantly poorer executive function. However, whilst both SPD groups had some degree of peripheral hearing loss, the SPD-positive group had a greater degree of hearing loss overall, making it difficult to ascertain whether those with impaired higher order listening function had poorer cognitive function independent of their significantly poorer peripheral hearing ability. That is, it is unknown whether participants with a SPD simply had significantly poorer executive function, or if those with a SPD had significantly poorer hearing which in turn related to significantly poorer executive function. What is clear from the results, however, is that those with a SPD were more likely to be presenting with poorer hearing, and were also more likely to be presenting with poorer executive function performance.

Little research has assessed the association between SP as measured by the LiSN-S and cognition, with only one study to date reporting a significant relationship between LiSN-S SP performance and cognition (Glyde et al., 2013). However, this result was obtained only before taking into account peripheral hearing ability and the age of participants, and unlike the present study, the population was not restricted to older adults (Glyde et al., 2013). As suggested by the authors, the results may have been limited to the choice of cognitive test used (COGNISTAT) and the small distribution in cognitive performance obtained. The COGNISTAT was a general measure of cognitive function and “could not observe relationships between specific cognitive functions and spatial-processing ability” (Glyde et al., 2013, p. 26). Additionally, the authors suggested that whilst the COGNISTAT has been validated as a tool that is sensitive to detecting cognitive decline in geriatric populations, the sample in their study demonstrated a small range of cognitive abilities, with all participants scoring above 80% on the test. This small range limited the statistical power of the study. Besser and colleagues (2015) suggested that to overcome the influence of impaired peripheral hearing observed in the Glyde et al. (2013) study, normal-hearing participants should be used. In their study with a cohort of older adults with normal peripheral hearing up to and including 3000Hz, Besser et al. (2015) reported that cognitive scores on a cognitive screening tool (MoCA) were predicted most by LiSN-S SRT scores. It is important to note that the 4FA of older adults in this study (although clinically normal), and hearing thresholds above and including 6000Hz were still significantly related to LiSN-S outcomes, with poorer hearing predicting poorer performance on the LiSN-S. This result confirms Glyde et al.’s (2013) findings that peripheral hearing measures are significantly related to LiSN-S outcomes. A limitation of both aforementioned studies was the use of a screening tool to measure cognition. This meant that it was not possible to examine performance on particular cognitive domains such as executive function, which has been reported to be significantly related to another CAP ability known as binaural integration (see Gates et al., 2011unlike the present study, neither study were able to compare group performance in cognition between those with a SPD and those without, as they used a continuous variable measure (SRT/advantage score obtained from the LiSN-S)..

Approximately 59% of participants in this study presented with a SPD, which is unsurprising given previous research has highlighted that older adults with hearing loss have poorer SP ability even after compensating for HI by using a prescribed gain amplifier (Glyde et al., 2013). This finding was further supported in the present study, with poorer hearing significantly related to worse spatial advantage scores, and those presenting with a SPD having significantly poorer hearing overall. In this study, poorer executive function was significantly associated with greater peripheral HI and also with poorer LiSN-S spatial advantage scores. The presence of a CAP disorder in the form of a SPD was significantly related to measurements of executive function in participants in this study. As would be expected, there was also a significant association between 4FA and SP ability. As highlighted by Besser et al (2015), the influence of hearing on LiSN-S may be explained by how those with decreased hearing acuity have reduced neural responses to speech stimuli and gray matter volume in primary auditory regions (Peelle et al., 2011). As concluded by Besser et al. (2015), LiSN-S outcomes may be dependent on peripheral hearing thresholds not as a direct consequence of peripheral processing, but rather via cortical changes. These conclusions by Besser and colleagues and the findings of the present study provide further support for the ‘indirect hypothesis’ between peripheral and central hearing measures, and may also suggest that there is a stepwise progression from peripheral ARHI, central ARHI and cognitive dysfunction. However, further longitudinal research would be required to confirm this suggestion.

The results of the present study highlight the complex relationship between hearing and different domains of cognition, and the difficulty of identifying specific contributors to this relationship. The association found between 4FA and LiSN-S scores after PGA was used also highlights the fact that despite personalised amplification, individuals still presented with compromised SP performance. This adds to previous findings that although cognitive factors may be an evident contributor to speech-understanding difficulties, there is a consistent inability to provide amplification to aid peripheral hearing difficulties in a way that makes speech stimuli sufficiently audible for listeners (Humes, 2007). That is, despite amplification, peripheral hearing deficits still remain a significant influencer on speech perception ability (Humes, Wilson, Barlow, Garner, & Amos, 2002). This result illustrates the fact that hearing devices do not restore normal listening, and this needs to be considered in rehabilitation and counselling post hearing-aid fitting. Accordingly, the hearing-cognition literature has begun to focus on longitudinal outcomes of hearing aid use on cognitive outcomes (see Amieva et al., 2015 for an example). However, this research is currently scarce, and more evidence of the effects long-term hearing aid use has on cognition is required to understand whether hearing aids may be effective in preventing cognitive decline.

The results of this study provide further support for an association between HI (peripheral and central) and cognition, however no causal implications can be drawn. CAP skills rely on pathways in the central auditory nervous system, therefore it is possible that hearing and cognition are related due to morphological changes in the CNS. However, it is important to note that the current study measured CAP using behavioural tests rather than morphological measures such as imaging techniques used in previous studies which identified brain regions important to both auditory and cognitive processes such as the auditory and frontal cortices (Rudner et al., 2019).

The present research emphasizes the importance of considering CAP in the relationship between hearing and cognition. Executive function was found to be related to performance on tests of SP and peripheral hearing loss. Those identified with a SPD as measured by the LiSN-S test were more likely to perform poorly on tests of executive function than those without. Overall, these results highlight that having poorer CAP function alone or in addition to peripheral HI is significantly related to poorer cognitive performance. Furthermore, it highlights the complex and multifaceted connection between hearing and cognition (Lin et al., 2013). Future research should aim to further understand the intricacies of this relationship, monitoring individuals longitudinally and with electrophysiological testing to help identify causal mechanisms (such as atrophy of auditory structures). A greater understanding of the relations between peripheral and central HI and cognitive function may help to advise future treatment options. Examples of such treatment could include placing greater emphasis on support for treatment of HI to reduce the likelihood of cognitive decline, or providing hearing specialists with the tools to make appropriate referrals if cognitive deficits are suspected. The present results demonstrate that, compared to older adults with normal hearing, individuals presenting with a significant degree of peripheral HI are more likely to have a SPD, and may also be more likely to have poorer executive function. That is, those presenting with a hearing loss are more likely to have multiple deficits that may not be remediated purely by amplification. Accordingly, rehabilitation strategies, expectations and client counselling should take into account this possibility. Including CAP tests and screening tests of executive function in the audiologist's test battery may therefore not only aid in understanding the nature of the HI experienced by an individual, but may also assist with identifying the overall communication difficulties and design of a patient centric rehabilitation strategy.

6.3 Binaural Integration Deficit and Cognitive Performance

The left ear and right ear DDT results were significantly negatively skewed (AD=2.187, $p<0.005$; AD=6.171, $p<0.005$). This indicated a plateau in performance, with most of the participants obtaining a score of greater than 80% correct, which was defined as being within the normal range (Tomlin et al. 2014). There was no significant correlation between DDT performance and any cognitive measure ($p>0.05$). Furthermore, to examine whether there was a significant difference between those identified with either a left ear, right ear, or a significant asymmetry DDT deficit in relation to their cognitive scores, a series of independent t-tests were conducted comparing participants with an identified DDT deficit and those with normal DDT performance. No significant relationship between the presence of any DDT deficit and any of the five cognitive measures was found, with similar performance between groups (see *figure 1*).

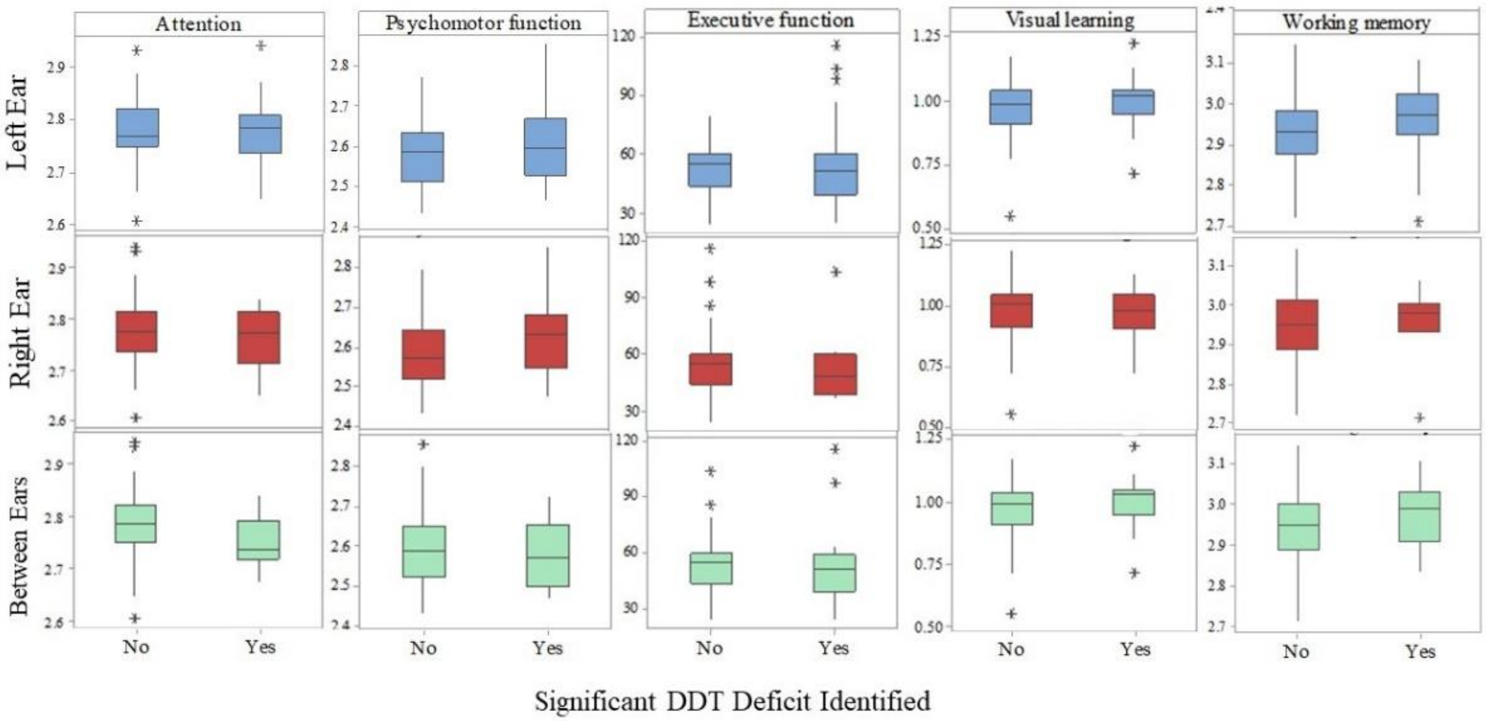


Figure 1. Group differences between those with a significant DDT deficit (left ear, right ear or between ears) and performance on tests of attention^, psychomotor function^, executive function^, visual learning and working memory^: ^results are reversed scored

Unlike previous research in the field of binaural integration (e.g. Gates et al., 2008; 2011), no significant relationship was found between cognition and a deficit in binaural integration. This may be since only a small percentage of this research cohort (approximately 16%) presented with a significant difference between ear performance on the DDT, making group comparisons statistically limited. Most participants reported having greater than a high school education. This may aid in explaining the low percentage of those presenting with a DDT deficit, as higher education has been shown to be related to better binaural integration performance (Gates et al. 2011). There is some dispute in the literature on the 'classification criteria' of a deficit in DDT scores. In this study, a cut off of -2.0 standard deviations from a calculated z-score (see Tomlin et al., 2014) was used, however other research has used various averages and standard deviations, or a cut-off score of 88% correct in the left ear and 90% correct in the right ear (Bellis, 2011; Kelly, 2007; Singer, Hurley, & Preece, 1998). When applying this same cut-off score to this cohort and re-assessing with another series of independent t-tests, there was still no significant relationship between the presence of a DDT deficit and performance on any of the cognitive tests ($p>0.05$). Whilst the non-significant finding of the present work contrasts with the work of Gates et al. (2008, 2011), it reflects findings of a study by Idrizbegovic, Hederstierna, Dahlquist, and Rosenhall (2013). In their study, a group of individuals with AD demonstrated significant decline in left ear DDT performance compared to controls with Subjective Memory Complaints (SMC) over a 1.5 year period (Idrizbegovic et al., 2013). Another group of participants in the study by Idrizbegovic et al. (2013) with identified MCI (in addition to those with SMC) demonstrated no apparent DDT decline during the study period (beside four participants who had developed dementia during the study period and showed DDT results like the AD group). Given that all participants in the present study were cognitively normal (with no participant failing the MMSE or outside normal ranges on any of the cognitive tests), perhaps the results demonstrate that DDT left ear performance is not significantly influenced by cognition in cognitively normal individuals, similar to the findings presented by Idrizbegovic et al.’s research.

CHAPTER 7 EXPERIMENT 3

The following paper is incorporated in its entirety in this chapter:

Manuscript under review

- Nixon, G, Sarant, J. Z., & Tomlin, D., & Dowell, R. Hearing Aid Uptake, Benefit and Use: The Impact of Hearing, Cognition and Personal Factors. Submitted manuscript January 2020 to Journal of Speech, Language and Hearing Research (constitutes Chapter 7).

Aim: to investigate how hearing, cognition and personal factors influence Hearing Aid (HA) outcomes (uptake/use/benefit).

Abstract

Purpose: To investigate the effects of hearing, cognition and personal factors on hearing aid (HA) outcomes (uptake/use/benefit).

Method: 85 older adults aged 60.33-80.08 years (*m =70.23, SD = 5.17*) participated in the study. Hearing was assessed using Pure Tone Audiometry (PTA) and the Listening in Spatialised noise-Sentences (LiSN-S) test. Cognition was measured using the Cogstate Brief Battery and the Cogstate Groton Maze Learning task. Personal demographics were recorded from participants' answers on a series of take-home questionnaires. HA benefit and use was subjectively reported at three and six-months post HA fitting for those who chose to use HAs.

Results: Participants who chose to be fitted with HAs had significantly poorer hearing as measured by PTA and the LiSN-S test. Poorer hearing in the mid and high frequencies was also significantly related to greater reported HA benefit. Stronger psychomotor function predicted greater reported use of HAs at three and six-months post HA fitting. Greater family interaction and attention scores also predicted greater HA use at three and six-months after fitting respectively.

Conclusions: A combination of hearing, cognitive and psychosocial factors impacted HA outcomes for the older Australians in this study. These factors should be considered in audiological rehabilitation to best maximise patient HA outcomes.

INTRODUCTION

Hearing loss affects approximately 30% of individuals aged 65 years and older, and up to 90% of those over the age of 85 (Amieva et al., 2015). It creates significant psychosocial and financial burden for individuals, families and communities (Access Economics, 2006). In Australia in 2005, for those over age 65, hearing loss accounted for 29% of health system expenditure (Access Economics, 2006). In the U.S., it has recently been estimated that the current total health care cost for each person with untreated hearing loss is $22 434 (USD) over a ten-year period (Reed et al., 2019). There are also indirect costs of hearing loss such as comorbid disease (e.g. depression/anxiety) and reduced productivity (work/volunteering etc.) which are not included in this figure and which contribute significantly to the financial impact of hearing loss. Despite the significant cost of providing hearing services and devices, it is estimated that 76% of people who need hearing aids (HAs) do not have them (Access Economics, 2006; Chien & Lin, 2012; Davis & Smith, 2013; Hartley, Rochtchina, Newall, Golding, & Mitchell, 2010; Simpson, Matthews, Cassarly, & Dubno, 2019).

The effectiveness of HAs is rapidly improving with advances in modern technology (Holube & Hamacher, 2005). However, reports of low HA usage continue (Davis & Smith, 2013; Hartley et al., 2010). Early research has demonstrated that the severity of hearing loss, both objectively measured with pure tone audiometry and subjectively measured with self-report, was significantly associated with self-reported HA use (Popelka et al., 1998). More recently, personal factors such as motivation, demographic factors such as age and sex, and external factors such as cost have also been shown to also affect HA uptake and use (Vestergaard Knudsen et al., 2010)

One of the most influential factors affecting HA uptake and use is self-reported hearing disability (Meyer & Hickson, 2012). This form of disability may include reduced hearing ability and/or increased difficulty understanding speech in background noise or in other complex listening situations (Besser et al., 2015; Glyde et al., 2013; Kortlang et al., 2016; Lesicko & Llano, 2017). Peripheral and central hearing pathways, including the inner ear, eighth nerve, the auditory brainstem and auditory cortex contribute to our ability to understand speech in complex listening environments (Jorgensen, 1961; Kirikae, Sato, & Shitara, 1964; Krmpotic-Nemanic, 1971; Stach et al., 1990). The term "Central Auditory Processing (CAP)" or "central hearing", refers to the process by which central auditory nervous system structures such as the auditory nerve, brainstem and cortex, perceive and interpret auditory information (American Academy of Audiology, 2010). Central auditory dysfunction is reportedly common in older adults and increases with age (Gates et al., 2011; Gates et al., 2008b; Stach et al., 1990). Central hearing deficits have been demonstrated to negatively impact the perceived benefit of HAs, with people with abnormal central hearing ability reporting less benefit from amplification than those without central hearing impairment (Chmiel & Jerger, 1996). In one recent longitudinal study, speech recognition in noise ability (a process which requires functional CAP) had a significant impact on the time it took to adopt hearing aids, with people with better speech recognition delaying treatment (Simpson et al., 2019).

Effective functioning of cognitive systems is also required to interpret speech, particularly in complex listening situations (Parham et al., 2013; Schneider et al., 2010). Cognitive function has been shown to be related to both aided and unaided speech in noise recognition, with poorer working memory significantly impacting the ability to report and manage issues with HAs (Lunner, 2003). Accordingly, it has been argued that cognitive capacity should be considered in audiological rehabilitation management (Lunner, Rudner, & Rönnberg, 2009). However, some studies have found no influence of cognitive factors such as attention and memory on self-reported hearing handicap after HA use (Chmiel & Jerger, 1996; Lin et al., 2011a; Lin et al., 2013), and no impact of cognition on self-reported or objectively measured HA benefit (Meister, Rählmann, Walger, Margolf-Hackl, & Kießling, 2015a). Given the inconsistency of reports, further research in this area is required to clarify the role of cognition on hearing handicap.

Despite the fact that successful communication requires both peripheral and central hearing abilities, peripheral hearing dysfunction currently remains the focus of audiological assessments and hearing device-related rehabilitation, and research examining influences on HA uptake and use has not yet explored factors that contribute to listening in complex situations such as cognition and higher order listening processes (Jorgensen, 1961; Kirikae et al., 1964; Krmpotic-Nemanic, 1971; Schneider et al., 2010; Schuknecht, 1964; Stach et al., 1990). However, the limited research available examining the relation between HAs and cognition and/or central auditory processes indicates that HA use may positively influence cognitive and/or CAP skills (Chmiel & Jerger, 1996; Dawes et al., 2015; Desjardins, 2016b; Doherty & Desjardins, 2015; Kalluri & Humes, 2012). Given the current low level of HA uptake and use, the significant impact on quality of life for those with hearing loss, and the high level of associated socioeconomic burden, it is of great importance to gain a better understanding of the factors that influence why and how HAs are used or not used, and to use this knowledge in improving clinical rehabilitation programs.

The current study expores the influence of hearing (measured both peripherally and centrally), cognition, and self-reported quality of life on HA uptake and use. The study also explores the impact cognition may have on HA outcomes, given the growing evidence for an association between hearing loss and cognition, despite the fact that the impact of cognition on hearing rehabilitation is relatively absent in the literature. The first aim of the study was to assess whether degree of hearing loss and cognition had an impact on whether individuals chose to uptake HAs, and it was hypothesised that the uptake of hearing aids would be positively influenced by poorer hearing measured peripherally and/or through tests of CAP, congruent with findings from previous studies (Popelka et al., 1998; Simpson et al., 2019; Vestergaard Knudsen et al., 2010). Once categorised into HA-users and non-users, the second aim of the study was to assess whether degree of hearing loss and/or cognition influenced self-reported HA benefit and use in the HA-user group. Again, it was hypothesised that poorer hearing would have a positive influence on HA uptake and use. Additionally, health and pscyhosocial factors (as measured through self-reported measures) were also hypothesised to positively influence HA uptake, perceived benefit and use, given greater social support was found to have a positive influence on HA rehabilitation (Meyer & Hickson, 2012). Further,those with poorer self-reported health may also be more likely to seek HA rehabilitation, given hearing loss has many associated comorbidities.

It was also hypothesised that cognitive performance would influence hearing aid uptake (aim 1), perceived benefit and use (aim 2). However, it is unclear from the literature what the direction of this influence may be. HA clients commonly report ‘forgetting’ to use their HAs and/or may have dexterity issues (Dupuis, Reed, Bachmann, Lemke, & Pichora-Fuller, 2019). Given this, stronger psychomotor skills, memory and attention may have a positive influence on HA uptake and use. However, those presenting with poorer hearing may also present with poorer cognitive function (Lin et al., 2011a; Uhlmann et al., 1989), which may also be related to an increased need for HAs.

METHOD

Participants

This study was approved by the School of Health Sciences Human Ethics Committee of the University of Melbourne (Ethics ID: 1748836). Written consent was obtained from 85 participants aged 60.33 to 80.08 years (*m =70.23, SD = 5.17*) who met the following recruitment criteria:

6. Aged 60 years or above.
7. No previous diagnosis of dementia.
8. Deemed unlikely by clinicians or family to have dementia at initial screening assessment.
9. Did not present with a visual or English impairment that precluded the ability to complete the assessment tasks.
10. Had not been previously fitted with or reported using a HA over the previous year.

Given the assessments used in this study were not standardised, there were no known effect sizes available for use in a power calculation for sample size. However, in order to estimate a sample size that would provide adequate statistical power, a conservative approach was taken. Assuming an effect size of 0.3 for a correlational analysis and a power of 0.2, the required number of participants was 85.

Forty males, forty-four females and one non-binary individual participated in this study. The same participants were part of another study examining baseline associations between cognitive and hearing measures and the longitudinal effect of HA use on cognition (see Nixon, Sarant, Tomlin, & Dowell, 2019).Of the 85 participants, 62 chose to use HAs in the six-month study period (54 bilateral users, 6 unilateral users and 2 BiCROS users. The remaining participants did not use HAs (10 tried and rejected them within a one-month period, and 13 declined fitting). All participants were recruited for this study through the University of Melbourne Audiology clinic following an audiological assessment. A HA needs discussion and subsequent HA fitting was conducted by an accredited audiologist from the Academic Hearing Aids team at the University of Melbourne Department of Audiology and Speech Pathology. During the HA needs discussion and consequent HA fitting appointment, devices were chosen and fitted based on degree/type of clients hearing loss, personal preferences (e.g. aesthetics/technology level etc.) and client communication needs. The NAL-NL2 prescription (Keidser, Dillon, Flax, Ching, & Brewer, 2011) was used for all hearing aid fitting unless clients preferred otherwise. All hearing aid fittings were verified with real ear insertion gain measures using the Interacoustics Affinity AC440 module and were adjusted for client individual preferences to optimise listening comfort. A review appointment was arranged two-to-four weeks after fitting, with further review appointments made as necessary. All clients returned for a routine 12-month follow up appointment.

Socioeconomic Status:

An Index of Relative Socio-economic Advantage and Disadvantage (ISRAD) (Australian-Bureau-of-Statistics, 2018) was recorded based on the residential postcode of each participant. Scores are standardised to a distribution with an average of 1000 and standard deviation of 100, with a higher score indicative of greater socio-economic advantage.

Procedure:

Test battery and initial questionnaires:

The test battery is summarised in Table I.

Table I. Behavioural Test Battery

Measure	**Test**	**Domain**	**Task**	**Definition of Normal Limits**
Cognition	Mini Mental State Examination (MMSE)	Screening tool for dementia/used in clinical research to measure cognitive impairment.	30-point questionnaire that assesses recall, attention, ability to follow instructions and orientation to time and place.	Any score greater than or equal to 24 (out of 30) indicates normal cognition.
	CogState Brief Battery + Groton Learning Test (CSSB)	Psychomotor function (processing speed)	Respond yes when a card is turned over.	Compared to age related norms. Standardised with a mean of 100 and a standard deviation of 10. A score equal to or greater than 80 is considered normal.
		Visual learning	Respond yes or no to whether or not they had seen a card before during the testing.	
		Working memory	Respond yes or no to whether or not the card they are viewing is the same as the card viewed immediately prior.	
		Attention	Respond yes or no to whether or not the card they are viewing is red.	
		Executive function	Moving one step at a time, must move through a hidden pathway by touching a tile next to their current location,	
Auditory function	Pure Tone Audiometry	Peripheral hearing	Participants must respond to the softest sound they can hear across octave frequencies between 250Hz to 8000Hz as well as 3000Hz and 6000Hz	Across all frequencies: <20dBHL = Normal 20 – 40dBHL = Mild 45 – 65dBHL = Moderate 70 – 90dBHL = Severe >90dBHL = Profound
	Listening in Spatialized Noise–Sentence (LiSN-S) test (High-Cue)	Central Auditory Processing: Binaural Interaction	Repeat a target sentence in various signal to noise ratios to produce a speech reception threshold.	A z-score is produced from the SRT dBHL score based on norms for a 60-year-old participant, with a standard deviation of >-2.0 being considered normal.

Pure Tone Audiometry (PTA) was assessed by an audiologist using the Interacoustics Affinity 2.0 Audiometer in a sound-attenuating room as part of the standard audiological work up. This included assessment of (bilateral air conduction thresholds at octave frequencies between 250 Hz and 8000 Hz, 3000 Hz and 6000 Hz, and bilateral bone conduction thresholds at octave frequencies between 500Hz and 4000Hz. For each individual, a hearing average was calculated and categorised as follows: low frequency (average of 250 Hz, 500 Hz and 1000 Hz), high frequency (average of 2000 Hz, 3000 Hz, 4000 Hz, 6000 Hz and 8000 Hz), and four-frequency (average of 500 Hz, 10000 Hz, 2000 Hz and 4000 Hz). Although a four-frequency average (4FA) is traditionally used to measure overall hearing, given the sloping nature of age-related hearing loss, low and high frequency averages were also calculated and included in analyses where appropriate.

Within a month of the audiological assessment, participants completed one two-hour appointment in which the cognitive and the Listening in Spatialised Noise-Sentences (LiSN-S) test (Cameron & Dillon, 2007) assessments were administered. The Mini Mental State Examination (MMSE) (Folstein et al., 2000) was presented verbally at the beginning of the appointment to screen for cognitive decline, with a score of less than 24 set as an exclusion criterion for the study. The MMSE is not adjusted for age. No participant scored less than 24.

The cognitive test battery was presented next on a Windows laptop with an additional wired mouse. Two sessions were run (“practice” and “session one”), with at least a 30-minute break between sessions. The first of these was a training session as indicated by test administration instructions, and the second session yielded the outcome measures. An advantage of this cognitive assessment tool is that performance remains stable once the respondent has learned how to do the tasks, with test-retest reliability for each measure ranging between .84 and .94 (Collie et al., 2003; Falleti et al., 2006; Maruff et al., 2009). In the first session, the assessor remained in the room with the participant. The instructions were presented on screen for the participant to read and were also read out loud by the assessor to minimise any effect of vision or hearing difficulties. A shorter version with fewer trials of each of the tasks was then given in an interactive demonstration. Once participants demonstrated an understanding of and ability to perform the task during the interactive demonstration, a 30-minute break was given, after which the full task began. Excluding the executive function task, the four tasks were in the form of card games in which the participant was required to respond “yes” and/or “no” to a stimulus via the right and left mouse click or the “k” and “d” keys on the keyboard (this was the participant’s choice). The second condition was performed independently by the participant with the assessor outside the room. The results for this session were recorded. The primary outcome measure for the executive function task was calculated based on the number of errors made. The outcome measures from the other tasks were calculated using both speed and/or accuracy information, automatically outputted and transformed for accuracy to normalise the variables using either mean of the log10 transformed reaction times for correct responses (speed) or arcsine transformation of the square root of the proportion of correct responses (accuracy) (see Maruff et al. (2009) for further description of the Cogstate Battery).

Lastly, all participants were assessed with the LiSN-S test (high-cue condition) with prescribed gain amplifier (PGA) mode. In the high-cue condition of the LiSN-S, the target and distractor speakers differ, and are spatially separated by 90º. This is considered to be the condition most reflective of a real-life listening scenario in background noise. The PGA mode is embedded within the LiSN-S software and amplifies and shapes the target and distracting stimuli according to the National Acoustic Laboratories – Revised Profound (NAL-RP) prescription, based on participant's bilateral hearing thresholds (for both bone- and air-conduction) as manually entered by the tester (Cameron et al., 2014; Glyde et al., 2013). The LiSN-S was administered using a personal computer, a Buddy 6G USB soundcard and Sennheiser HD215 circumaural headphones. Initial presentation levels for target speaker and distractors were 62 dB SPL and 55 dB SPL respectively._A Speech Reception Threshold (SRT) was calculated in dB SNR based on participants' abilities to repeat target sentences in varying levels of background noise for up to a total of 30 sentences (see Cameron et al. (2014) for a full description of LiSN-S procedures).

At the completion of the appointment, all participants were given six questionnaires designed to assess various aspects of health, psychosocial function and quality of life and a return envelope, with instructions to complete the questions at any time prior to their HA fitting (if applicable). Most of the questionnaires were well-established, with moderate to high test-retest correlations (Boston College, 2017; Cox & Alexander, 1995; Crook et al., 1992; De Jong-Gierveld & Kamphuls, 1985; Furlong et al., 2000; Zigmond & Snaith, 1983). Table II describes the questionnaires. All participants were given the questionnaires to complete regardless of whether they chose to uptake HAs with the exception of the communication difficulties questionnaire (APHAB). Seventy-five of the participants returned the initial questionnaires. Of the ten participants who did not return questionnaires, seven had chosen to uptake HAs and had not. Participants who did not return questionnaires were followed up via mail, email and phone calls as appropriate. In total, the six questionnaires were estimated to take no more than one hour to fill in.

Table II. Initial Questionnaires

Questionnaire	Content	Items	Scaled	Interpretation
Loneliness Scale[1]	- Social and emotional loneliness.	11 items (5 social loneliness and 6 emotional loneliness).	Five-point Likert scale (e.g. "There is always someone I can talk to about my day to day problems") on a five-point scale ("Yes!", "Yes", "More or less", "No" and "No!").	A social, emotional and total loneliness score is calculated, with a higher score indicative of a greater degree of loneliness.
18-item modified Lubben Social Network Scale (LSNS-18)[2]	- Social isolation - 3 categories including: Family, friends and neighbours.	18 items (6 for each category)	Six-point Likert scale (e.g. "How many relatives do you see or hear from at least once a month?") ranging from 0 to 5 (e.g. "0=none" to "5=nine or more").	The numbers are added to provide a total score, with a higher score indicative of less social isolation.
Hospital Anxiety and Depression Scale (HADS)[3]	- Generalised levels of anxiety and depression.	14 items (7 for each category).	Four-point Likert scale ranging from a score of 0 to 3.	Overall scores range from 0-21 for each category, with a higher score indicative of greater levels of generalised anxiety or depression.
Health Utilities Index Mark 3 (HUI3)[4]	- Assess an individual's overall self-perceived health over the domains of vision, mobility, hearing, cognition, emotion and pain.	17 items.	Four-point Likert scale.	Scores are calculated according to the Mark 3 procedure manual and are then converted into a percentage score for analysis. A higher number indicates better perceived overall health, with 0 indicating 'dead' to 1 indicating 'perfect health'.
Abbreviated Profile of Hearing Aid Benefit (APHAB)[5]	- Assesses an individual's perception of how they hear without their hearing aid.	24 items.	Six-point scale ranging from "Always" to "Never".	The APHAB measures difficulty hearing in different settings, the higher the number on the scale the greater the difficulty. A 'global' benefit score is calculated from comparing the unaided score collected at baseline, to the aided score at 3- and 6-months post HA fitting, with a greater score indicating a greater perceived benefit from the HA overall. The global score is the mean result of all items in the 'ease of communication', 'reverberation' and 'background noise' subscales.
Memory Complaint Questionnaire (MCQ)[6]	- Self-perceived age-related memory decline	6 items	Five-point Likert scale from "Much better now" to "Much poorer now" comparing how they remember now to how they remembered when they were in their "late teen years or early 20s"	A higher score is indicative of greater memory complaints

[1]De Jong-Gierveld & Kamphuls (1985), [2]Lubben (1988), [3]Zigmond & Snaith (1983), [4] Furlong et al. (2000), [5] Cox & Alexander (1995), [6] Crook et al. (1992)

Follow up questionnaires:

Participants who chose to use HAs in the months following the initial assessment were sent the Abbreviated Profile of Hearing Aid Benefit (APHAB) (Cox & Alexander, 1995). Of the 62 participants who chose to use HAs, 52 returned at least one follow-up HA questionnaire at three months post HA fitting and 47 returned at least one follow up HA questionnaire at six-months post HA fitting. Participants who failed to return questionnaires (baseline, three- and/or six-month post HA fitting) were contacted via email, phone and/or letter requesting they do so.

Participants were required to fill in the “with my hearing aid” column of the APHAB, which yielded an APHAB aided score. These responses were then compared to the baseline “without my hearing aid” score to produce a benefit score after three and six months of HA use. A higher benefit score indicated greater perceived benefit.

In the follow up HA case history, participants were asked a series of questions about how often, in what configurations, and in what listening conditions they used their HAs.

Follow up data collection:

Six months after HA fitting, each participant’s audiology clinical record was examined to obtain information about how many HA follow-up appointments were attended, which HA was chosen, and whether the fitting was unilateral or bilateral.

Statistical analysis

Minitab 17 (2010) Statistics package was used for analysis.

Aim 1: To explore the difference between those who chose to uptake HAs and those who did not, a series of two-sample t-tests were used with Bonferroni corrections applied. Following this, a binary logistic regression analysis was conducted to explore the impact of the identified significant variables on the binary dependent variable of “yes” or “no” to HA uptake. Aim 2: Pearson’s correlation coefficients were used as a first step in examining the strengths of the associations between the outcome continuous variables (HA benefit, as measured by APHAB global benefit score, and HA daily use (hours) as self-reported three- and six-months post HA fitting) and experimental variables (hearing, cognition and take-home questionnaires). Further regression analyses were then conducted where appropriate to examine the relations between continuous predictor and outcome variables. Analysis of HA use was stratified by left and right ears (rather than averaged across the two ears). This was necessary to appropriately present the data obtained in the HA case history, and to account for unilateral HA users and discrepancies between left and right HA use for bilateral users.

RESULTS:

Demographic information for this cohort is presented in Table III. The average audiogram for the cohort is presented in Figure I.

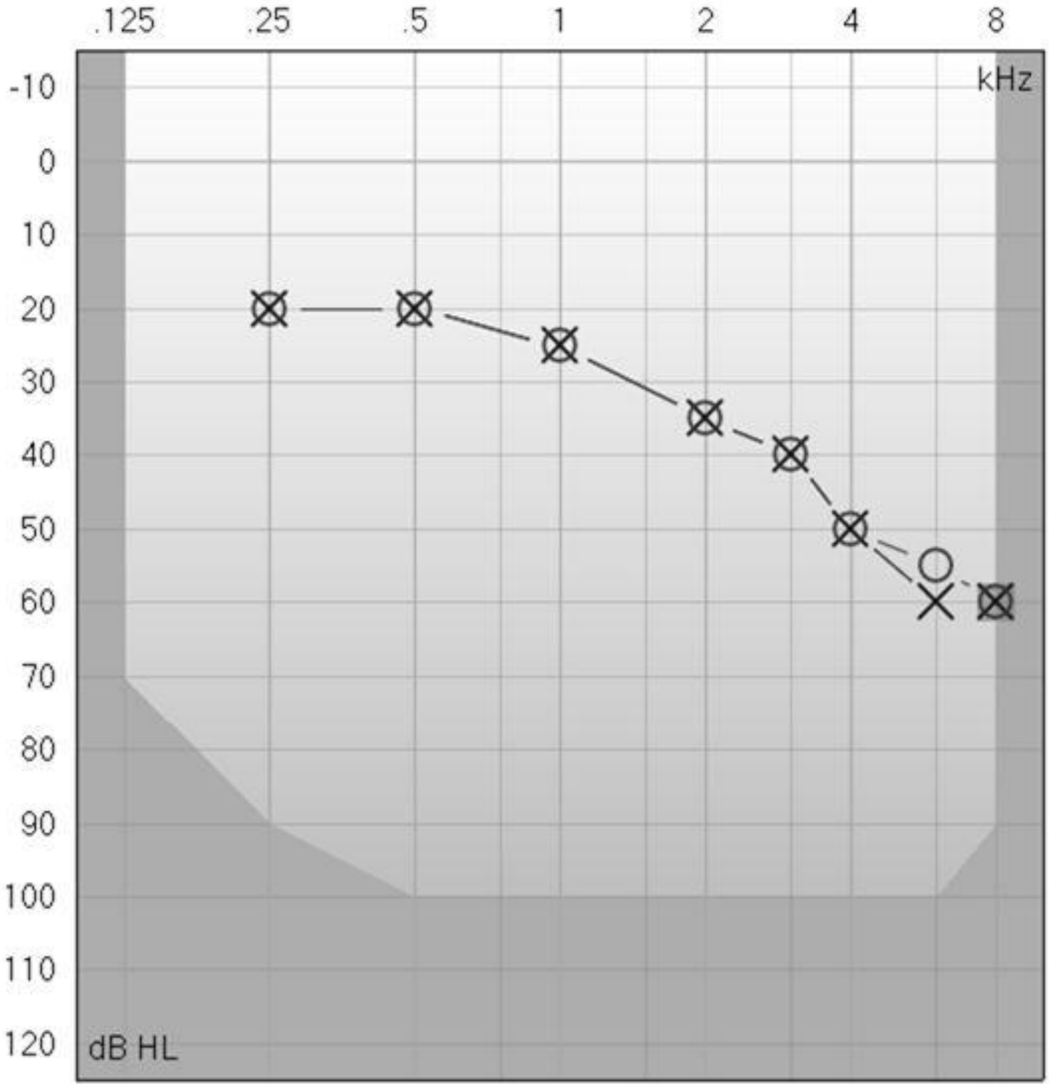


Figure 1. Average Audiogram.

Hearing Aid Uptake

Age, SES and cognition were not significantly different between the group that chose to use HAs and the group that did not choose/rejected HAs (see Table III). Additionally, as explored through a chi-squared analysis, there was no difference in gender between the groups ($\chi^2(1, n = 84) = 0.002, p = 0.963$).

As shown in Table III, significant differences were found between the HA and non-HA groups for peripheral hearing as measured by 4FA, with the group who chose to use HAs having greater hearing loss. The HA group also demonstrated poorer speech perception in background noise as measured by a significantly poorer result in the high-cue condition of the LiSN-S test (central measure of hearing ability). Those with self-reported poorer overall health (as measured by the HUI3) were also more likely to use HAs. No differences in responses between HA-users and non-users were found across any of the remaining five self-reported health measures. A binary logistic regression model, with dependent variable ‘yes’ or ‘no’ to HA uptake, and independent continuous predictors 4FA, LiSN-S high cue (HC) score and HUI percentage scores, was statistically significant (R^2=26.59, p<0.001), and accounted for approximately 27% of the variance in the decision to use HAs. A significant effect of speech perception ability in noise on the decision to use HAs was not found, likely due to the significant association between speech perception ability (LiSN-S performance) and degree of hearing loss (4FA; r=.599, p<.001). However, the regression also identified that degree of hearing loss (4FA) and self-reported quality of life (HUI3) significantly predicted the decision of whether or not to use HAs, with odds ratios of 1.17 (95% CI (1.07, 1.28), p<0.001) and 0.96 (95%CI (0.93, 1.0), p=0.028) respectively. For example, holding the other variables constant, an increase in hearing loss of 10 dB from 40 to 50 dB HL increased the probability of HA use by 0.21.

Table III. Demographic and descriptive statistics separated between Hearing Aid User and non-user groups variable results, and subsequent two-Sample t-test results with Bonferroni corrections applied.

	Hearing Aid User						95% CI for Mean Difference		
	No			Yes					
	M	SD	n	M	SD	n		p	df
Age	70.74	5.44	23	70.72	5.11	62	-2.63, 2.67	0.988	37
SES	1049.6	49.5	23	1053.1	49.4	62	-28.0, 20.9	0.769	39
MMSE	28.913	1.24	23	28.90	1.30	62	-0.610, 0.630	0.975	41
Attention^	2.78	0.04	23	2.78	0.07	62	-0.0271, 0.0226	0.856	59
Psychomotor Function^	2.61	0.10	23	2.59	0.08	62	-0.0253, 0.069	0.357	35
Executive Function^	51.7	18.0	23	54.7	15.4	62	-11.58, 5.65	0.489	34
Visual Learning	1.0	0.09	23	0.98	0.11	62	-0.0306, 0.0646	0.477	47
Working Memory^	3.0	0.06	23	3.0	0.09	62	-0.0341, 0.0374	0.927	56
4FA[a]^	**25.49**	**7.71**	**23**	**35.16**	**8.41**	**62**	**5.68, 13.67**	**<0.001**	**42**
LiSN-S High Cue score (dBHL)^	**-11.07**	**-2.76**	**23**	**-7.88**	**5.82**	**62**	**0.67, 5.71**	**0.014**	**77**
Loneliness Scale	3.48	3.75	21	2.82	2.98	57	-1.206, 2.509	0.479	29
LSNS-18 (Total)	41.1	15.7	21	45.4	10.7	57	-11.91, 3.31	0.257	27
HADS (Anxiety)	5.19	3.23	21	4.30	3.23	57	-0.736, 2.521	0.273	32
HADS (Depression)	2.76	2.39	21	2.67	2.45	57	-1.149, 1.340	0.878	36
HUI 3	**0.853**	**0.164**	**21**	**.729**	**0.203**	**57**	**-0.2234, -0.0265**	**0.014**	**44**
MCQ	24.57	4.53	21	24.65	3.55	57	-2.32, 2.16	0.944	29

Significant results post Bonferroni corrections are presented in bold.

[a] 500Hz, 1000Hz, 2000Hz & 4000Hz.

^ Results are reversed scored with a lower score indicative of better performance.

Self-reported Hearing Aid benefit for HA-users

Poorer high-frequency hearing (LiSN-S performance) was significantly associated with greater self-reported HA benefit, as measured by the APHAB global benefit score (see Table II) at three months (R^2=12.31, p = 0.012) and six months (R^2=10.44, p = 0.03). Poorer overall hearing (as measured by the 4FA) was also associated with significantly greater self-reported HA benefit at six months (R^2=9.28, p = 0.042).

Self-Reported Hearing Aid use; HA-users

The average reported daily use of HAs at three-months was 9.7 hours (0.5 - 16 hours) and at six-months was 9.6 hours (0 - 16 hours). Exploratory correlational analysis examined the relations between average hours of HA use per day at three- and six-months post-fitting for overall hearing loss and high-frequency hearing (PTA and LiSN-S), cognition (performance on the Cogstate assessment) and self-reported questionnaire (see Table II) variables. Significant results are presented in Figure II. Given there were six unilateral and two BiCROS users, HA use data was separated into left and right ears to appropriately include these individuals in the analyses. Better psychomotor function pre-HA fitting was significantly associated with higher HA use bilaterally at three (Left: $R^{2=}$19.22, p =0.001; Right: $R^{2=}$13.73, p =0.008) and six months (Left: $R^{2=}$26.50, p <0.001; Right: $R^{2=}$22.52, p =0.001). Additionally, pre-HA fitting, a higher amount of reported family contact and better performance on tests of attention were positively associated with greater HA use at three (Left: $R^{2=}$14.46, p =0.006; Right: $R^{2=}$12.83, p =0.012) and six months (Left: $R^{2=}$9.59, p =0.034; Right: $R^{2=}$10.36, p =0.029) respectively.

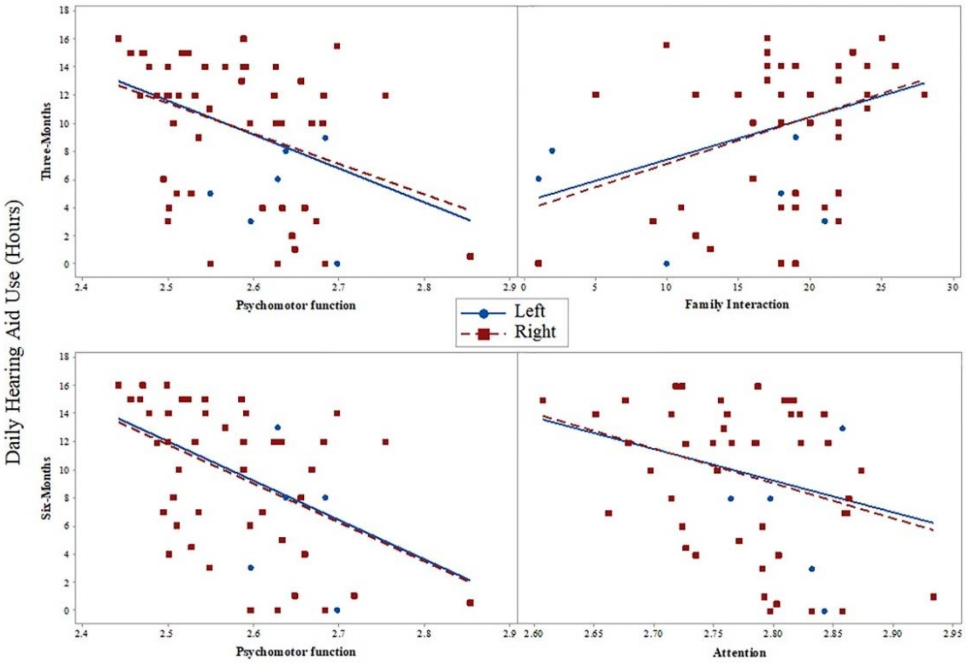


Figure 2. Figure 2. Scatterplots of Hearing Aid use at Three- and Six-Months post Hearing Aid fitting, against Psychomotor Function Performance^, Attention Performance^ and Family Interaction Score.
^Results are reversed scored.

DISCUSSION

Hearing Aid Uptake

Average peripheral hearing thresholds as measured by 4FA were significantly poorer in people who chose to uptake HAs. This is consistent with the findings of previous work which reported that increased subjective and objective severity of hearing loss increased HA use (Meyer & Hickson, 2012; Popelka et al., 1998; Vestergaard Knudsen et al., 2010).

Those who chose to uptake HAs also had poorer ability to listen in background noise (a common reason for self-reported hearing disability/hearing-related activity limitations). This finding is also in agreement with reports of original studies and reviews detailing the motivational effect of hearing activity limitations for HA use (Humes et al., 2012; Humes, Wilson, & Humes, 2003; Meyer & Hickson, 2012; Popelka et al., 1998; Vestergaard Knudsen et al., 2010). In particular, a longitudinal study by (Simpson et al., 2019) found that speech recognition ability had a significant impact on the time it took to adopt hearing aids, with better speech recognition ability significantly delaying treatment. The high-cue LiSN-S test represents a real-world listening condition in which individuals with better spatial processing ability (the ability to detect a signal better when it is spatially separated from distractors) perform better at detecting a target speaker in background noise than individuals with poorer spatial processing ability. Although there is still a degree of confounding between peripheral hearing and central hearing in the interpretation of results on this test, the LiSN-S gives some measure of central hearing ability, (i.e. of hearing/cognitive processes beyond what is measured by peripheral hearing assessments). The ability to listen in background noise reportedly deteriorates faster than peripheral hearing ability in older adults (Gates et al., 2008). Poor performance on measures such as the LISN-S that provide a more accurate measure of real-world listening performance than do hearing threshold tests administered in quiet listening conditions (i.e. listening to target speech in complex listening environments) may provide additional important information about an individual’s need and likelihood to use HAs.

No group differences were found in this cohort for demographic factors such as age and gender. A previous review similarly described strong evidence that HA adoption was not associated with gender, however it did report that HA adoption was associated with increasing age (Meyer & Hickson, 2012). A possible reason for the discrepancy between the findings of the current study and other research such as that by Popelka et al. (1998) (which did find a positive association between increased age and HA adoption) could be the smaller sample size and reduced age range in the current study. The age range of the current cohort of 85 individuals was 60- to 80-years compared with the larger cohort of 1629 individuals aged 48- to 92 years in Popelka et al.’s (1998) study.

A new finding of the current study was that more people with overall poorer self-reported health (as measured by the HUI3) chose to uptake HAs than those with better self-reported health. The HUI3 assessment of health considers sensory health, physical health and psychological health, which are intercorrelated. The results of previous studies have highlighted the relationship between greater degree of hearing impairment and poorer overall health. Poorer hearing has been associated with: poorer overall quality of life (Dalton et al., 2003), significantly more depressive symptoms, feelings of loneliness and smaller social networks (Kramer, Kapteyn, Kuik, & Deeg, 2002), as well as poorer physical health, with an increased likelihood of experiencing comorbidities (e.g. heart disease and stroke) (Crews & Campbell, 2004). Therefore, people with hearing loss are more likely to report poorer psychological and physical health overall, and as stated earlier, poorer hearing increases the likelihood of seeking HAs (Meyer & Hickson, 2012; Vestergaard Knudsen et al., 2010). Consequently, the finding that poorer self-reported health as measured by the HUI3 is related to HA uptake may be a reflection of the greater physical, social, mood and listening difficulties faced by older adults with hearing impairment.

Hearing Aid Benefit

The finding that perceived HA benefit at three- and six-months was also related to participants' hearing thresholds in this cohort was consistent with those of previous studies (see, for example, Vestergaard Knudsen et al., 2010). Degree of high-frequency hearing impairment as measured by PTA was significantly related to perceived benefit at both three- and six-months, and 4FA was related to six-month perceived benefit. This last result may reflect the demographic limitations of the study cohort. On average, participants demonstrated only a mild hearing loss in the mid-frequencies and slightly poorer hearing in the high frequencies. In this cohort it appears that reduced severity of hearing loss (i.e. in the 4FA as compared to the high-frequency average) was not associated with immediate HA benefit (at three-months) but was at a later time point (six-months). As the poorest hearing thresholds were in the high-frequency range, these results are consistent with previous findings that severity of hearing loss impacts HA use (Meyer & Hickson, 2012; Vestergaard Knudsen et al., 2010). Adding to previous conclusions, this finding from the present study suggests that the severity of peripheral hearing loss not only predicts HA uptake but also the period of use required until benefit is recognised; i.e. people with a lesser degree of hearing loss appear to take longer to perceive relatively smaller benefits in comparison to those with more significant hearing loss. In support of this finding, Hosford-Dunn and Halpern (2001) and Uriarte, Denzin, Dunstan, Sellars and Hickson (2005) reported that poorer hearing thresholds were significantly related to increased HA satisfaction. However, these reports conflicted with the findings of other similar studies (Hickson, Timm and Worrall (1999) and Cox, Alexander and Gray (2007)), which found that HA use and overall satisfaction was not significantly influenced by pure tone audiometry results. Given these contradictory findings, in their literature review a decade ago, Vestergaard Knudsen et al. (2010) concluded that there was insufficient evidence that hearing thresholds have a significant impact on HA satisfaction. The results of the current study however, provide further support for the theory that poorer hearing thresholds positively impact the benefit, and consequently the satisfaction, received from HAs. The clinical implications of this are that those with better hearing thresholds may need more time to recognise the perceived benefits of HA use than those with more severe hearing losses, and that this should be taken into account in counselling and provision of rehabilitation for people with lesser degrees of hearing loss.

Hearing Aid Use

Self-reported HA use was significantly greater for participants with better performance on psychomotor function. Psychomotor function is typically measured with tests of accuracy and speed, and refers to the planning and execution of physical movements (Shukitt-Hale, Thangthaeng, Kelly, Smith, & Miller, 2017). It has previously been established that successful management of HAs requires reasonable manual dexterity skills (Kumar, Hickey, & Shaw, 2000). Having better psychomotor function pre-HA fitting resulted in greater HA use in three and six months after HA fitting. It is logical that people who can better manage their devices would use them more than people for whom this was more difficult.

Greater family interaction in the early stages of HA experience may also play a significant role in HA use. Those with greater family interaction scores prior to fitting reported significantly higher use of HAs at the three-month time point. It has previously been established that the support of significant others can act as a major positive influence to HA uptake and help-seeking behaviour, with those who perceive significant others' attitudes to HAs as positive more likely to engage in actively seeking hearing rehabilitation due to increased motivation and social pressure (Meyer & Hickson, 2012). However, at the six-month point, psychomotor function remained a significant predictor of HA use and family interaction did not. Previous research investigating the support of significant others has also reported that the primary benefit of the involvement of significant others was related to help-seeking behaviour for hearing impairment and the initial adoption of HAs (Mahoney, Stephens, & Cadge, 1996; Meister, Walger, Brehmer, von Wedel, & von Wedel, 2008), rather than the long term use of HAs. The findings of the present study provide further evidence that significant others may play a supportive role in the initial HA adoption process. Thus, family interaction may be more important for the establishment of initial use of HAs in terms of support while adjusting to HA use, and is less important once HA use is established.

In addition to psychomotor function, attentional skills, which allow us to prioritise and maintain focus on information of interest (Petersen & Posner, 2012), predicted greater HA use at six-months post HA fitting. This is a further new finding which suggests that cognitive skills may influence HA use. This supports the theory that the ongoing management of HAs may require stronger cognitive function, particularly in areas important for the physical maintenance of the device (psychomotor function) and the ability and need to attend to environmental surroundings (attention). Attention skills may be more important for longer term HA use, as it was not until six-months (rather than three-months) post HA fitting that greater attention positively impacted the amount of hearing aid use. In summary, the results of this study suggest that psychomotor function and family interaction and support are highly important for the initial use of HAs whilst adaptation is taking place. Following this, physical management of the devices is still required. Additionally, engagement in one's environment and the ability to maintain focus on information of interest (i.e. attentional ability) appears to also be a significant factor in longer-term HA use.

Study limitations

Limitations of this study were the relatively short time-frame over which it was conducted and the limited range of degree of hearing impairment within the sample of participants. The maximum time-frame between HA fitting and HA outcome follow up was six-months. However, little research has investigated beyond a six-month follow up period for use and perceived benefit, and those studies that have done so have still reported conflicting results. Early research found no significant difference in use and benefit between six- and twelve-months post fitting (Bentler, Niebuhr, Getta, & Anderson, 1993), although results of Humes and colleagues (2002) reported significantly lower HA use at twelve-months' time compared to six-months' time. Given the shorter time-frame of the present study, the current results regarding factors that predict HA use/benefit cannot be generalized beyond a six-month time frame. Additionally, in comparison to other research cohorts, the current cohort had a relatively small range of/degree of hearing impairment, which likely reduced statistical power. For example, the 4FA of this cohort was 30 dB HL, whereas in Gatehouse (1994), the 4FA was 48 dB HL. Moreover, the 4FA of those that used HAs compared to those who did not in the present study were 35 dB HL to 26 dB HL, respectively. In other research cohorts, those that tried HAs had averages of 42.5 dB HL (Garstecki & Erler, 1998) and 60 dB HL (Gussekloo et al., 2003), compared to those who declined, with averages of

33.2 dB HL (Garstecki & Erler, 1998) and 48 dB HL (Gussekloo et al., 2003) (see Vestergaard Knudsen et al., 2010, for more examples).

Conclusions

The results of this study provide support for the effects of degree of hearing impairment (both peripheral and central) and social factors on HA uptake, benefit and use. The findings that degree of hearing impairment (measured peripherally and through speech in background noise tests) and poorer overall health positively influenced HA uptake suggest that faster referral for people who have a greater degree of hearing impairment or poorer health overall is indicated. The results of this study also underscore the importance of understanding how much familial support is available to clients, and suggest that including a family-centred approach to HA rehabilitation may improve patient HA outcomes. A novel finding was that cognitive factors (psychomotor function and attention) also impact on regularity of HA use. Future research on HA use in older adults should consider the longitudinal impact of cognitive ability on HA outcomes, and the best way to approach HA rehabilitation in adults with cognitive impairments. For example, if a there is a known attentional difficulty or psychomotor dysfunction, modified rehabilitation approaches may be necessary (e.g. more frequent follow-ups for cognitively-impaired patients or longer HA fitting appointments). Further investigation of the effects of central auditory processing, cognitive ability and family support should yield important information on, and significantly impact, HA benefit and clinical management in the future. These factors should be taken into account in the management of individuals with hearing impairment in order to facilitate better outcomes

CHAPTER 8
OVERALL DISCUSSION & CONCLUSIONS

8.1 PURPOSE

The purpose of this research was to explore, in order to further understand, the relationship between hearing impairment (both peripherally and centrally measured) and cognition. The study also assessed the impact SNHL, central hearing impairment, cognition and psychosocial variables had on short term hearing rehabilitative outcomes such as HA uptake, use and perceived benefit. The results of this research have been presented and discussed in each of **Chapters 4, 5, 6** and **7**. This final chapter provides overall conclusions and considers future research and clinical implications of this work.

8.2 FINDINGS

8.2.1 Study 1: The relationship between peripheral hearing loss and higher order listening function and cognition in older adults (Chapter 5)

The first aim of this thesis was to investigate whether there was a relationship between hearing impairment (peripheral and/or central) and cognition (across multiple domains) in this cohort of older adults. The hypothesis was that there would be a negative relationship between scores on the Cogstate cognitive test battery and: 1) increased level of SNHL, and 2) decreased binaural integration and interaction performance. As outlined in chapter 5, this hypothesis was partially supported, with a significant negative correlation between degree of SNHL and attention/executive function skills. Additionally, poorer higher order listening function (binaural interaction), as measured by the LiSN-S, was significantly related to poorer cognitive performance. However binaural integration (measured by the DDT) was not related to any measures of cognitive function.

Previous research has demonstrated that cognitive- and hearing- decline are both positively associated with age, and are also independently related to each other (Cruickshanks et al., 1998; Hofman et al., 1991; Loughrey et al., 2018). If the aim is to understand not *if* hearing and cognition are related but rather *how*, further information about these impairments is required. As discussed earlier, the "common cause" hypothesis suggests that deterioration on a central level impacts both hearing and cognitive processes (Lindenberger & Baltes, 1994b; Valentijn et al., 2005). If this is the case, examining higher order listening function, measured by different domains of central auditory processing, is key. If it is central rather than peripheral auditory dysfunction that is significantly related to cognitive function, and if this is a result of aging, then this may provide further support for a common cause hypothesis for such age-related neural degeneration within the central nervous system. Less research assessing the relation between hearing and cognition has focused on the area of central auditory processing. The studies that have examined this relation have primarily focused on the area of binaural integration (Gates et al., 2008a; Gates et al., 2011; Gates et al., 2010a).

The current study was one of the first studies to consider the relationship between LiSN-S performance and cognition in an older population using a more in-depth, non-auditory reliant, assessment of cognition. The DDT has commonly been used in previous studies in this area by Gates et al. (2008, 2010, 2011), however cognition was measured in these cases with screening assessments rather than using a full assessment of cognitive performance across many domains.

Both peripheral- and central-hearing measures were significantly related to performance on at least one cognitive domain in this study. In the better hearing ear, poorer hearing as measured by the 4FA was significantly related to poorer performance on tests of executive function. Additionally, poorer hearing was significantly related to poorer performance on tests of attention. Whilst there was no association between scores on the cognitive screening tool used in this study (the MMSE) and peripheral hearing measures, performance on individual domains of cognition (attention and executive function) were negatively associated with increased SNHL. The results of this research also highlighted the benefit of measuring hearing via tests of central auditory processing, specifically in this study, the LiSN-S test. Performance in the LiSN-S low-cue condition and spatial advantage scores were positively correlated with executive function performance. Spatial advantage scores were also positively correlated with visual learning, and tonal advantage scores were positively correlated with stronger attention and psychomotor function. These results identified an additional two cognitive domains (psychomotor function and visual learning) that were related to measurements of higher-level listening that were not identified using pure-tone hearing test results. Moreover, results of a stepwise multiple regression analysis suggest a stronger relationship for LiSN-S performance (CAP ability) with attention scores than for 4FA.

The results of this study provide further evidence relating hearing impairment and poorer cognitive performance in an older population. They also highlight that audiology patients with hearing problems may be presenting with greater difficulties than what may be suggested from their audiometric results alone. Ultimately, this research demonstrated the importance of considering the relationship between cognition and both SNHL, and measures of CAP in an older population. The clinical implications of this finding are discussed later in this chapter.

8.2.2 Study 2: Peripheral hearing, spatial processing ability and executive function in older Australians
(Chapter 6)

Extending from the aims and findings of the first study detailed in **chapter 5**, this study aimed to examine group differences in cognitive performance between those with both CAP dysfunction and SNHL in comparison to those with a SNHL alone. The hypothesis was that those presenting with both SNHL and impaired CAP ability would perform more poorly on tests of cognition than those presenting with SNHL alone. This hypothesis was supported. However, it is important to note that whilst those presenting with a SPD performed poorer on tests of executive function, they also had significantly poorer pure-tone audiometry thresholds. The results demonstrated that those with worse hearing measured via PTA were more likely to present with a SPD, and were also more likely to perform poorer on tests of executive function. This research question was deemed a significant point of focus for this thesis due to several reasons. Firstly, there is limited literature available that directly compares the cognitive performance between these two hearing-impaired groups (SNHL alone vs. SNHL and central hearing impairment). Secondly, this study aimed to help clarify the relationship between hearing loss and cognition by comparing performance of those with central hearing impairment to those without. Lastly, from a clinical perspective, many functions beyond what is obtained on an audiogram that contribute to potential communication difficulties (such as CAP and cognition), are not represented by current audiological test batteries. Understanding what issues a patient may be presenting with beyond their PTA test may help to best address their individual needs, particularly if cognitive issues are more likely to be present in individuals with SNHL and/or central hearing impairment.

Unlike study 1, CAP results were not assessed only as “a final score”, but rather participants were categorised into groups with identified deficits on the DDT and LiSN-S test (defining binaural integration or SP issues respectively) based on previous research definitions (Cameron et al., 2014; Tomlin et al., 2014). A small number of participants (15.66%) were identified to have a significant binaural integration deficit as defined by a significant difference in performance between ears on the DDT. Just over 59 percent of participants presented with a SPD. Most participants performed within normal limits in both left and right ear DDT conditions, with the results demonstrating a significant negative skew, highlighting a ceiling effect. This ceiling effect is consistent with previous research showing that performance on the DDT is impacted by education level (Gates et al., 2011), and is not surprising given that more than half of the participants in this study had a tertiary education. Furthermore, the cohort of older adults did not present with any cognitive impairment. The findings of Idrizbegovic et al. (2013) highlighted that only those with identified AD had a significant decline in DDT left ear performance whereas those with MCI or SMC did not. The high number of participants presenting with a SPD is consistent with previous reports that SP is negatively impacted by SNHL; with a negative correlation found between performance on the spatial advantage measure of the LiSN-S and 4FA (Glyde et al., 2013). This last finding indicated that those presenting with poorer pure-tone audiometry thresholds may also be presenting with SP issues also.

Limited research to date has provided evidence of a relationship between cognitive function and SP ability in older adults. The current study highlighted the presence of this relationship. Additionally, there is evidence for poorer executive function in those with both a CAP deficit (in this case, SPD) and SNHL, compared to those with SNHL alone. These findings emphasise the importance of considering central hearing processes in studying the relation between hearing and cognition. Moreover, the results recognise that those with poorer hearing will be more likely to be presenting with other difficulties such as CAP dysfunction and/or poorer cognition, all of which contribute to decreased communication ability.

8.2.3 Study 3: Hearing aid uptake, benefit and use: the impact of hearing, cognition and personal factors (Chapter 7)

The aim of this study was to assess how the objective variables (peripheral hearing, CAP and cognition) in addition to self-reported psychosocial function relate to HA uptake, use and perceived benefit. The hypothesis was that these factors would influence how individuals use HAs. Functional hearing measured using pure-tone audiometry and the LiSN-S test was significantly poorer in those who chose to uptake HAs. Furthermore, in those that used HAs, increased hearing loss was related to increased self-perceived HA benefit. Another finding of this study was that stronger psychomotor function (measured pre-HA fitting) was significantly associated with greater self-reported HA use at three- and six-months post HA fitting. Better performance on tests of attention (measured pre-hearing aid fitting) was also significantly associated with greater HA use, six-months post HA fitting. Lastly, increased family interaction was significantly associated with increased HA use in the first three months. This final study was a valuable contribution to this thesis as it extends beyond the question of “if” there is an association between hearing and cognition, to begin to consider “how” do these factors impact current audiological rehabilitative practices.

In past research, increased severity of peripherally measured hearing loss (using PTA) or self-reported hearing loss has been associated with increased self-reported HA use (Popelka et al., 1998). Reviews of research in this area looking at the factors that influence HA uptake concluded that HA uptake was primarily related to the following factors: cost, self-perceived hearing disability, motivation, support of significant others, age and gender (Meyer & Hickson, 2012; Vestergaard Knudsen et al., 2010). There has been less focus on how CAP and cognitive factors influence HA outcomes, even though hearing, particularly in complex listening environments, relies on not only peripheral hearing functions but central hearing and cognitive functions as well (Committee on Hearing Bioacoustics and Biomechanics, 1988; Musiek & Chermak, 2013). Previous research into how hearing levels and other factors influence HA outcomes has sometimes relied on self-reported hearing loss. Self-reported hearing loss may refer to reduced hearing across all listening situations and/or the ability to listen in complex listening situations (Besser et al., 2015; Glyde et al., 2013; Kortlang et al., 2016; Lesicko & Llano, 2017). These functions may be influenced by central hearing and cognitive functions. The little research that is available in this area may indicate that there is an association between HAs and CAP/cognition (Chmiel & Jerger, 1996; Dawes et al., 2015; Desjardins, 2016b; Doherty & Desjardins, 2015; Kalluri & Humes, 2012). However, this research has focused more on how HAs impact these processes rather than how CAP/cognition influence the uptake and use of HAs. Another point to consider in this area of research is how psychosocial factors may influence any relationship between HAs, hearing, and cognition. As previously mentioned, a review highlighted the positive impact that the support of significant others has on HA uptake (Meyer & Hickson, 2012). Poorer hearing and/or poorer cognitive function have also been reported to be negatively associated with psychosocial functions such as perceived loneliness, and mental health conditions such as depression (Cornwell & Waite, 2009; Gopinath et al., 2009; Hawkley, Burleson, Berntson, & Cacioppo, 2003).

In support of past research, increased severity of SNHL was significantly related to increased HA uptake and perceived benefit at three- and six-months post HA fitting (Popelka et al., 1998; Vestergaard Knudsen et al., 2010). Increased self-reported hearing disability was also significantly poorer in the group that chose to use HAs. A new finding that has not been measured before was that performance on a test of CAP ability (the LiSN-S test) was significantly poorer in the group that chose to use HAs. This result was not surprising given the significant relationship between pure-tone audiometry thresholds and LiSN-S scores. Additionally, there is previous research reporting an association between increased HA use and self-reported hearing disability. Nevertheless, the results of this study recognise that CAP ability may also influence the uptake of HAs, and poorer performance on these tests may suggest increased likelihood of an individual exploring amplification options.

The number of hours individuals reported using HAs was significantly higher in those with greater family interaction and stronger cognitive abilities, measured pre-HA fitting. Increased self-reported family interaction was significantly associated with increased self-reported HA use at three-months post HA fitting. This supports previous claims that HA uptake is positively influenced by greater support of significant others (Meyer & Hickson, 2012). Better performance on tests of attention was positively related to greater HA use in six-months-time, and better psychomotor function was positively related to greater HA use in both three- and six-months' time. This area of cognitive factors influencing HA use appears to be unexplored in previous research focusing on HA outcomes. The results of this study emphasise that cognitive function is an important area to consider not only in research, but also clinical practice.

This research identified the influence of previously unexplored factors (performance on tests of cognition and CAP ability) on HA uptake and use. Additionally, this study further expanded on and supported the results of past research that had previously identified the importance of significant others and SNHL/self-reported hearing disability on HA outcomes. This research was limited by its short time frame and small cohort size in comparison to other studies. Addressing these issues in future research would be of great benefit in the area, particularly given the focus on longitudinal outcomes of HAs (i.e. perceived benefit/use over time). If the measured factors (SNHL, CAP, family support and cognition) are identified as having a significant influence on the use of HAs, audiological rehabilitation should begin to take these into account. The current primary focus of HA fitting is based on pure-tone hearing thresholds. If other factors also are impacting HA outcomes for individuals, they should also be considered to best manage the needs and audiological rehabilitative outcomes of individuals with hearing impairment. This may mean including auditory training programs as part of a client's hearing rehabilitation, emphasising the inclusion of significant others in hearing rehabilitation, liaising with other health professionals (such as social workers/neurologists) on how best to address client-specific needs, and/or allowing longer appointment times for clients with known cognitive issues.

8.3 SUMMARY OF FINDINGS

The results of this research emphasise the importance of considering central auditory processing (“central hearing”) when investigating the relationship between hearing and cognition. Both PTA and CAP measures were related to multiple aspects of cognition. In some cases, the results of CAP as measured by the multiple conditions of the LiSN-S test, highlighted associations with cognitive domains such as psychomotor function and visual learning, that were not otherwise associated with SNHL. Furthermore, those with poorer pure-tone thresholds were more likely to have a SPD, and those with a SPD had poorer executive function. This result may suggest a step-wise-progression to the issues faced by hearing impaired individuals, with SNHL occurring first, followed by CAP difficulties, followed by cognitive dysfunction. Of course, given the current results, this hypothesis is only speculative. Future research which compares cognition between normal (peripheral) hearing listeners with identified CAP to those without, may help to better address the second research question and give an indication of whether the presence of a SNHL is required for CAP dysfunction to relate to cognition. Furthermore, a longitudinal design which follows the progression of CAP and cognitive dysfunction in individuals presenting with a gradually deteriorating mild SNHL may also provide further knowledge in this area.

As detailed throughout this thesis, there have been many hypotheses postulated to explain how hearing and cognition are related. Whilst this research has not been able to solidify definitive support for a singular hypothesis, it does suggest that hearing impairment may precede cognitive decline, most likely with a neurological underpinning, given the relationship between cognitive measures and CAP. Overall, the theory best supported by the present research from the five postulated hypotheses (see Figure 1, Chapter 2.3.) is the ‘sensory deprivation’ hypothesis (Baltes & Lindenberger, 1997; Desjardins, 2016a; Lindenberger & Baltes, 1994a; Valentijn et al., 2005) rather than the ‘resource allocation’ or ‘cognitive load’ hypotheses. Degree of SNHL is known to increase over time in age-related hearing loss. The results demonstrated that individuals with poorer audiometric thresholds were more likely to have CAP difficulties, and that those with more SNHL and CAP difficulties were more likely to perform poorer on tests of cognition. Given what is known about the progression of SNHL and the results of this study, it is logical that hearing loss is more likely to precede cognitive dysfunction (the sensory deprivation hypothesis). However, longitudinal and/or neuroimaging and physiological studies would be necessary to support this conclusion. The ‘resource allocation’ hypothesis was not able to be supported with the present study’s findings as cognitive function would need to improve post successful hearing rehabilitation. This was not measured in the present study. The ‘cognitive load’ hypothesis was also not supported from the present results. Whilst there was a range in cognitive performance, no participant was identified to have performed significantly poorly on cognitive assessments. However, there was a range of clinically defined SNHL and CAP dysfunction. Therefore, it is unlikely that cognitive dysfunction is a causal mechanism for hearing difficulties.

Furthermore, as age was not a significant mediator in this relationship, no support has been provided for a 'common cause' hypothesis that suggests hearing and cognitive decline are connected through a common cause such as aging. Lastly, the alternative theory that hearing and cognition are related due to test error (i.e. measuring cognitive function via aural tests in hearing impaired individuals) has been addressed in this study, as hearing was not required for successful completion of cognitive tests.

Although these five theories are popularly referenced within the literature, they do not highlight the multiple complexities of age-related decline in hearing and cognitive function. It is evident that listening requires an intricate combination of sensory, cognitive and social abilities (Pichora-Fuller et al., 2017). In fact, these intricacies underline the basis of the framework for understanding effortful listening (FUEL) (Pichora-Fuller et al., 2016). It is also evident that the link between hearing and cognitive decline is complex, and may involve multiple aspects of auditory and neurological pathways, in addition to psychosocial factors As shown in studies one and two, SNHL and central hearing impairment may be contributing in a intricate way to cognitive function. Additionally, the results of study three highlight associations between family interaction and hearing rehabilitation, and factors beyond peripheral hearing that may fit into this larger picture of the hearing-cognition link. The multifaceted, complex relationship between SNHL, CAP dysfunction and cognition, may indicate that there is a range of factors that can influence an individual's communicative ability that are not currently recognised in audiological assessment and practice.

A greater understanding of the association between hearing and cognition may help to guide future clinical practice and recommendations. For example, this may include modification of current rehabilitative practice and/or referrals for those at risk of cognitive decline. The final study highlighted that poor cognitive performance may negatively impact HA outcomes in individuals, whilst poorer hearing and greater social support may hold a positive influence for HA outcomes (i.e. use, uptake, perceived benefit). Therefore, knowledge of an individual's cognitive status may help guide realistic expectations and inform when additional assistance (e.g. from an audiologist or loved one) may be necessary. Overall, the combination of the studies included in this research have further highlighted the existence of a multifaceted, complex relationship between hearing and cognition, which has been previously discussed in models such as the FUEL (Pichora-Fuller et al., 2016).The results of this research have also demonstrated that these factors may be currently affecting rehabilitative outcomes for individuals with hearing loss. This emphasises the importance for the current generation of audiology practitioners to be literate in cognitive decline, and reflexive in rehabilitation approaches in order to provide true patient centred care, particularly in older populations.

8.4 CLINICAL IMPLICATIONS

The results of this research suggest that evaluating central auditory processing (particularly listening ability in background noise) in audiological assessments may be beneficial to patients for numerous reasons. Firstly, poorer results on the LiSN-S test, despite appropriate amplification, may help aid counselling for HA rehabilitation. This may be by creating realistic expectations for

HA users and/or by influencing rehabilitation plans for an individual (e.g. placing greater emphasis on communication strategies in addition to HA use) (Glyde et al., 2013). Secondly, poorer results on a LiSN-S test during initial audiological assessments may be indicative of a persons’ likelihood to choose to uptake HAs. Lastly, in addition to a SNHL, poorer CAP ability and/or an identified SP disorder may suggest potential cognitive issues. This may also influence HA rehabilitation, and may also be an indicator for the need for early intervention for cognitive impairment, as suggested by previous researchers in the area of hearing and cognition (Gates et al., 2011).

In addition to the clinical benefit of assessing CAP ability, this research has also identified further influential factors on HA rehabilitation. In addition to the impact of hearing impairment on HA uptake and perceived benefit, other factors including cognitive ability and increased family interaction positively influence HA use. If stronger cognitive ability in attention and psychomotor function is associated with increased self-reported HA use post HA fitting, then theoretically, those identified to have poorer cognition in these areas may need an adaptive approach to their hearing rehabilitation. This may include increased number of rehabilitative sessions, clearly written instructions, greater accessibility through telehealth where necessary, and/or ongoing communication with the patients support team (significant others, general practitioners etc.). This may assist in maximising HA use and function. Likewise, if increased family support/interaction also positively influences HA use, future research and clinical management should focus on the inclusion of significant others in hearing impairment rehabilitation.

8.5 STRENGTHS AND LIMITATIONS

As demonstrated by the increase in recent literature, the subject area of cognition and hearing is growing fast. Many projects have assessed whether hearing impairment (measured via PTA and/or self-report) and cognition are related. This has more recently been extended to a lesser number of studies which also considered associations between central hearing measures and cognition.

This project's novelty, in addition to its test battery, are the major strengths of the presented research, providing a unique approach and extending beyond previous literature in the area. Potential influencing factors such as physical, mental and social health were measured and analysed to assess if they were contributing factors in the associations found between hearing impairment and cognition, and significant findings were presented where appropriate (i.e. chapter 7).

No study to the best of my knowledge has compared cognitive performance between individuals with SNHL against a CAP impairment directly. Furthermore, the LiSN-S test has been used in few studies investigating binaural interaction skill and cognitive ability in older adults specifically. The LiSN-S provides an example of real-world listening ability (listening to target speech amongst spoken background noise, a common reported difficulty in older adults), and can also identify issues with SP. In the studies which have used the LiSN-S test as the primary assessment of CAP performance, LiSN-S performance was either: related to cognition using a screening assessment (the MoCA) (Besser et al., 2015), or was only related to cognitive performance before age and pure-tone hearing thresholds were accounted for (Glyde et al., 2013). Another strength of this study was the Cogstate cognitive assessment tool: a validated, visually presented assessment of cognition which assesses five different domains of cognitive performance. Many of the studies with a larger number of participants in this field have relied on a screening tool as the cognitive measurement, which has been unable to provide specific detail on what area of cognitive function is associated with hearing.

Whilst this study demonstrated some methodological strengths with the chosen form of assessments, there were some limitations to the tools used, study sample and overall methodology. Firstly, the DDT demonstrated a ceiling effect in the present sample and was not sensitive enough to replicate the findings of previous work. The sample size of this research was small compared with some studies in the field. The sample was also negatively skewed regarding SES and educational background, making this sample relatively limited for generalised conclusions about the overall population of older adults. Furthermore, there is ongoing debate about the specificity of the LiSN-S test, or CAP tests in general, to isolate CAP ability. That is, many contributing factors may be at play in reference to CAP skills including cognitive function, language and pure-tone hearing thresholds (Glyde et al., 2013). Peripheral hearing, as highlighted by the findings in study 2, significantly influenced performance on the LiSN-S, making it difficult to isolate CAP ability. Because of this, it is not possible to draw conclusions regarding whether cognition is separate to and/or related to CAP in isolation from other contributing variables from this study alone. Moreover, the time-frame of this study limited the ability to draw conclusions about changes to cognition over time in relation to hearing. Lastly, whilst the results of study 3 were promising in terms of HA outcomes, no long-term (beyond a six-month time frame) findings are available from this research.

8.6 FUTURE DIRECTIONS

Identifying long term cognitive outcomes of older adults presenting with CAP deficits, and the consequential potential benefit of early intervention may have significant positive impacts for an individual’s level of function and the socioeconomic burden associated with cognitive impairment. This may mean beginning referral pathways for those at risk of significant cognitive impairment such as dementia sooner (e.g. referring to a neuropsychologist for further assessment and long-term management). Some limited research suggests that remediation of SNHL with HAs may have a positive impact on cognitive function (see Amieva et al., 2015). However, there currently is no published high quality evidence (i.e. large number of participants and randomised-control study design) of this nature. If, like SNHL, poorer CAP ability is also shown to be related to faster cognitive decline, an area of future research may be the development and investigation of the efficacy of CAP training programs targeted at older adults with CAP difficulties. There is some evidence to suggest that AP training in children can significantly improve deficit specific CAP ability (Cameron, Glyde, & Dillon, 2012; Moncrieff & Wertz, 2008; Tomlin & Vandali, 2019). There are fewer AP training programs targeted to older adults, with little research available to date detailing whether AP training may improve CAP ability in this age group, or whether there are any potential long-term benefits of CAP improvement for cognitive function. However, one systematic review and meta-analysis revealed that following auditory training of varied lengths (from one week to two months) in those with hearing loss, there was a small but statistically significant improvement in both working memory and overall cognition (Lawrence et al., 2018). This may indicate a promising area of future research into the effects of auditory training programs and/or HAs on long-term cognitive function.

A better understanding of the complex mechanism/s through which hearing and cognitive impairment are interacting may contribute to an improved understanding of dementia. Future research should also consider hearing rehabilitation outcomes, both with regard to the management of hearing loss for individuals with factors that may impact the efficacy of rehabilitative outcomes (i.e. cognitive skills, social support etc.), and also the potential positive benefit that appropriate management of hearing impairment may have overall on long-term cognitive function. One randomized control trial currently set to be completed in 2022 known as the "ACHIEVE" study, reportedly will provide "...definitive evidence of the effect of hearing treatment on cognitive decline in community-dwelling older adults with mild-to-moderate hearing impairment" (Deal et al. 2018, p. 506). The findings of this research will provide promising insights into the effects of rehabilitation of hearing loss on cognitive function, and will hopefully guide further research direction. The association between hearing and cognition may be a promising link to optimising patient outcomes and reducing socioeconomic burden.

It has previously been suggested that audiologists may be appropriate sources of early identification of cognitive dysfunction in older adults with hearing loss/CAP dysfunction (Gates et al., 2011). Future research should investigate the feasibility of screening for cognitive dysfunction in audiology appointments in a population of those with hearing impairment. Additionally, another area of future research could be to find the most clinically applicable way to do so. The MMSE is a common screening tool for AD and was subsequently used in this research. However, other tools such as the MoCA may be more applicable to identify MCI and AD in a general population (De Roeck et al., 2019). Perhaps, as episodic memory is a cognitive domain most commonly declining in MCI patients who progress to dementia (Albert et al., 2011, p. 3), tests such as word-list learning test may be most appropriate to identify at risk clients. How verbal delivery may impact these tests in a hearing-impaired population however may be an important consideration to also make. Alternatively if there are time constraints, as outlined by Albert et al. (2011), a core component of the clinical criteria for the diagnosis of MCI would be reported change to cognition. This could be a rehabilitation clinician who knows the client well enough to identify this change themselves, or by asking the client/family members about cognitive concerns directly. Nevertheless, it is obvious there is need for future research to help learn how best to identify those at risk of MCI and/or dementia in a high-risk, hearing-impaired elderly population.

In the clinical setting, the older hearing-impaired patient will likely present with a complex combination of hearing loss, CAP dysfunction, variable cognitive function, alongside many other individual factors. In light of the findings of this research it is prudent to consider the multitude of factors an individual may be experiencing when determining the appropriate management pathway and expectations of both the clinician and the patient. A full understanding of the complex combination of abilities that a patient will present with is needed in order to provide a truly patient-centred rehabilitation approach.

8.7 GENERAL CONCLUSIONS

This research adds to current knowledge that peripheral hearing and CAP ability are associated with cognition. It specifically identified cognitive domains and measures of “hearing” that may form this relationship. Furthermore, those identified to have a SPD in addition to SNHL had significantly poorer executive function performance, indicating the importance of CAP function in the relationship between hearing and cognition. Future research should investigate the longitudinal cognitive implications of hearing impairment, particularly when accompanied by CAP deficit. Lastly, a combination of hearing, cognitive and psychosocial factors were found to impact HA outcomes in older Australians. These factors should be considered in audiological rehabilitation to best maximise patient rehabilitation outcomes, and further research should consider the long-term clinical implications of HA fitting on ‘natural’ cognitive decline in older adults.

APPENDICES

I. LiSN-S and DDT Score sheet

Participant:

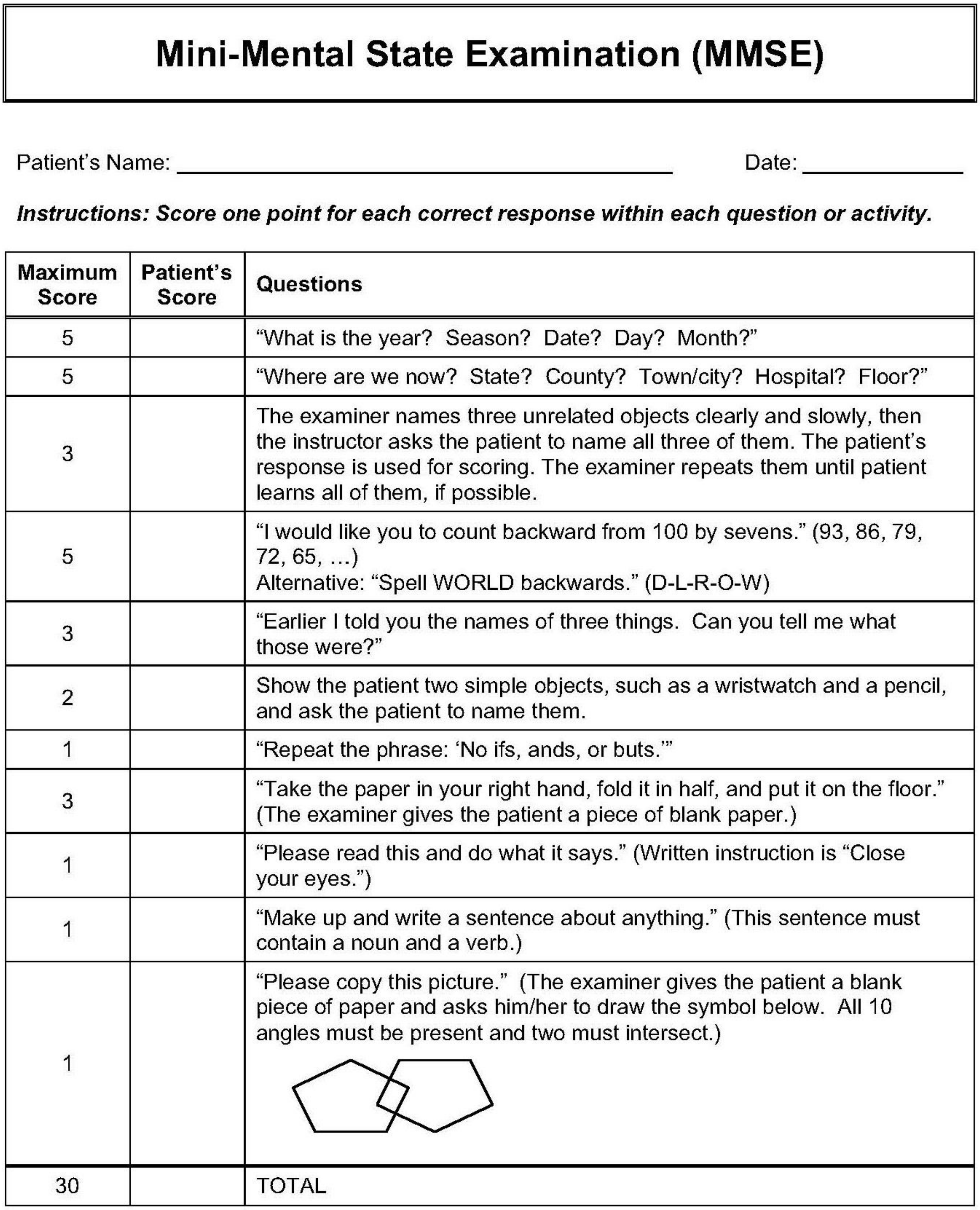
LiSN-S:

	High Cue	**Low Cue**	**Spatial adv**	**Tonal adv**	**Total adv**
Participants score					
SD					
Within normal range?					

DDT:

	LEFT	**RIGHT**
% Correct		
SD		

II. Mini-Mental State Examination (MMSE)



Mini-Mental State Examination (MMSE)

Patient's Name: ______________________________ Date: ____________

Instructions: Score one point for each correct response within each question or activity.

Maximum Score	Patient's Score	Questions
5		"What is the year? Season? Date? Day? Month?"
5		"Where are we now? State? County? Town/city? Hospital? Floor?"
3		The examiner names three unrelated objects clearly and slowly, then the instructor asks the patient to name all three of them. The patient's response is used for scoring. The examiner repeats them until patient learns all of them, if possible.
5		"I would like you to count backward from 100 by sevens." (93, 86, 79, 72, 65, …) Alternative: "Spell WORLD backwards." (D-L-R-O-W)
3		"Earlier I told you the names of three things. Can you tell me what those were?"
2		Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.
1		"Repeat the phrase: 'No ifs, ands, or buts.'"
3		"Take the paper in your right hand, fold it in half, and put it on the floor." (The examiner gives the patient a piece of blank paper.)
1		"Please read this and do what it says." (Written instruction is "Close your eyes.")
1		"Make up and write a sentence about anything." (This sentence must contain a noun and a verb.)
1		"Please copy this picture." (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below. All 10 angles must be present and two must intersect.)
30		TOTAL

Interpretation of the MMSE:

Method	Score	Interpretation
Single Cutoff	<24	Abnormal
Range	<21	Increased odds of dementia
	>25	Decreased odds of dementia
Education	21	Abnormal for 8th grade education
	<23	Abnormal for high school education
	<24	Abnormal for college education
Severity	24-30	No cognitive impairment
	18-23	Mild cognitive impairment
	0-17	Severe cognitive impairment

Interpretation of MMSE Scores:

Score	Degree of Impairment	Formal Psychometric Assessment	Day-to-Day Functioning
25-30	Questionably significant	If clinical signs of cognitive impairment are present, formal assessment of cognition may be valuable.	May have clinically significant but mild deficits. Likely to affect only most demanding activities of daily living.
20-25	Mild	Formal assessment may be helpful to better determine pattern and extent of deficits.	Significant effect. May require some supervision, support and assistance.
10-20	Moderate	Formal assessment may be helpful if there are specific clinical indications.	Clear impairment. May require 24-hour supervision.
0-10	Severe	Patient not likely to be testable.	Marked impairment. Likely to require 24-hour supervision and assistance with ADL.

Source:

- Folstein MF, Folstein SE, McHugh PR: “Mini-mental state: A practical method for grading the cognitive state of patients for the clinician.” *J Psychiatr Res* 1975;12:189-198.

III. Memory Complaint Questionnaire

Participant ID: **Participant Initials:** **Date:** **Ax:**

As compared to when you were in your late teenage years or early 20s, how would you describe your ability to perform the following tasks involving your memory?

Please tick one of the boxes for each question

	Much better now 1	Somewhat better now 2	About the same 3	Somewhat poorer now 4	Much poorer now 5
Remembering the name of a person just introduced to you?					
Recalling telephone numbers or postcodes that you use on a daily or weekly basis					
Recalling where you have put objects (such as keys) in your home or office?					
Remembering specific facts from a magazine or a newspaper article you have just finished reading?					
Remembering the item(s) you intended to buy when you arrive at the grocery store or pharmacy?					

In general, how would you describe your memory as compared to when you were in high school?	2	4	6	8	10

TOTAL_______/35

IV. Loneliness Scale

Participant ID: **Participant Initials:** **Ax:**

Please indicate for each of the 11 statements, the extent to which they apply to your situation, the way you feel now.

<u>Please circle the appropriate answer</u>

1. There is always someone I can talk to about my day to day problems	Yes!	yes	More or less	No!	no
2. I miss having a really close friend	Yes!	yes	More or less	No!	no
3. I experience a general sense of emptiness	Yes!	yes	More or less	No!	no
4. There are plenty of people I can lean on when I have problems	Yes!	yes	More or less	No!	no
5. I miss the pleasure of the company of others	Yes!	yes	More or less	No!	no
6. I find my circle of friends and acquaintances too limited	Yes!	yes	More or less	No!	no
7. There are many people I can trust completely	Yes!	yes	More or less	No!	no
8. There are enough people I feel close to	Yes!	yes	More or less	No!	no
9. I miss having people around me	Yes!	yes	More or less	No!	no
10. I often feel rejected	Yes!	yes	More or less	No!	no
11. I can call on my friends whenever I need them	Yes!	yes	More or less	No!	no

De Jong Gierveld & Kamphuis (1985)

V. Lubben Social Network Scale – 18 (LSNS-18)

LUBBEN SOCIAL NETWORK SCALE – 18 (LSNS-18)

FAMILY: *Considering the people to whom you are related by birth, marriage, adoption, etc…*

1. How many relatives do you see or hear from at least once a month?
0 = *none* 1 = *one* 2 = *two* 3 = *three or four* 4 = *five thru eight* 5 = *nine or more*

2. How often do you see or hear from relative with whom you have the most contact?
0 = *less than monthly* 1 = *monthly* 2 = *few times a month* 3 = *weekly* 4 = *few times a week*
5 = *daily*

3. How many relatives do you feel at ease with that you can talk about private matters?
0 = none 1 = one 2 = two 3 = three or four 4 = five thru eight 5 = nine or more

4. How many relatives do you feel close to such that you could call on them for help?
0 = *none* 1 = *one* 2 = *two* 3 = *three or four* 4 = *five thru eight* 5 = *nine or more*

5. When one of your relatives has an important decision to make, how often do they talk to you about it?
0 = *never* 1 = *seldom* 2 = *sometimes* 3 = *often* 4 = *very often* 5 = *always*

6. How often is one of your relatives available for you to talk to when you have an important decision to make?
0 = *never* 1 = *seldom* 2 = *sometimes* 3 = *often* 4 = *very often* 5 = *always*

NEIGHBORS: *Considering those people who live in your neighborhood…*

7. How many of your neighbors do you see or hear from at least once a month?
0 = *none* 1 = *one* 2 = *two* 3 = *three or four* 4 = *five thru eight* 5 = *nine or more*

8. How often do you see or hear from the neighbor with whom you have the most contact?
0 = *less than monthly* 1 = *monthly* 2 = *few times a month* 3 = *weekly* 4 = *few times a week*
5 = *daily*

9. How many neighbors do you feel at ease with that you can talk about private matters?
0 = *none* 1 = *one* 2 = *two* 3 = *three or four* 4 = *five thru eight* 5 = *nine or more*

10. How many neighbors do you feel close to such that you could call on them for help?
0 = *none* 1 = *one* 2 = *two* 3 = *three or four* 4 = *five thru eight* 5 = *nine or more*

11. When one of your neighbors has an important decision to make, how often do they talk to you about it?
0 = never 1 = seldom 2 = sometimes 3 = often 4 = very often 5 = always

12. How often is one of your neighbors available for you to talk to when you have an important decision to make?
0 = *never* 1 = *seldom* 2 = *sometimes* 3 = *often* 4 = *very often* 5 = *always*

FRIENDSHIPS: *Considering your friends who do not live in your neighborhood…*

13. How many of your friends do you see or hear from at least once a month?
0 = *none* 1 = *one* 2 = *two* 3 = *three or four* 4 = *five thru eight* 5 = *nine or more*

14. How often do you see or hear from the friend with whom you have the most contact?
0 = *less than monthly* 1 = *monthly* 2 = *few times a month* 3 = *weekly* 4 = *few times a week*
5 = *daily*

15. How many friends do you feel at ease with that you can talk about private matters?
0 = *none* 1 = *one* 2 = *two* 3 = *three or four* 4 = *five thru eight* 5 = *nine or more*

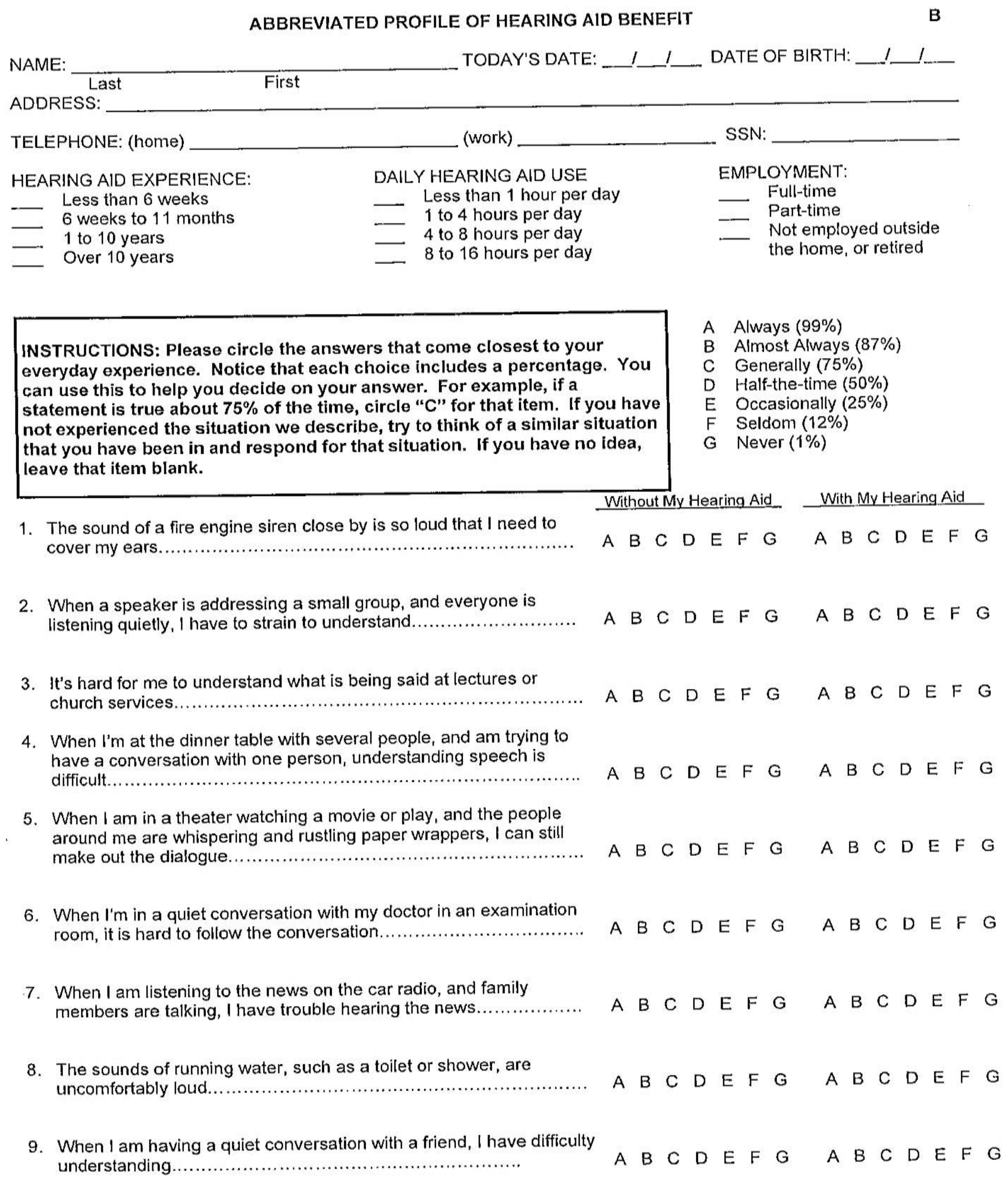
16. How many friends do you feel close to such that you could call on them for help?
0 = *none* 1 = *one* 2 = *two* 3 = *three or four* 4 = *five thru eight* 5 = *nine or more*

17. When one of your friends has an important decision to make, how often do they talk to you about it?
0 = never 1 = seldom 2 = sometimes 3 = often 4 = very often 5 = always

18. How often is one of your friends available for you to talk to when you have an important decision to make?
0 = *never* 1 = *seldom* 2 = *sometimes* 3 = *often* 4 = *very often* 5 = *always*

LSNS-R total score is an equally weighted sum of these twelve items. Scores range from 0 to 90

VI. Abbreviated Profile of Hearing Aid Benefit (APHAB)



ABBREVIATED PROFILE OF HEARING AID BENEFIT B

NAME: ______________________ TODAY'S DATE: ___/___/___ DATE OF BIRTH: ___/___/___
Last First
ADDRESS: ______________________
TELEPHONE: (home) ______________ (work) ______________ SSN: ______________

HEARING AID EXPERIENCE:
___ Less than 6 weeks
___ 6 weeks to 11 months
___ 1 to 10 years
___ Over 10 years

DAILY HEARING AID USE
___ Less than 1 hour per day
___ 1 to 4 hours per day
___ 4 to 8 hours per day
___ 8 to 16 hours per day

EMPLOYMENT:
___ Full-time
___ Part-time
___ Not employed outside the home, or retired

INSTRUCTIONS: Please circle the answers that come closest to your everyday experience. Notice that each choice includes a percentage. You can use this to help you decide on your answer. For example, if a statement is true about 75% of the time, circle "C" for that item. If you have not experienced the situation we describe, try to think of a similar situation that you have been in and respond for that situation. If you have no idea, leave that item blank.

A Always (99%)
B Almost Always (87%)
C Generally (75%)
D Half-the-time (50%)
E Occasionally (25%)
F Seldom (12%)
G Never (1%)

	Without My Hearing Aid	With My Hearing Aid
1. The sound of a fire engine siren close by is so loud that I need to cover my ears........	A B C D E F G	A B C D E F G
2. When a speaker is addressing a small group, and everyone is listening quietly, I have to strain to understand........	A B C D E F G	A B C D E F G
3. It's hard for me to understand what is being said at lectures or church services........	A B C D E F G	A B C D E F G
4. When I'm at the dinner table with several people, and am trying to have a conversation with one person, understanding speech is difficult........	A B C D E F G	A B C D E F G
5. When I am in a theater watching a movie or play, and the people around me are whispering and rustling paper wrappers, I can still make out the dialogue........	A B C D E F G	A B C D E F G
6. When I'm in a quiet conversation with my doctor in an examination room, it is hard to follow the conversation........	A B C D E F G	A B C D E F G
7. When I am listening to the news on the car radio, and family members are talking, I have trouble hearing the news........	A B C D E F G	A B C D E F G
8. The sounds of running water, such as a toilet or shower, are uncomfortably loud........	A B C D E F G	A B C D E F G
9. When I am having a quiet conversation with a friend, I have difficulty understanding........	A B C D E F G	A B C D E F G

A	Always (99%)
B	Almost Always (87%)
C	Generally (75%)
D	Half-the-time (50%)
E	Occasionally (25%)
F	Seldom (12%)
G	Never (1%)

	Without My Hearing Aid	With My Hearing Aid
10. I can understand conversations even when several people are talking..	A B C D E F G	A B C D E F G
11. The sounds of construction work are uncomfortably loud..............	A B C D E F G	A B C D E F G
12. I have trouble understanding others when an air conditioner or fan is on..	A B C D E F G	A B C D E F G
13. I have trouble understanding the dialogue in a movie or at the theater..	A B C D E F G	A B C D E F G
14. Traffic noises are too loud...	A B C D E F G	A B C D E F G
15. When I am in a small office, interviewing or answering questions, I have difficulty following the conversation......................................	A B C D E F G	A B C D E F G
16. I miss a lot of information when I'm listening to a lecture...............	A B C D E F G	A B C D E F G
17. I have to ask people to repeat themselves in one-on-one conversation in a quiet room...	A B C D E F G	A B C D E F G
18. Unexpected sounds, like a smoke detector or alarm bell are uncomfortable..	A B C D E F G	A B C D E F G
19. I can follow the words of a sermon when listening to a religious service...	A B C D E F G	A B C D E F G
20. When I am in a crowded grocery store, talking with the cashier, I can follow the conversation...	A B C D E F G	A B C D E F G
21. I can communicate with others when we are in a crowd................	A B C D E F G	A B C D E F G
22. The sound of screeching tires is uncomfortably loud.....................	A B C D E F G	A B C D E F G
23. I have difficulty hearing a conversation when I'm with one of my family at home..	A B C D E F G	A B C D E F G
24. When I am talking with someone across a large empty room, I understand the words...	A B C D E F G	A B C D E F G

HARL
Hearing Aid Research Lab.

VII. Hearing Aid Case History (3/6 Months)

HA Case History Update Form – 3/6 months

This form helps us track your hearing aid usage, general health and progress. It also ensures our data in our study is accurate and up to date.

SECTION 1: GENERAL INFORMATION

Name:____

Since we last had contact with you have any of these details changed? Yes / No (If yes please give details)

Next of kin:____

Telephone: Preferred contact number_________________

Preferred time to call _________________

Email address: ______________________________________

The following questions relate to your HA usage

Since we last had contact have you change your hearing aid provider? Yes / No (please circle)

If yes, please provide new details: ____

____

In general, how much time a day do you wear your HA? (Please circle)

Right HA	**Left HA**
1. Greater than 90% of waking hours	1. Greater than 90% of waking hours
2. Greater than 60% of waking hours but less than 90%	2. Greater than 60% of waking hours but less than 90%
3. 30-60% of waking hours	3. 30-60% of waking hours
4. Less than 30% of waking hours	4. Less than 30% of waking hours
5. Hearing aid no longer useful, therefore stopped using it	5. Hearing aid no longer useful, therefore stopped using it
6. Do not use hearing aid at all in this ear	6. Do not use hearing aid at all in this ear

Time taken to adapt to achieve >90% use when awake:

1. Within the first week
2. 1 week to 3 months
3. 3-6 months
4. 6-12 months
5. Greater than 12 months
6. Other (i.e. I have only had my HA for less than 3 months, specify) ____

Give details of the times that you did not wear your HA *(not including sleeping, bathing and swimming)*

On average how many hours per day do you wear your Left HA? (Skip if no left HA) ______

On average how many hours per day do you wear your Right HA? (Skip if no right HA) ______

On average, how many hours per day would you spend listening to speech in a quiet environment (e.g. one to one conversation at home)? _______

On average how many hours per day would you spend listening to speech in a noisy environment (e.g. Café, restaurant or group situation)? __________

On average how many hours per day would you spend in a noisy environment (e.g. Outside in traffic, in a room with a television, using tools/machinery or a sewing machine)? __________

On average how many hours per day would you spend in a quiet environment (e.g. at home with little conversation, reading quietly)? ________

On average how many hours per day would you spend listening to music? _________

Have you been fitted with a second HA since we last saw you? (If so please enter the date of fitting)

Bilateral hearing aid use

If you have two HAs please answer the following question.

Bilateral HA use: In general, how much time a day do you wear both HAs together (*Please circle)*
(Skip if not applicable i.e. only wearing one HA at the moment)

1. Greater than 90% of waking hours
2. Greater than 60% of waking hours but less than 90% of waking hours
3. 30-60% of waking hours
4. Less than 30% of the time
5. Not wearing both together

Unilateral hearing aid use

If you have one HA please answer the following questions.

Unilateral HA use: In general, how much time a day do you wear your HA *(Please circle)*
(Skip if not applicable i.e. you wear two HA at the moment)

1. **Most waking hours** (>90% of the time)
2. **Greater than** 60% of waking hours
3. **Inconsistent** use (30-60% of waking hours)
4. **Minimal use** (less than 30% of the time)
5. **Does not use hearing aids at all**

Form completed by: **Date:**

Thank you very much for your time in completing this form. It is greatly appreciated by the team.

VIII. Additional Materials

A copy of the following have not been included in the attached appendices due to length and/or copyright issues (however can be made available upon request):

- HUI
- HADS
- Educational history form
- Case history form

IX Ethics Documentation

Plain Language Statement

School of Medicine, Dentistry and Health Sciences
Department of Audiology and Speech Pathology

Project: The Effect of Higher Order Listening Function and Hearing Loss on Cognition in the Elderly

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Introduction

Thank you for your interest in participating in this research project. The following few pages will provide you with further information about the project, so that you can decide if you would like to take part in this research.

Please take the time to read this information carefully. You may ask questions about anything you don't understand or want to know more about.

Your participation is voluntary. If you don't wish to take part, you do not have to. If you begin participating, you can also stop at any time.

What is this research about?

Cognitive decline and hearing loss are two common conditions that increase with age. These two conditions impact on people's independence and quality of life, and create a significant financial cost to the community. Research has shown that hearing loss and cognitive decline often occur together. Impairments in higher order listening processes have also been associated with cognitive function.

Hearing aids have been shown to improve hearing, independence and quality of life. Recent research has shown that the use of hearing aids may help with cognitive function and delay dementia onset. Further investigation of this is required. Tests that assess higher order listening processes have been found to predict the likelihood of developing dementia, even before there are symptoms. It is therefore also important to understand how higher order listening skills are related to cognitive function and whether or not these affect the successful use of hearing aids. The aim of this study is to see if higher order listening skills are connected to cognition. It also aims to explore if any of these factors affect the use of hearing aids.

What will I be asked to do?

Should you agree to participate, you will be asked to contribute in the following way:

a. Complete the CogState Brief Battery (a computerized assessment of cognitive function). This takes approximately 30 minutes.

b. Complete auditory processing testing (listening to sentences in differing degrees of background noise [LiSN-S: Listening in Spatialized Noise-Sentences test] and the presentation of two number to each ear at the same time [DDT: Dichotic Digits Test]; 30 minutes).

c. Complete fourquestionnaires initially (which you are welcome to take home and post back in a stamped, addressed envelope), as follows:

Quality of Life:

The Hospital Anxiety and Depression Scale (HADS – 2-5 minutes)

The Health Utilities Index-3 Quality of Life Questionnaire (HUI-3 – 8 minutes)

Health and Lifestyle:

The International Physical Activity Questionnaire (IPAQ -20 minutes)

The Bayer Activities of Daily Living Scale (10-15 minutes).

e) Medical History

You will be asked to provide a detailed medical history, including family medical history (including family history of mental illness and other neurological illnesses, including dementia) and personal medical history, including smoking, current and past alcohol, illicit drug and medication use.

f) Complete two short questionnaires and return in the mail at three and six month's after hearing aid fitting:

Device use questionnaire

The abbreviated Profile of Hearing Aid Benefit (APHAB)

g) information about the duration of your hearing aid use will be extracted from your Academic Hearing Aids clinic file over 6 months after your review visits at the clinic.

How long is my participation expected to take?

Only one visit will be required. The estimated time for that visit will be 90 – 150 minutes, and the time required to respond to the questionnaires will be 65 -86 minutes. The maximum total time required of you will not exceed 3.5 hours.

What are the possible benefits?

Expected benefits to participants from this research include:

- The opportunity to receive support from an experienced professional who understands what it means to have a hearing loss through both

previous experiences with hard of hearing individuals and also with a personal experience of hearing loss and spatial processing disorder.
- The opportunity to help others in the future through participating in this research.
- Knowledge about your cognitive function and your speech perception ability.

A further benefit of this research is that it will increase understanding about which aspects and tests of auditory processing are related to cognition. The results of this study may help to inform future clinical practice in both the testing and the management of older adults who attend hearing assessments. It may encourage future research into auditory processing as a screening tool for cognitive issues which could alleviate some burden of cost and care required by the elderly population.

What are the possible risks?

While this research does not involve any interventional treatment, and there are no physical risks, you will be participating in assessments of your cognitive function and speech perception abilities. You may find some parts of these assessments boring and/or difficult. If you are unable to do the tasks required in the assessment, you may find this frustrating. You are entitled to know about your performance on these assessments, and we will be happy to provide your results if you request them. If your performance is poor, you may find this distressing.

If at any time you find participating in this project distressing or difficult, you may suspend or end your participation.

Do I have to take part?

Participation is completely voluntary. Should you wish to withdraw at any stage, or to withdraw any unprocessed data you have supplied, you are free to do so without prejudice.

You do not have to take part in this research project to receive treatment at this clinic. You will receive exactly the same program of care whether or not you participate in this study, and whether or not your audiologist is directly involved with this research.

Your decision whether to take part or not to take part, or to take part and then withdraw, will not affect your care, your relationship with those treating you or your relationship with the University of Melbourne School of Audiology Clinic.

Additional costs and reimbursement

There are no costs associated with participating in this research project, nor will you be paid. You will be reimbursed for any of the following costs that you incur as a result of participating in this research. You will be reimbursed for any reasonable travel, parking, refreshments and petrol associated with the research project visits.

Will I hear about the results of this project?

The results of this study will contribute to a graduate research PhD project. No names will be used in the presentation of data at any time. No data will be available online, and no person other than the research team will have access to any data. A brief summary of the research findings can be made available to you in the form of a written report.

What will happen to information about me?

We intend to protect your anonymity and the confidentiality of your responses to the fullest possible extent, subject to any legal requirements. Your name and contact details will be kept in a password-protected computer file, separate from any data that you supply. Electronic data will be stored on the University server and will be accessed only by project staff, using individual passwords and authorised by University IT, under the instructions of Dr. Sarant. In order to ensure that others cannot match data to specific participants or access data in any way, all identifiable paper records will be locked in filing cabinets, the keys to which will be stored in a secure place known only to project staff.

At the conclusion of the study and until 5 years after publication of the final data, the paper data will be stored in the archives in locked filing cabinets. Only authorised staff members have access to this locked room.

What happens after the project is finished?

The results of this study will be published in a graduate research PhD project. No names will be used in the presentation of data at any time. No data will be available online, and no person other than the research team will have access to any data. A brief summary of the research findings will be made available to you in the form of a written report.

Where can I get further information?

If you would like more information about the project, please contact the researchers; Grace Nixon nixon.g@unimelb.edu.au, or Julia Sarant jsarant@unimelb.edu.au

Who can I contact if I have any concerns about the project?

This research project has been approved by the Human Research Ethics Committee of The University of Melbourne. If you have any concerns or complaints about the conduct of this research project, which you do not wish to discuss with the research team, you should contact the Manager, Human Research Ethics, Office for Research Ethics and Integrity, University of Melbourne, VIC 3010. Tel: +61 3 8344 2073 or Email: HumanEthics-complaints@unimelb.edu.au. All complaints will be treated confidentially. In any correspondence please provide the name of the research team or the name or ethics ID number of the research project.

Consent Form

School of Medicine, Dentistry and Health Sciences.
Department of Audiology and Speech Pathology

Project: The Effect of Higher Order Listening Function and Hearing Loss on Cognition in the Elderly

Primary Researcher: Dr. Julia Sarant (Responsible Researcher)

Additional Researchers: Grace Nixon (PhD Student)

Name of Participant: ______________________________

1. I consent to participate in this project, the details of which have been explained to me, and I have been provided with a written plain language statement to keep.
2. I understand that the purpose of this research is to investigate the link between listening function and cognition.
3. I understand that my participation in this project is for research purposes only.
4. I acknowledge that the possible effects of participating in this research project have been explained to my satisfaction.
5. In this project I will be required to participate in assessments of speech perception ability and cognitive function, as well as complete questionnaires.
6. I understand that my participation is voluntary and that I am free to withdraw from this project anytime without explanation or prejudice and to withdraw any unprocessed data that I have provided.
7. I understand that the data from this research will be stored at the University of Melbourne and will be destroyed after 5 years.
8. I have been informed that the confidentiality of the information I provide will be safeguarded subject to any legal requirements; my data will be password protected and accessible only by the named researchers.
9. I understand that after I sign and return this consent form, it will be retained by the researcher.

Participant Signature: ____________________ **Date:** ______________

HREC Number: [*1748836.1*] Project Start Date: [23/01/2017] Version: [Version 1]

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